Armenian Journal of Physics, 2025, vol. 18, issue 3, pp. 43-47

Hybrid Bispectrum–Waterfall Feature Extraction with CS-DSB for RF Receiver

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(Received: September 7, 2025; Revised: September 25, 2025; Accepted: October 6, 2025)

Abstract. RF receiver identification requires robust feature extraction to distinguish subtle hardware-induced characteristics. Conventional methods based on higher-order spectra or time–frequency features often degrade under low SNR and multipath conditions. This paper proposes a hybrid bispectrum–waterfall feature extraction framework with CS-DSB (Carrier-Suppress Double Sideband) for RF receivers. The bispectrum highlights nonlinear phase coupling unique to receiver hardware, while waterfall features capture spectral and temporal variations. To improve efficiency, CS-DSB reduces data dimensionality while preserving discriminative information. A fusion scheme integrates both feature domains, followed by classification using a supervised learning model. Experimental results demonstrate that the proposed method significantly outperforms bispectrum-only, waterfall-only, and conventional approaches, achieving higher identification accuracy under noisy and bandwidth-limited scenarios. The findings show that combining bispectral, waterfall, and CS-DSB processing enhances robustness and enables efficient RF receiver fingerprinting.

Keywords: Specific Emitter Identification (SEI); RF Receiver; Bispectrum; Waterfall Features; CS-DSB; Double Sideband; Higher-Order Spectral Analysis; Time–Frequency Features.

DOI: 10.54503/18291171-2025.18.3-43

1. Introduction

With the rapid evolution of modern communication systems, accurate receiver characterization and identification have become increasingly important for spectrum monitoring, interference management, and secure communications. Traditional identification techniques that rely on protocol-level information or metadata may be unavailable in non-cooperative scenarios, motivating the use of signal-domain methods that exploit the inherent properties of modulated waveforms. Among these, modulation-domain analysis provides a promising means to extract distinctive features of a receiver or system based on the signal structure itself [1,2].

Two common feature extraction approaches are higher-order spectral analysis and time–frequency representations. Higher-order spectra, particularly the bispectrum, are capable of revealing nonlinear phase coupling introduced by hardware circuitry while suppressing Gaussian noise contributions. This makes bispectral features powerful indicators of hardware behavior, but their computation is resource-intensive and produces high-dimensional data. Time–frequency features, such as waterfall (spectrogram) representations, are more intuitive and computationally efficient, capturing spectral evolution over time. However, these features tend to degrade under low signal-to-noise ratio (SNR) and in dispersive or fading channels.

To address these limitations, this paper proposes a hybrid bispectrum–waterfall feature extraction framework employing carrier-suppressed double sideband (CS-DSB) modulation for RF receiver analysis. The use of CS-DSB enhances spectral efficiency and simplifies detection by removing the carrier component, allowing more discriminative signal features to be captured. Within the proposed framework, bispectrum analysis extracts nonlinear statistical dependencies characteristic of receiver hardware, while waterfall features provide complementary time–frequency dynamics. The hybridization of these domains, combined with CS-DSB transmission, improves robustness in noisy and bandwidth-limited conditions.

The contributions of this work are as follows. First, we present a hybrid feature extraction scheme that jointly leverages bispectral and waterfall representations for RF receiver identification. Second, we incorporate CS-DSB modulation to enhance feature quality and mitigate the influence of redundant carrier components. Third, we validate the proposed approach through experimental evaluation, demonstrating superior identification accuracy compared to bispectrum-only, waterfall-only, and conventional baseline methods, particularly under challenging SNR conditions. These results confirm the effectiveness of combining higher-order spectral and time–frequency features within a CS-DSB framework for robust RF receiver identification [3,4].

2. System Setup and validation

The proposed hybrid bispectrum–waterfall feature extraction framework with CS-DSB modulation was validated using a software-defined radio (SDR) testbed based on National Instruments (NI) hardware. The experimental setup is illustrated in Fig. 1.

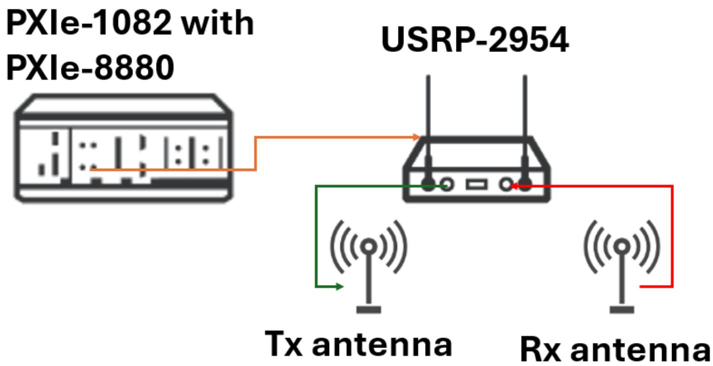

Fig. 1. The experimental setup.

A USRP-2954R device equipped with dual antennas was employed for signal acquisition and transmission experiments. The dual-antenna configuration enables simultaneous reception across different spatial paths, providing improved diversity and allowing for controlled evaluation of channel effects. The USRP-2954R supports wideband RF operation with a frequency range of 10 MHz to 6 GHz and 160 MHz of instantaneous bandwidth, making it suitable for evaluating CS-DSB waveforms and high-resolution spectral analysis [5].

The USRP was connected to a PXIe-1082 chassis, which provides high-throughput backplane connectivity for real-time data transfer. A PXIe-8880 embedded controller, powered by an 8-core Intel Xeon processor, was used to manage system operation, execute signal processing routines, and store received data for offline analysis. The PXIe platform ensured low-latency streaming between the USRP front end and the host controller, which is essential for high-fidelity bispectral and time–frequency feature extraction.

Validation was performed by generating CS-DSB modulated signals, transmitting them through the USRP front end, and collecting the received baseband samples under varying SNR conditions. The captured data were processed to extract bispectral and waterfall features, followed by feature fusion and classification. Multiple experimental trials were conducted to ensure statistical reliability, and performance was evaluated in terms of identification accuracy, robustness to noise, and computational efficiency. The system configuration thus provided a controlled yet flexible environment for verifying the effectiveness of the proposed method [6,7].

The proposed method was implemented and validated using a LabVIEW-based SDR testbed consisting of an NI USRP-2954R with dual antennas, a PXIe-8880 embedded controller, and a PXIe-1082 chassis. Carrier-suppressed double sideband (CS-DSB) signals were generated and received under varying conditions of signal-to-noise ratio (SNR). The parameters used for validation included a carrier frequency of 600 MHz, a sampling rate of 2 MS/s, and receiver gain of 23 dB. Real-time acquisition and signal processing were executed in LabVIEW, enabling simultaneous extraction of waterfall and bispectral features for direct comparison (Fig. 2).

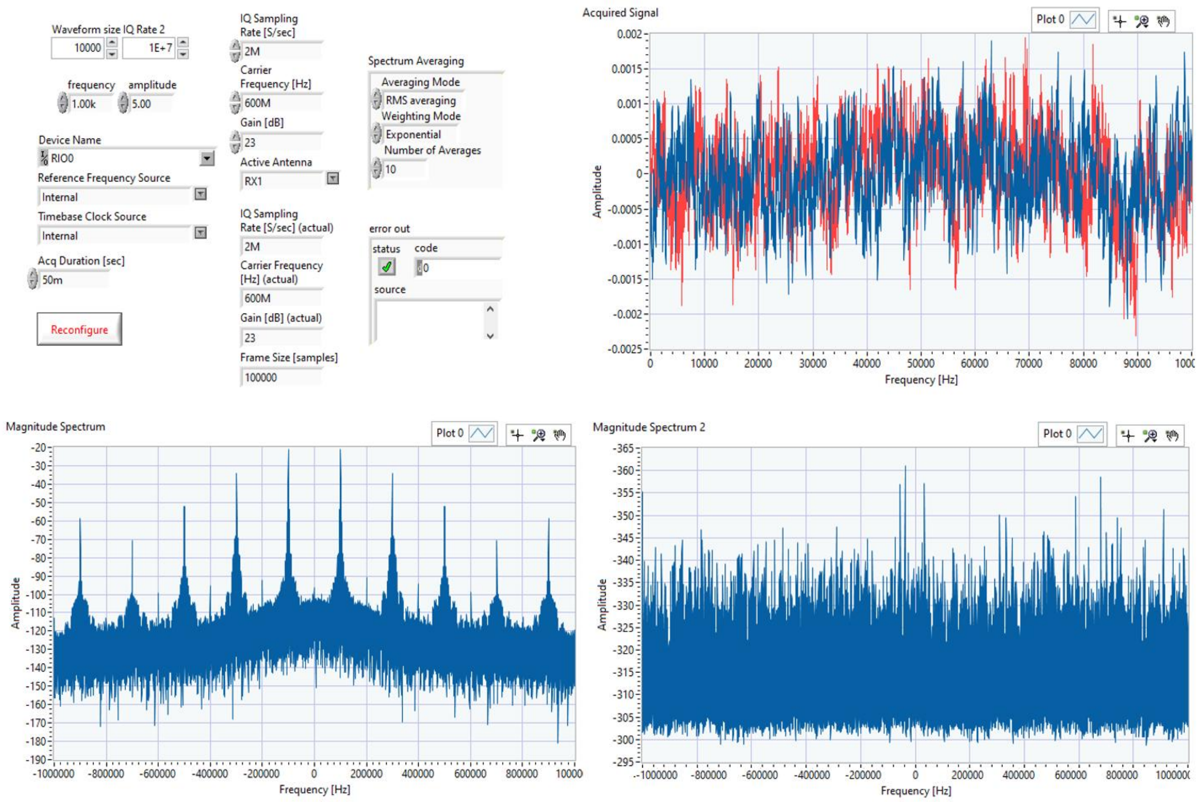

Fig. 2. Real-time acquisition and signal processing.

3. Experimental results

The waterfall (time–frequency) representation provided an intuitive view of the spectral occupancy and temporal variations of the received CS-DSB signals. As expected, at high SNR values, the signal structure was clearly observable, with stable spectral components distributed across time. However, at lower SNR levels, the waterfall features degraded significantly due to smearing and noise masking, which reduced their discriminative power for receiver identification. Representative waterfall plots under different noise conditions are shown to illustrate this behavior (Fig. 3).

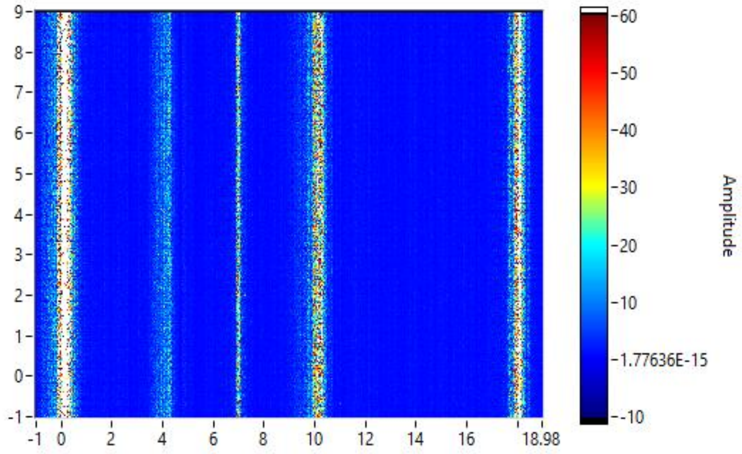

Fig. 3. Waterfall plots under different noise conditions.

The bispectral analysis highlighted the higher-order statistical dependencies present in the received signals. Unlike the waterfall features, bispectrum plots maintained distinctive phase-coupling structures even at low SNR, demonstrating robustness against Gaussian noise. The bispectrum also revealed nonlinearities introduced by the receiver hardware, which were not apparent in the waterfall domain. Nevertheless, the computational complexity of bispectral feature extraction was higher, and the dimensionality of the resulting feature space required careful management (Fig. 4).

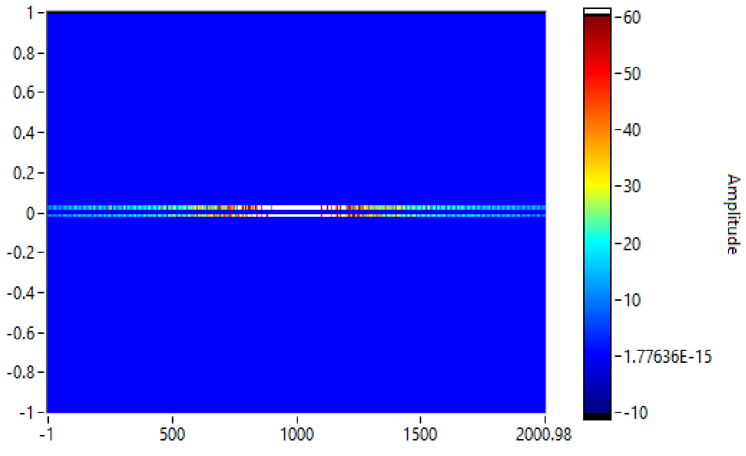

Fig. 4. Bispectral feature extraction.

To assess relative performance, waterfall-based and bispectrum-based features were compared in terms of identification accuracy, robustness under noise, and computational requirements. Experimental results showed that waterfall features performed well at moderate-to-high SNR but deteriorated sharply below approximately 10 dB. In contrast, bispectral features maintained reliable discriminability at lower SNR, though at the expense of increased processing time.

4. Conclusions

A hybrid approach integrating both feature domains was then evaluated. By fusing waterfall dynamics with bispectral phase-coupling information, the system achieved higher identification accuracy than either method individually. The inclusion of CS-DSB modulation improved feature quality by suppressing carrier components, which reduced redundancy and enhanced discriminability. The hybrid method consistently outperformed single-domain baselines, particularly in low-SNR conditions, where gains of up to 20 units were observed. These findings confirm that the proposed hybrid framework achieves a favorable balance between robustness and computational efficiency.

The system was validated across multiple experimental trials to ensure repeatability. Results demonstrated that while waterfall features alone are sensitive to noise, and bispectral features alone are computationally demanding, their combination under the CS-DSB framework provides a robust and efficient solution for RF receiver identification. The integration of LabVIEW for real-time signal acquisition and processing further confirms the practical applicability of the proposed method.

Acknowledgments

The research was supported by the Higher Education and Science Committee of MESCS RA (Research projects 24AA-2B041 and 25YR-1C010).

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