Spectrum Sensing System 1 Electronics and Computing, UNAL, Manizales

Spectrum Sensing System

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0.1 High-Level Tasks in Cognitive Radio and Spectrum Sensing

0.1.1 Power Spectral Density (PSD) Estimation

This task involves estimating the distribution of power across different frequency components of a signal. It is fundamental to understanding the spectral characteristics of the observed environment.

1. **Spectral Parameter Estimation.** Key features derived from the PSD include:
   - Peak frequencies (locations of maximum power),
   - Bandwidth (range of occupied frequencies),
   - Power levels at specific frequencies,
   - Center frequency (mean spectral centroid).
2. **Quantitative Reconstruction of PSD.** This involves reconstructing the original PSD from noisy or undersampled data using techniques such as interpolation, smoothing, or model-based estimation.
3. **Demodulation Support.** PSD estimation assists in identifying carrier frequencies and modulation schemes, facilitating demodulation of the received signals.

0.1.2 Signal Detection

This task focuses on determining the presence of informative content within the received signal.

1. **Detection of Signal Presence (Thresholding).** A threshold is applied to a test statistic (e.g., energy) to decide whether a signal is present.
2. **Symbol Detection.** Once signal presence is confirmed, the next step is identifying the transmitted symbols, such as bits in digital communication systems.

0.1.3 Identification and Classification of Signals

This task involves characterizing signals based on observed features.

1. **Modulation Classification.** Determining the modulation format (e.g., AM, FM, QAM, PSK) is critical for enabling correct demodulation and decoding.
2. **Spatio-Temporal Identification of Spurious Signals.** This involves localizing and characterizing unwanted signals across both spatial and temporal domains.

3. **Spatio-Temporal Identification of Interference.** Identifying and profiling interference sources that affect the desired signal, considering their spatio-temporal evolution.

0.1.4 Channel State Estimation

Characterizing the wireless channel is essential for compensating for impairments such as fading or noise.

1. **Channel Impulse Response (CIR).** Estimation of how the channel distorts the temporal profile of the signal.

2. **Channel Frequency Response (CFR).** Estimation of the channel's effect on signal amplitude and phase across frequency.

0.1.5 Decision-Making

Based on the outcomes of the previous steps, appropriate decisions are made to complete the communication or control loop.

1. Decoding of the received data.

2. Choosing an optimal action in adaptive or control-oriented systems.

3. Interference identification and mitigation strategies.

0.2 Recent Civilian-Focused RF Spectrum Sensing Systems

System	**Year**	**Application Focus**
GBSense	2024	Wideband RF spectrum monitoring with low-cost setup. Utilizes sub-Nyquist sampling for real-time analysis.
Compressed-Sensing Localization System	2024	Real-time RF emitter detection and localization for non-cooperative civilian radio monitoring using compressed sensing.

Table 1: Recent civilian-focused RF spectrum sensing systems developed since 2024.

0.3 Implementation Details of GBSense: A GHz-Bandwidth Compressed Spectrum Sensing System

0.3.1 Core Architecture and Sampling Strategy

- **Periodic Non-Uniform Sampling via Time-Interleaved ADC (TI-ADC):** Utilizes multiple ADC lanes operating in parallel, interleaved in time, to form structured non-uniform sampling patterns. Enables capture of up to 2 GHz of RF bandwidth with only 400 MHz average sampling rate.
- **Clock Distribution and Synchronization:** A dedicated subsystem ensures precise timing across ADC channels, mitigating jitter and preserving temporal alignment.

0.3.2 Hardware Components

- **Power Splitter Subsystem:** Distributes incoming RF signals to multiple ADC lanes for parallel capture.
- **Time-Interleaved Sampling Subsystem:** Incorporates off-the-shelf ADC modules phased across time to support sub-Nyquist sampling.
- **Logic Device Subsystem:** FPGA or microcontroller-based logic handles sample alignment, decimation, buffering, and transmission to the host processor.

0.3.3 Real-Time Software Integration

- **Low-Power Processor:** A Raspberry Pi processes ADC output for spectral reconstruction using compressed sensing algorithms.
- **Software Pipeline:**
  1. Data decimation and formatting,
  2. Compressed sensing-based spectrum reconstruction,
  3. Spectral detection via thresholding.
- **Latency:** Real-time spectrum sensing achieved with $\sim$30 ms frame processing latency.

0.3.4 Performance Metrics

- **Detection Accuracy:**
  - 100% accuracy for spectrum occupancy below 100 MHz,

  - Over 80% accuracy for 200 MHz occupancy levels.

- **Throughput:** Frame-wise analysis completed in under 30 ms.

0.3.5 System Design Innovations

- **Hardware-Friendly Design:** Avoids analog delay lines typical in multicoset architectures; instead, uses programmable digital timing via TI-ADC.
- **Adaptive Sampling Pattern Control:** Sampling patterns are programmable, allowing adaptation to varying spectral environments.
- **Modular and Cost-Efficient:** Constructed with commercially available components and low-cost processing, suitable for scalable and field-deployable applications.

0.3.6 Summary of Key Specifications

Feature	**Specification**
RF Bandwidth	2 GHz
Average Sampling Rate	400 MHz
ADC Methodology	Time-Interleaved ADC (TI-ADC)
Processor	Raspberry Pi
Frame Processing Latency	∼30 ms
Detection Accuracy @ <100 MHz Occupancy	100%
Detection Accuracy @ 200 MHz Occupancy	>80%

Table 2: Key technical characteristics of the GBSense system.

0.4 Implementation Details of the Compressed-Sensing Localization System

0.4.1 System Overview

A prototype designed for real-time monitoring and localization of non-cooperative RF emitters, using compressed sensing combined with TDoA (Time Difference of Arrival) measurements.

0.4.2 Hardware Architecture

- **Multiple Sensing Nodes:** Distributed SDR units capture wideband RF signals.

- **Compressed Sampling at Nodes:** Each node applies a measurement matrix (e.g., Gaussian) to compress incoming signals before transmission to a fusion center.
- **Fusion Node:** Collects compressed samples from nodes and performs joint reconstruction and localization.

0.4.3 Signal Processing Pipeline

1. **Compressed Sensing Reconstruction:** Implements greedy algorithms (e.g., OMP) or convex recovery to reconstruct wideband signals from undersampled measurements.
2. **TDoA Estimation:** Uses the reconstructed signals at multiple nodes to extract arrival-time differences for source localization.
3. **Localization Algorithm:** Estimates emitter coordinates using TDoA multilateration based on reconstructed timing differences.

0.4.4 Software and Computational Aspects

- **Localization Logic:** Fusion center runs CS recovery and TDoA multilateration algorithms in real time.
- **Mapping Interface:** Localization results are displayed on a digital/interactive map, even in offline settings.

0.4.5 Performance and Evaluation

- **Sample Compression Ratio:** Significant data reduction at nodes via CS before transmission.
- **Detection Performance:** ROC curves indicate that CS-enabled sensing achieves performance comparable to full-rate sampling even at moderate SNRs.
- **Localization Accuracy:** TDoA-based multilateration yields precise emitter positions; specific error metrics vary by node geometry and quality.

0.4.6 Innovations and Advantages

- **Efficient Use of Bandwidth:** Combines sub-Nyquist sampling and compressed sensing to reduce node-to-fusion bandwidth.
- **Scalable Architecture:** Easily extensible by adding SDR nodes to improve localization precision.
- **Real-Time Mapping:** Integration with digital map interfaces enables near real-time emitter tracking.

0.4.7 Key Specifications and Summary

Feature	Specification
Number of Nodes	Multiple SDR-based sensing units
Sampling Technique	Compressed sensing (e.g., using random Gaussian projections)
Signal Recovery	Greedy (OMP) or convex CS algorithms
Localization Method	TDoA multilateration on reconstructed signals
Interface	Real-time display on digital/offline map
Performance	ROC curves similar to full-rate systems at moderate SNR

Table 3: Technical summary of the compressed-sensing localization system.

0.5 Similar Spectrum Sensing Systems from 2024

0.5.1 Commercial and Industrial Systems

Anritsu-DeepSig AI-Based RF Sensing Solution

Release: Demonstrated at Mobile World Congress 2024

System Overview: Integration of Anritsu MS2090A Field Master Pro Spectrum Analyzer with DeepSig's AI-powered wireless signal detection and classification software. Employs deep learning, data-driven approach to rapidly incorporate new radio signal models using DeepSig's ML training tools.

Key Features:

- **AI-Native Architecture:** Built on patented artificial intelligence deep learning algorithms
- **Rapid Signal Learning:** RF signals of interest from diverse new sources like drones and IoT devices can be learned quickly and accurately in days rather than months
- **Real-Time Adaptation:** Enables real-time adaptation to changing RF conditions
- **6G Readiness:** Forms foundation for AI-native RF sensing for 6G networks

Applications:

- Spectrum awareness and optimization
- Network performance enhancement
- Dynamic spectrum sharing
- IoT and drone signal detection

CRFS RFeye Node Plus Series

Release: Enhanced models introduced throughout 2024

System Overview: Powerful, portable, and rugged RF sensors built for any environment that receive and record signals and geolocation of transmitters. Ultra-wide frequency, high-performance radio direction finding that synchronously uses TDoA and DF techniques.

Key Features:

- **Multi-Technique Localization:** Combined Time Difference of Arrival (TDoA) and Direction Finding (DF)
- **Wide Frequency Coverage:** Ultra-wideband RF sensing capabilities
- **Environmental Ruggedness:** Designed for harsh operational environments
- **Real-Time Processing:** Allow users to see who is using the spectrum, where and when they are using it, and what they are using it for

0.5.2 Academic and Research Systems

Deep Learning-Based Compressed Spectrum Sensing Systems

Publication: Multiple IEEE papers published in 2024

System Overview: Compressive spectrum sensing (CSS) systems critical for efficient wideband spectrum sensing (WSS) using deep learning approaches. Wideband signal CS reconstruction algorithm by merging iterative shrinkage thresholding with deep learning.

Key Features:

- **Sub-Nyquist Sampling:** Efficient wideband sensing with reduced sampling rates
- **Deep Learning Integration:** CNN and RNN-based signal reconstruction
- **Adaptive Sparsity:** Handles unknown and dynamically changing sparsity orders
- **Reduced Complexity:** Eliminates hand-crafted optimization parameters

Multiband SDR-Based Spectrum Sensing Systems

Publication: Enhanced implementations published in 2024

System Overview: Novel multiband spectrum sensing technique based on multiresolution analysis (wavelets), machine learning, and the Higuchi fractal dimension. Real-time implementation using affordable software-defined radios.

Key Features:

- **Multiband Capability:** Simultaneous sensing across multiple frequency bands
- **Machine Learning Integration:** Wavelet-based feature extraction with ML classification
- **Cost-Effective:** Uses affordable SDR platforms
- **Modular Design:** Linkable SDR units for wide-band coverage

0.5.3 Key Trends and Innovations in 2024

Common Characteristics

1. **AI/ML Integration:** Most systems incorporate deep learning or machine learning
2. **Real-Time Processing:** Emphasis on low-latency, real-time operation
3. **Compressed Sensing:** Widespread adoption of sub-Nyquist sampling techniques
4. **Cooperative Networks:** Distributed sensing with centralized fusion
5. **SDR-Based Platforms:** Cost-effective software-defined radio implementations
6. **Multi-Band Capability:** Simultaneous sensing across multiple frequency bands

Technical Advances

- **Improved Reconstruction:** Deep learning-based signal reconstruction
- **Adaptive Algorithms:** Self-configuring parameters and sparsity handling
- **Enhanced Localization:** Combined TDoA/DF techniques for precise geolocation
- **Reduced Complexity:** Streamlined algorithms for real-time deployment
- **Better Accuracy:** Superior performance in challenging RF environments

Application Focus

- Civilian spectrum monitoring and compliance
- IoT and drone signal detection
- 5G/6G network optimization
- Interference detection and mitigation
- Regulatory enforcement support

0.6 Implementation

0.6.1 Power Spectral Density (PSD) Estimation

This task involves estimating the distribution of power across different frequency components of a signal. It is fundamental to understanding the spectral characteristics of the observed environment.

- Peak frequencies (locations of maximum power),
- Bandwidth (range of occupied frequencies),
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- Center frequency (mean spectral centroid).

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(box1) at (0,2) [box] Theoretical model; (box2) at (0,0) [box] Estimation Method; (box34) at (4,1) [box, minimum height=3.5cm] Statitical Analysis;

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[arrow] (box1.south) – (box2.north);