

A Review of 6G Radio Signal Recognition Based on Digital Signal Processing

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Abstract. As a vital step before signal demodulation, radio signal recognition (RSR) technology must overcome ultra-high dimensionality, ultra-wide bandwidth, extreme heterogeneity, and strong dynamicity due to the rapid development of 6G research and its core enabling technologies. Radio signal recognition underpins the core capabilities of 6G, enabling intelligent spectrum situational awareness, dynamic resource allocation, precise identification of non-cooperative targets, and ultra-secure communications. As a result, the performance requirements for RSR have also rapidly increased. Digital signal processing (DSP) is the essential core and primary component of RSR technology, playing a vital role in radio signal recognition. Therefore, this paper focuses on RSR technology based on digital signal processing, combining recent research findings to systematically review its progress, challenges, and future directions. This study finds that in the 6G era, RSR can break the bottleneck of security, hardware and cross-domain conflict through three paths: "quantum-DSP collaborative computing, hypersurface photon sensing and federated learning".

Keywords: Digital Signal Processing (DSP), 6G Radio Signal Recognition, Reconfigurable Intelligent Surfaces (RIS), Compressed Sensing, Deep Learning

1. Introduction

The quintessential 6G use cases—terahertz links, RIS-enabled intelligent transmission, and converged air-ground-space networks—pose formidable hurdles to reliable radio-signal identification. For example, the sparsity and high path loss of terahertz channels, the complexity of dynamic beamforming in RIS, and multi-domain interference issues in air-ground-space heterogeneous protocol stacks all highlight the urgent need for a new paradigm of high-robustness, low-complexity recognition [1]. In this context, digital signal processing (DSP), as the mathematical foundation of signal recognition, has seen its core role further strengthened in the 6G era. DSP not only enables the analysis of time-varying non-stationary signals through time-frequency analysis but also leverages compressed sensing techniques to overcome sampling constraints, efficiently capturing broadband sparse signals. Additionally, deep learning integrates traditional DSP processes into differentiable architectures, enabling end-to-end feature learning and decision-making, thereby collectively forming a full-stack technology chain from sampling to analysis.

This study establishes a framework relationship between DSP core theory and 6G scenario-specific issues by methodically integrating DSP approaches with 6G signal recognition. It covers recent core accomplishments and focuses on state-of-the-art innovations, explains the main obstacles and potential paths in 6G mobile communication recognition. It provides a ground-landing identification paradigm and theoretical anchor point for the next generation wireless system.

2. Fundamentals of Radio Signal Recognition and the new paradigm of 6G

Radio Signal Recognition (RSR)—the automatic inference of modulation, standard, transmitter ID and intent from RF waveforms—must evolve into an intelligent, efficient and adaptable framework to match 6G's unprecedentedly complex spectrum.

2.1. Traditional identification process

The traditional radio signal identification process follows the paradigm of 'feature engineering + shallow machine learning,' primarily covering three core stages: signal preprocessing, feature extraction, and classification identification. During the signal preprocessing stage, the received radio frequency (RF) signal undergoes downconversion, filtering, and synchronization processing, including carrier synchronization, symbol synchronization, and frame synchronization, to convert it into a baseband signal suitable for analysis. Analogue-to-digital conversion (ADC) is a critical step in this phase, and its sampling rate must comply with the Nyquist sampling theorem, which poses significant challenges for wideband signals. Feature extraction, as the core and performance bottleneck of the traditional process, relies on engineers manually designing and extracting a set of features from the preprocessed signals based on domain knowledge to distinguish between different signal categories. Typical features include instantaneous statistics—mean, variance, skewness and kurtosis of amplitude, phase and frequency—plus transform-domain coefficients from spectra, wavelets and time–frequency tools (Wigner-Ville, STFT); they also embrace higher-order cumulants (fourth- and sixth-order) that resist noise and fading, and cyclostationary descriptors (cyclic spectrum, cyclic cumulants) that excel for BPSK and QPSK. The extracted feature vectors are then input into shallow machine learning classifiers for classification and identification. Commonly used classifiers include support vector machines (SVM), decision trees (DT), k-nearest neighbours (KNN), naive Bayes (NB), and ensemble methods (e.g., random forests). The performance of the classifiers largely depends on the quality and separability of the extracted features.

However, in 6G scenarios, traditional feature engineering buckles: hand-crafted descriptors laboriously miss the richness of complex waveforms, collapse in low-SNR, interference-rich, multipath channels, and incur prohibitive latency from higher-order statistics and cyclic spectra; their poor generalisation cannot keep pace with dynamic air–land–sea–space links, while ultra-wide bandwidths push Nyquist-rate ADCs beyond cost and power limits.

2.2. Revolutionary features of 6G signals

Driven by the 6G vision, continuous technological advancements have endowed wireless signals with a series of revolutionary features that have profoundly altered the objects and environments in which signals are identified. First, spectrum has leapt from Sub-6 GHz and millimetre-wave to the terahertz band (0.1–10 THz), offering tens-to-hundreds of gigahertz of bandwidth yet introducing severe path loss, altered propagation models, heightened hardware-sensitivity, and ADC rates that outrun current Nyquist theory. Secondly, network architectures have undergone profound

transformations [2]. The application of massive MIMO and intelligent metasurfaces (RIS) has greatly expanded the spatial dimension of signals, with signal models involving high-dimensional channel matrices and programmable electromagnetic environments. The identification process must consider the characteristics of the joint space-time-frequency domain. Additionally, the emergence of integrated sensing, communication, and computing (ISAC) has enabled communication signals to carry sensing functions themselves, with signal waveform design integrating communication and sensing requirements (e.g., orthogonal time-frequency space (OTFS) modulation) [1]. Identification targets now include not only communication parameters but also sensing information such as distance, velocity, and imaging. Furthermore, the construction of integrated air-ground-sea networks has resulted in highly heterogeneous signal sources, including satellites, drones, ground stations, and ships, with significant differences in signal format, power, and mobility, leading to dynamic changes in signal feature distributions and domain shift issues. Third, the upgrading of service scenarios and application requirements has imposed extreme demands on the real-time performance, robustness, and accuracy of identification. Emerging services, such as immersive XR, holographic communication, precise industrial control and large-scale machine communication, demand real-time, explainable, evolvable and lightweight recognition. Finally, multi-band, multi-antenna, and multi-node collaborative sensing now yields torrents of high-dimensional, multi-modal data that overwhelm rule-based or shallow models, compelling a new theoretical and algorithmic framework for signal recognition.

2.3. New recognition framework enabled by DSP

Faced with the revolutionary characteristics of 6G signals and the fundamental limitations of traditional methods, an intelligent recognition framework that integrates advanced DSP technology and deep learning (DL) has become an inevitable trend. In particular, the 'compressed sensing + deep learning joint architecture has shown great potential because it can effectively break through the bottleneck of high-dimensional signal sampling and achieve end-to-end intelligent recognition [3]. This architecture optimises signal sampling and feature extraction/recognition as an integrated process, thereby breaking traditional workflows' strict boundaries. Compressed sensing (CS), as the mathematical foundation of intelligent sampling, theoretically demonstrates that signals exhibiting sparsity in transform domains like wavelets or DCT can be reliably reconstructed from non-correlated linear measurements at rates far below the Nyquist rate. This is crucial for overcoming the sampling bottleneck of 6G ultra-wideband signals. Meanwhile, DL, as a powerful engine for feature learning and recognition, possesses the capability to automatically learn multi-level abstract features from raw data or compressed measurements through its models (especially convolutional neural networks (CNN), recurrent neural networks (RNN), Transformers, and their variants). This avoids the limitations of manual feature engineering and demonstrates excellent modelling capabilities for complex patterns and non-linear relationships. The advantages of this joint architecture are primarily reflected in the following aspects: First, it significantly addresses sampling issues, reducing requirements for the sampling rate of analogue-to-digital converters, thereby resolving challenges in acquiring ultra-wideband signals such as 6G terahertz signals and lowering hardware costs and power consumption. Second, end-to-end joint optimisation enables feature extraction and classifiers to achieve collaborative optimisation for compressed measurement and recognition tasks, resulting in significant performance improvements under low signal-to-noise ratio and low sampling rate conditions. Additionally, the model can better learn invariant features under complex channel impairments and interference, and joint training enhances robustness against measurement noise and model mismatch. By bypassing explicit reconstruction or simplifying the reconstruction process,

combined with the efficiency of deep learning models, the overall system latency and computational overhead can be reduced. Finally, the model exhibits strong adaptability, capable of learning to adapt to new signal types and dynamic environments through data-driven learning. Despite its promising prospects, this joint architecture still faces numerous challenges. For example, the hardware implementation complexity of the learnable measurement matrix is high, the stability and efficiency of the joint training algorithm require further improvement, the model's generalisation capability and interpretability in open environments need to be strengthened, and dedicated network designs for new scenarios such as 6G ISAC (Integrated Sensing and Communication) are urgently needed. Therefore, future research must continue to achieve breakthroughs in multiple areas, including theory, algorithms, architecture, and hardware co-design, to fully leverage its core enabling role in 6G intelligent wireless sensing and communication. The deep integration of compressive sensing and deep learning is establishing a new technological paradigm for efficient intelligent wireless signal recognition in the 6G era.

3. Research progress in DSP-driven signal recognition

3.1. Efficient processing of ultra-wideband signals

Core DSP technological innovations have become the key driving force in overcoming the bottlenecks in ultra-wideband (UWB) signal processing. In communication environments within the terahertz (THz) frequency band of 0.1–10 THz, traditional ADC systems based on the Nyquist sampling theorem face an irreconcilable contradiction between sampling rate and power consumption—sampling requirements exceeding 200 GS/s are accompanied by astonishing power consumption of over 10 W, severely limiting real-time signal processing capabilities. To address this challenge, sparse Fourier transform (SFT) technology has emerged, leveraging the inherent sparsity of THz signals in a specific transform domain to reconstruct the entire spectrum with high probability using only partial frequency domain sampling [4]. The adaptive SFT framework proposed by the MIT research team in 2023 in *Nature Communications* improved the efficiency of THz signal analysis by 3.8 times while reducing the computational complexity from the traditional $O(N\log N)$ to $O(k\log N)$, where k represents the signal sparsity, opening up new avenues for real-time ultra-wideband processing on resource-constrained devices.

In the face of the widespread issue of nonlinear distortion in ultra-wideband channels, adaptive wavelet packet decomposition technology has demonstrated its advantages. This technology dynamically adjusts the wavelet basis functions and decomposition depth to precisely match the signal's instantaneous characteristics. Compared to fixed wavelet transforms, its distortion resistance has improved by approximately 40%, making it particularly suitable for complex multipath propagation environments in 6G scenarios. Early research has demonstrated that wavelet feature extraction based on DSP can compress signal feature vectors, significantly reducing the burden of subsequent processing. This technical approach has continued to evolve in recent years, forming a collaborative framework of multi-resolution analysis and neural network classification, laying the foundation for ultra-wideband signal recognition.

The introduction of quantum-inspired algorithms marks a new phase of interdisciplinary integration in ultra-wideband processing. The quantum-inspired spectrum compression algorithm (QSCA) borrows the concept of quantum superposition states to perform probabilistic encoding on spectrum data, transforming the matrix operations of traditional FFT into sparse optimisation problems [5]. This algorithm is implemented on an FPGA-DSP hybrid platform, significantly reducing the computational resources required to achieve the same spectral analysis accuracy

compared to traditional methods. Its core innovation lies in modelling the spectral energy distribution as quantum probability amplitudes, and through amplitude-phase joint optimisation, significantly improving feature retention efficiency, particularly suitable for UWB radar signal processing scenarios with bandwidth exceeding 2 GHz. As shown in Table 1, SFT focuses on computational efficiency optimisation, adaptive wavelet packet decomposition emphasises distortion resistance, and QSCA prioritises real-time performance. By balancing the technical capabilities of these three approaches, current hardware architecture innovations form the material foundation supporting these algorithms. The FPGA-embedded DSP hard core solution has become the mainstream choice for addressing the challenges of parallel processing of ultra-wideband signals.

Table 1. Performance comparison of ultra-wideband signal processing technology

Technology type	Key indicator improvement	Applicable scenarios	Hardware implementation complexity
Sparse Fourier Transform (SFT)	Computational efficiency, reduced memory usage	Terahertz spectrum sensing, broadband radar signal processing	Medium to high (requires programmable logic acceleration)
Adaptive Wavelet Packet Decomposition	Resistance to non-linear distortion, feature dimension compression	Signal recognition in complex channel environments, low SNR scenarios]	Medium (suitable for general-purpose DSP implementation)
Quantum-Inspired Spectral Compression (QSCA)	Reduced computational complexity, improved real-time performance	Ultra-wideband real-time processing, resource-constrained edge devices	Low to medium (compatible with AI accelerators)

3.2. Joint identification of RIS scenarios

As a revolutionary technology in 6G communications, reconfigurable intelligent surfaces (RIS) are profoundly changing the paradigm of wireless signal identification. These extremely large antenna arrays (ELAA), composed of hundreds to thousands of low-cost passive reflective elements, can dynamically reconstruct the electromagnetic propagation environment by programming to adjust the phase shift of the incident signal. However, the traditional approach of separating RIS control from signal recognition has significant limitations. Its phase optimisation focuses solely on maximising channel capacity, neglecting the role of feature enhancement for recognition tasks. The joint modelling framework proposed by Tsinghua University in 2024 breaks this limitation by embedding RIS phase matrix optimisation into the signal recognition feature extraction front-end, achieving synergistic optimisation of environmental reconstruction and feature learning [6].

The innovative core of this framework lies in constructing an end-to-end differentiable physical layer model, enabling the digital signal processing (DSP) processing chain to propagate recognition loss back to the RIS configuration units. Specifically, in terms of channel-feature joint mapping, the framework establishes a mathematical relationship model between RIS unit phase shifts and the time-frequency features of received signals, and derives the analytical impact of phase changes on the Wigner-Ville distribution; in the distributed compressed sensing architecture, a group-based subspace observation matrix is designed for a 128-unit RIS array, significantly reducing the optimisation dimension; in the online incremental learning mechanism, the RIS configuration strategy is dynamically adjusted according to environmental changes, effectively addressing modelling mismatch issues in near-field-far-field mixed channels. Experimental validation shows that in a 28 GHz indoor scenario, this scheme improves the recognition accuracy of QPSK signals compared to traditional schemes. More importantly, the active beamforming capability of RIS

effectively overcomes the blind spot offset challenge in near-field communication (NFC). The 'deviation beam focusing model' proposed by the Nantong University team demonstrates that by optimising the spatial arrangement of RIS units (particularly using a square structure layout), signal strength can be enhanced by 8.7 dB in low elevation angle scenarios, significantly improving the reliability of edge region recognition.

The expanded application of RIS in optical communication is equally noteworthy. Traditional modulated retro-reflectors (MRRs) are limited by fixed reflection angles, while RIS-enabled active reflection systems can achieve multi-region independent control. The RIS-enhanced MRR system proposed in 2023 divides the reflection surface into multiple independent controllable modules, enabling reflection nodes to simultaneously perform signal transmission, reception, and forwarding functions. In actual tests of drone-to-ground station optical communication, this architecture successfully achieved dynamic adjustment of the reflection angle by $\pm 15^\circ$, reducing the bit error rate by two orders of magnitude and solving the problem of traditional relay nodes being unable to transmit their own information simultaneously at the same frequency and with the same code. Near-field effects pose a unique challenge for RIS-assisted recognition. As the array aperture increases, the Rayleigh distance significantly expands, rendering the far-field assumption invalid. To address this issue, partial near-field beam training (PNBT) schemes have emerged. These schemes use neural networks to predict the optimal beam direction, reducing training overhead while maintaining recognition accuracy, thereby providing a feasible solution for cross-domain signal recognition in integrated air-ground-sea networks.

3.3. End-to-end recognition for semantic communication

The rise of semantic communication has driven the transformation of signal recognition from traditional physical layer feature extraction to a semantic information decoding paradigm. The core challenge of this transformation lies in overcoming the architectural gap between traditional digital signal processing (DSP) and deep learning models, specifically manifested in the incompatibility between complex signal processing and real-number neural networks, as well as the end-to-end training obstacles caused by the non-differentiability of digital filters. Google's complex-domain Transformer architecture, proposed at ICASSP 2024, innovatively addresses this challenge. This architecture employs complex self-attention mechanisms to extend the Q, K, and V projections into the complex domain, thereby preserving the phase information integrity of RF signals. It also adopts time-frequency dual-stream processing to perform parallel analysis of the time-domain dynamics and frequency-domain structure of signals, enhancing feature representation capabilities. Additionally, it introduces learnable wavelet kernels to replace traditional FFT, enabling adaptive adjustment of time-frequency resolution and optimising semantic feature extraction [7].

Comparative studies on semantic communication performance have revealed revolutionary breakthroughs. In multi-modal semantic communication benchmark tests, end-to-end recognition systems have demonstrated significant advantages. Their spectral efficiency is 4.3 times that of traditional solutions, with particularly outstanding performance in short burst communication scenarios. In time-varying fading channels, the fluctuation range of semantic fidelity has been reduced by 60%. Additionally, it achieves direct conversion from RF signals to text commands, bypassing traditional physical layer demodulation and decoding steps. However, this architecture also faces significant challenges. Adversarial sample studies indicate that minor perturbations ($\epsilon < 0.03$) in input IQ data can cause a sharp decline in semantic recognition accuracy, revealing urgent semantic security vulnerabilities that need to be addressed.

4. Challenges and future directions

4.1. Existing challenges

Physical layer security threats have become a critical weakness in signal recognition systems. A report from USENIX Security 2024 revealed an alarming phenomenon: the success rate of adversarial sample attacks targeting hybrid systems combining digital signal processing (DSP) and deep learning reached as high as 79%. Attackers can inject low-power masking interference to confuse modulation recognition systems regarding QAM16 and QAM64 signals, resulting in extremely high misclassification rates. More concerning is that such attacks can affect models of different architectures through white-box transfer, and the attack signals are difficult to distinguish from background noise in the time-frequency spectrum, making the design of defence mechanisms highly challenging [8].

Hardware bottlenecks are particularly pronounced in the terahertz band. Currently, the most advanced silicon-based analogue-to-digital converters (ADCs) consume 6.7W of power at a sampling rate of 60GS/s. The sampling rate required for terahertz communication, exceeding 200GS/s, would push power consumption beyond the 10W threshold. This power consumption far exceeds the capacity of mobile devices, thereby imposing physical constraints on signal recognition deployment. Additionally, memory bandwidth limitations hinder the real-time implementation of complex recognition algorithms. Although high-end digital signal processors (DSPs), such as the FT-M6678N, have enhanced processing capabilities through multi-core parallel processing, they still need to reduce recognition accuracy to meet real-time constraints when processing 1 GHz bandwidth signals.

Cross-domain signal conflicts are becoming increasingly severe in non-cooperative spectrum environments. As a potential 6G technology, orbital angular momentum (OAM) vortex waves face numerous challenges in pattern recognition. First, the orthogonality between signals of different OAM modes within the same frequency band is compromised, leading to mode confusion. Second, atmospheric turbulence-induced phase distortion of the wavefront causes the vortex phase to fail to unfold at the receiving end, known as de-spinning distortion. Finally, miniaturised devices cannot meet the array size requirements for high-order OAM, constituting a receiving aperture limitation. Experimental results show that in the 28 GHz band, when the number of OAM modes exceeds 4, the error rate increases exponentially with increasing transmission distance, severely limiting its practical application.

4.2. Future directions

The integration of digital signal processing (DSP) and quantum computing offers a path to address the exponential growth in computational complexity. As a core enabling technology in this field, the quantum Fourier transform (QFT) can reduce the complexity of the fast Fourier transform (FFT) from $O(N\log N)$ to $O((\log N)^2)$, making it particularly suitable for processing large-scale multiple-input multiple-output (MIMO) signals. The quantum random-access memory (QRAM) and QFT co-architecture developed by Tokyo Institute of Technology theoretically achieves up to a 1,000-fold acceleration ratio in a system with 64 antennas. However, the coherence time of current quantum bits remains a major limiting factor. Therefore, hybrid computing architectures have emerged as a feasible solution in the near term, where quantum coprocessors handle high-complexity sub-tasks in feature extraction, such as large-scale matrix diagonalisation, while traditional DSPs handle data pre-processing and post-processing.

Metamaterial-enabled recognition technology has the potential to completely revolutionise traditional signal processing workflows. In 2023, Nature Photonics proposed optical domain direct processing technology, which utilises the electromagnetic properties of reconfigurable intelligent surface (RIS) units to perform feature extraction in the analog domain [9]. Recent research indicates that by designing tunable metasurface microstructures, time-frequency analysis operations such as the Gabor transform can be directly implemented in the optical frequency band, thereby bypassing the traditional analogue-to-digital converter (ADC) sampling stage. The 'RIS optical domain convolution' scheme proposed by the Nantong University team utilises the spatial filtering characteristics of metasurfaces for edge detection, reducing the power consumption of image recognition by 96%. With the deep integration of metasurfaces and photonic integrated circuits, it is expected to achieve nanosecond-level delay feature extraction in the terahertz (THz) band, thereby completely resolving the 'digital bottleneck' challenge.

Federated learning, as an emerging paradigm, provides a privacy-preserving solution for distributed signal recognition. Its core idea is to retain raw data locally on terminal devices and only upload gradient parameters updated by the feature extraction model to the cloud for aggregation. To address the specific requirements of wireless signal recognition, this paradigm must overcome three major challenges: first, it must achieve compatibility across heterogeneous devices, spanning the full range of hardware from high-performance DSPs to resource-constrained IoT devices; second, it must design sparsification and quantisation strategies to reduce communication overhead; and third, it must implement adversarial defence mechanisms to detect and filter gradient contamination from malicious nodes. The innovative architecture of the Ceva-XC21 DSP provides the hardware foundation for this, with its 256-bit single instruction multiple data (SIMD) vector units and dynamic vector threading technology enabling edge devices to efficiently perform local feature extraction. Preliminary experiments indicate that in modulation recognition tasks, the federated learning framework achieves 97.3% accuracy while protecting data privacy, paving the way for the construction of large-scale collaborative cognitive radio networks.

5. Conclusion

DSP-driven signal recognition technology is at a critical juncture of paradigm shift. From sparse Fourier transforms and quantum-inspired algorithms in ultra-wideband processing, to RIS-enabled joint recognition architectures, to end-to-end semantic communication systems, technological innovations are breaking through traditional limitations in all directions. However, challenges such as physical layer security threats, THz hardware bottlenecks, and cross-domain signal conflicts remain to be addressed. Future development directions will exhibit multi-dimensional integration characteristics: quantum computing provides exponential acceleration for feature extraction, metamaterials enable direct processing in the optical domain, and federated learning constructs privacy protection frameworks. These trends collectively point toward a core objective—building an efficient, intelligent, and secure signal recognition ecosystem adapted to the 6G paradigm, laying the perceptual foundation for the intelligent interconnection of all things. With the deep integration of DSP with artificial intelligence, quantum computing, and metamaterials, wireless signal recognition will transition from 'passive sensing' to 'active cognition,' ushering in a new chapter in intelligent radio.

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