DOF:
A Local Wireless Information Plane

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Problem

Unlicensed spectrum (e.g. ISM Band - 2.4 GHz) has historically been managed “socially”

How can we design a smart radio which maximizes throughput while causing minimal harm to coexisting radios?
Can we use current mechanisms to design these smart radios?

Current coexistence mechanisms
- Carrier Sense, RTS/CTS
- Rate Adaptation
- Adaptive Frequency Hopping
- ...

Current mechanisms are not sufficient for designing high performance smart radios
How would we build a smart radio which coexists with legacy devices?

**Knowledge of**

1. The protocol types operating in the local vicinity
2. The spectrum occupancy of each type
3. The spatial directions of each type
DOF
(Degrees Of Freedom)

Local wireless information plane which provides all 3 of these quantities (type, spectral occupancy, spatial directions) in a single framework

DOF Performance Summary

• DOF is robust to SNR of detected signals
  • Accurate at received signals as low as 0dB

• DOF is robust to multiple overlapping signals
  • Accurate even when three unknown signals are present

• DOF is relatively computationally inexpensive
  • Requires 30% more computation over standard FFT
DOF: High Level Architecture

DOF operates on windows of raw time samples from the ADC

Raw samples are processed to extract feature vectors

Feature Vectors are used to detect
1. Signal Type
2. Spectral Occupancy
3. Spatial Directions

The MAC layer utilizes this mechanism to inform its coexistence policy
For almost all “man-made” signals – there are hidden repeating patterns that are unique and necessary for operation.

Key Insight

Leverage unique patterns to infer 1) type, 2) spectral occupancy, and 3) spatial directions.
Extracting Features from Patterns

If a signal has a repeating pattern, then when we
• Correlate the received signal against itself delayed by a fixed amount, the correlation will peak when *the delay is equal to the period at which the pattern repeats.*

Cyclic Autocorrelation Function (CAF) \[ R_x^\alpha(\tau) = \sum_{n} x[n][x^*[n - \tau]]e^{-j2\pi\alpha n} \]

Pattern Frequency (\(\alpha\)) – The frequency at which the pattern repeats

**Advantages**
• Robustness to noise,
• Uniqueness for each protocol

**Disadvantage:** Computationally expensive to calculate the patterns in this manner
Feature Extraction: Efficient Computation

The CAF can be represented using an equivalent form called the Spectral Correlation Function (SCF)

\[ S_x^\alpha(f) = \sum_{\tau=-\infty}^{\infty} R_x^\alpha(\tau) e^{-j2\pi f \tau} = \frac{1}{L} \sum_{l=0}^{L-1} X_{lN}(f) X_{lN}^*(f - \alpha) \]

WiFi Spectral Correlation Function

SCF can be calculated for Discrete Time Windows using just FFTs

Feature Vectors are calculated by computing \( S_x^\alpha(f) \) at different values of \( \alpha \)
Classifying Signal Type

- Single signals are well separated in the feature vector space, $\tilde{F}$

- Support Vector Machines (SVM) can be used to classify signal type, $T$

Works well when there is a single signal but fails when there are multiple interfering signals
Multiple interfering signals are not straightforward to classify

- Multiple signals are made up of components and features of single signals, making them difficult to distinguish

Need a robust algorithm to determine the number of interfering signals
Inferring the number of signals: Exploiting Asynchrony

1) Real signal packets are asynchronous

2) This asynchrony shows up in \( \tilde{F}(i) \) as an increase or decrease in the number of non-zero components

Measuring differences in \( \tilde{F}(i) \) is more robust than differences in energy
DOF: High Level Architecture

The signal types can be leveraged along with the feature vectors to estimate
1) Spectrum Occupancy
2) Spatial Directions

- Signal
  - ADC
    - Time Samples
      - Feature Extraction
        - Classification
          - DOF Estimation (Spectrum Occupancy)
            - DOF Estimation (AoA Detection)
              - \{\Theta, Type, F_c, BW\}_{n=1}^N
              - \{\Theta\}_{n=1}^N

- \{Type, F(i)\}_{n=1}^N

- While DOF = Active
  - Feature Extraction
    - Classification
      - Asynchrony Detector/Power Normalization
        - Counter++
          - SVM-1
            - Sig1 Class
          - ... 
            - Sig i Class
          - ... 
            - SigN Class
        - Counter--
          - SVM-N
            - SigN Class
          - ... 
            - Sig i Class
          - ... 
            - Sig1 Class

While \( \Delta L > \text{Threshold} \)
- Counter++
- SVM-1
- Sig1 Class
- ... 
- SVM-N
- SigN Class

While \( \Delta L < -\text{Threshold} \)
- Counter--
- SVM-N
- SigN Class
- ... 
- SVM-1
- Sig1 Class
- ... 
- Sig i Class
- ... 
- Sig1 Class
Estimating Spectrum Occupancy

- Communication signals are sequences of periodic pulses
  \[ s(t) = b\cos(2\pi f_b t)e^{j2\pi f_c t} \]

- These pulses are patterns embedded within the signal which repeat at a particular frequency
- These frequencies at which these patterns repeat tell us the bandwidth \( f_b \) and carrier frequency \( f_c \) of the signal
Estimating Spectrum Occupancy

- Because these patterns repeat, they are natural components of the feature vector.

**Modulated Zigbee Signal**

**ZigBee Spectral Correlation Function**

### Relationship between feature vector and Bandwidth/Carrier Frequencies

<table>
<thead>
<tr>
<th>Signal Type</th>
<th>Feature Vector Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>WiFi</td>
<td>all $\alpha'$s between $[f_c - \frac{BW}{2}, f_c + \frac{BW}{2}]$</td>
</tr>
</tbody>
</table>

DOF leverages this relationship to compute the spectral occupancy of each signal type.
Each array element experiences a delay of $\tau$ relative to the first element, which is a function of the Angle of Arrival ($\text{AoA}$).

DOF uses the same feature vector to infer
1) type, 2) spectral occupancy, 3) spatial directions
Implementation

- Channel traces were collected using a modified channel sounder with a frontend bandwidth of 100MHz spanning the entire ISM band.
- Wideband Radio Receiver placed at 3 different locations while transmitter was placed randomly in the office.
- Raw Digital Samples are collected and processed offline on a PC with Intel Core i7 980x Processor and 8GB RAM.
Experimental Setup

**Comparison Setup**
- Each testing “run” consists of 10 second channel traces.
- Random Subset of 4 different radios are selected in each “run” (WiFi, Bluetooth, ZigBee, Microwave) with varying PHY parameters
- 30 Different “runs” for each signal combination

**Compared Approaches**

**Identifying Protocol Types**
- RF Dump (CoNEXT 2009) – Energy Detection + Packet Timing

**Estimating Spectrum Occupancy**
- Jello (NSDI 2010) – Edge Detection on Power Spectral Density

**Estimating Angles of Arrival**
- Secure Angle (HOTNETS 2010) – MUSIC (subspace based approach)
DOF achieves greater than 85% accuracy when the SNR of the detected signal is as low as 0dB
DOF classifies all component signals with greater than 80% accuracy, even with 3 interfering signals.
DOF’s spectrum occupancy estimates are at least 85% accurate at SNRs as low as 0dB
DOF’s spectrum occupancy estimates are robust in the presence of multiple overlapping signals
Evaluation: Angle of Arrival

Multiple Signals: AoA Detection Accuracy

In addition to being accurate, DOF can also associates each AoA with each signal type.
DOF-SR (Policy Aware Smart Radio)

- **Policy 0** – Only use unoccupied spectrum
- **Policy 1** – Use all unoccupied spectrum. Further use spectrum occupied by microwave ovens.
- **Policy 2** – Use all unoccupied spectrum + microwave occupied spectrum. Further compete for spectrum occupied by WiFi radios and get half the time share on that spectrum.
DOF-SR Performance

DOF-SR Policy 0 and Jello

DOF-SR Policy 1 and Jello

DOF - SR Policy 2 and Jello

Legend
- DOF-SR
- Jello

DOF-SR enables users to decide how aggressive their policy should be
Conclusion

DOF exploits repeating patterns to infer 1) type, 2) spectral occupancy, and 3) spatial directions

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