UCLA

Electrical Engineering Department

2008 Annual Research Review

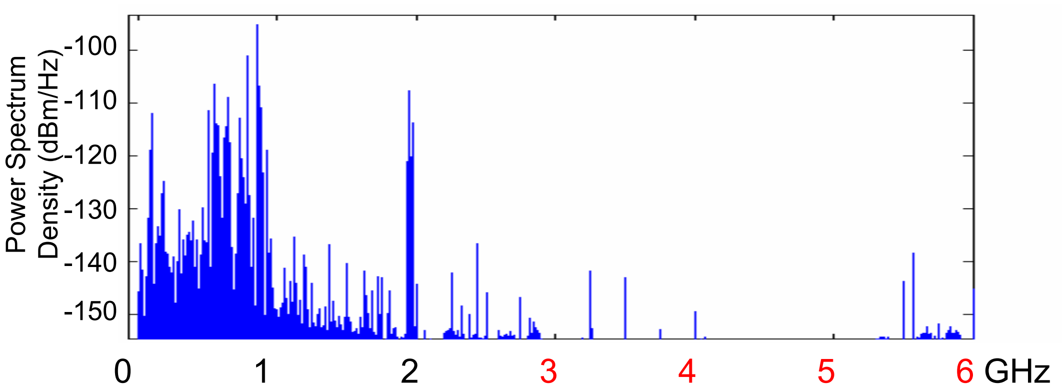
28 January 2008

Spectrum Sensing Design for Cognitive Radios

Prof. Danijela Cabric

danijela@ee.ucla.edu

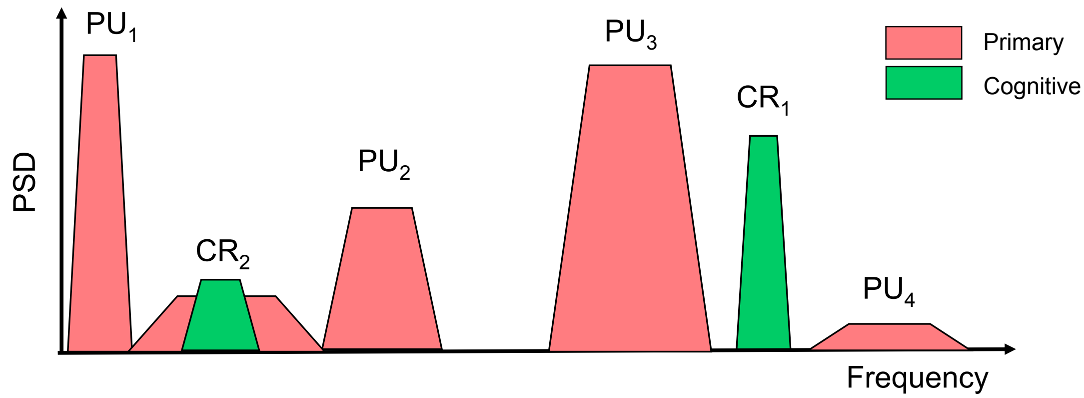
Spectrum Utilization



Freq (GHz)	0~1	1~2	2~3	3~4	4~5	5~6
Utilization(%)	54.4	35.1	7.6	0.25	0.128	4.6

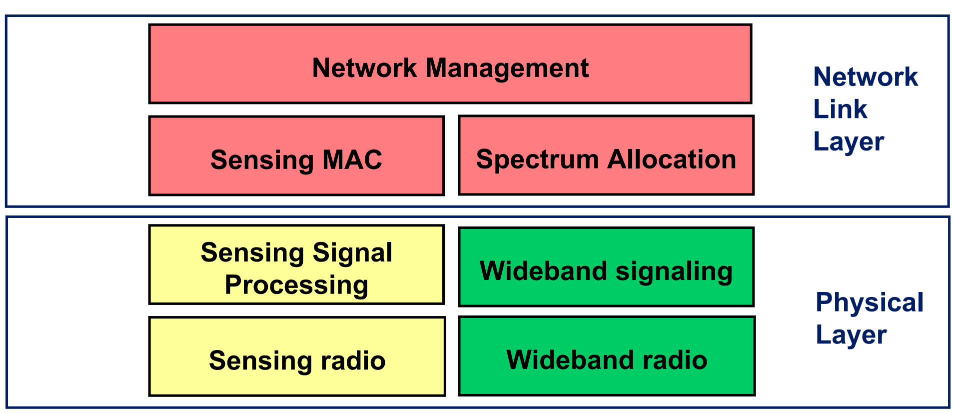
- Even though the spectra is allocated it is almost unused
- Cognitive Radios can make better use of the spectrum

How Does a Cognitive Radio Operate?



- Sense **the spectral environment over a wide bandwidth**
- Transmit **in "white space" &** Adapt **bandwidth and power**
- Detect **if primary user appears**
- Move **to new white space**

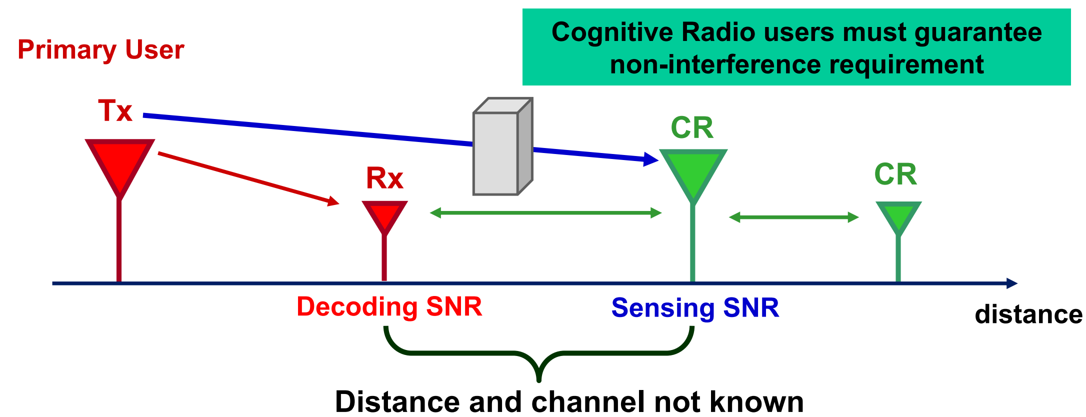
Cognitive Radio System Design



Spectrum sensing is the key enabling functionality

How do we implement spectrum sensing in a system?

Spectrum Sensing Problem



- Cognitive radio can only observe (sense) primary system Tx signals
- Need to sense signals in highly negative SNR

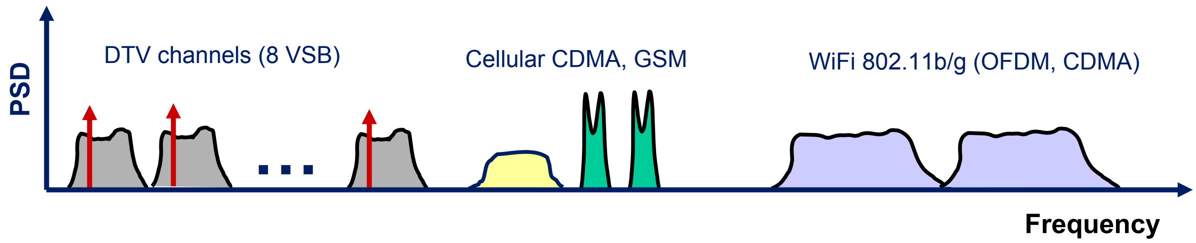
Sensing SNR < Decoding SNR – worst case channel

Sensing SNR < [5dB to 20 dB] – [20 dB to 40 dB] = [-35 to 0 dB]

Designing Spectrum Sensors

- Sensing Requirements set by Primary User system
  - Signal level (dBm)
  - Maximum detection time (s)
  - Interference protection (%)
- Can we use standard detection techniques?
  - Energy detection
  - Pilot detection
  - Feature detection
- Can a radio sense primary signals robustly and guarantee non-interference to primary users in negative SNR regimes?

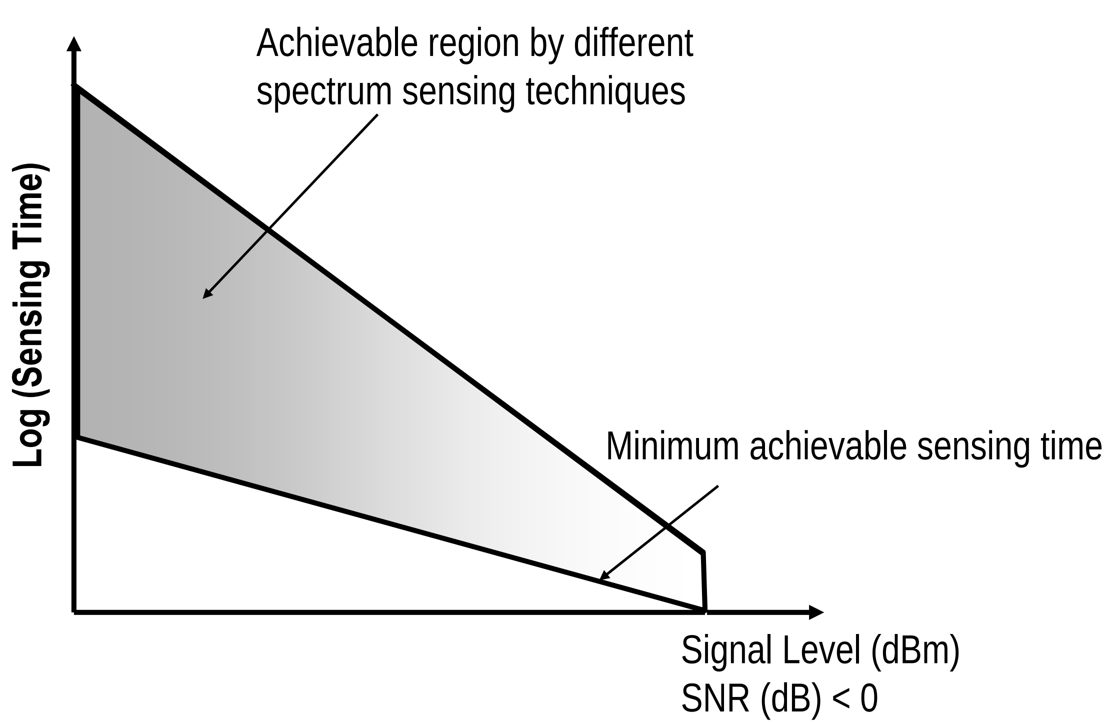
Sensing Signal Presence



Use N samples to detect signal with required probability of detection and false alarm

Energy	Pilot	Feature
Requires knowledge of - carrier and bandwidth - noise power Non-coherent processing, Sensing time scales as: $N \sim \frac{1}{\lvert SNR \rvert^2}$ [Urkovitz1967]	Requires knowledge of - pilot data - perfect synch Coherent processing, Sensing time scales as: $N \sim \frac{1}{p \lvert SNR \rvert}$ *p is % of signal energy in pilot* [Middleton 1957]	Requires knowledge of - carrier and bandwidth - modulation type Statistical processing, Sensing time scales as: ? Used for modulation classification in positive SNR regimes [Gardner1986]

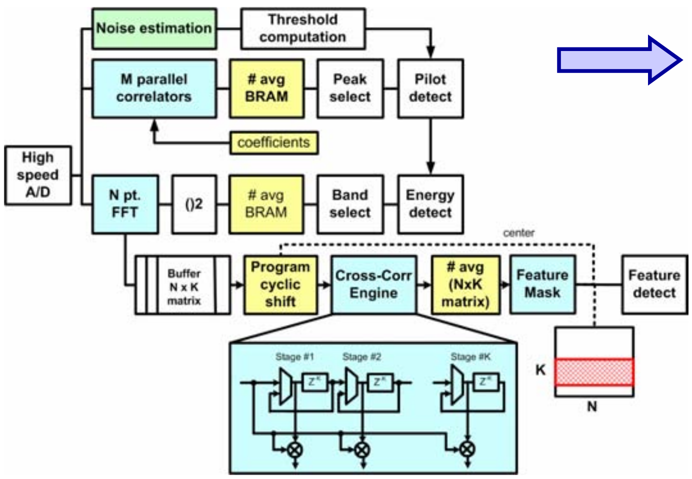
Sensing Time vs. SNR Trade-off

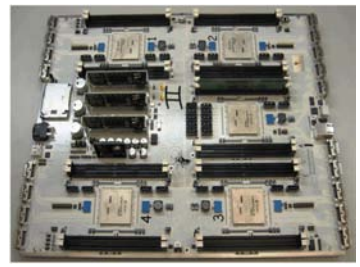


Spectrum Sensing Implementation

Signal Sensing DSP

Hardware testbed



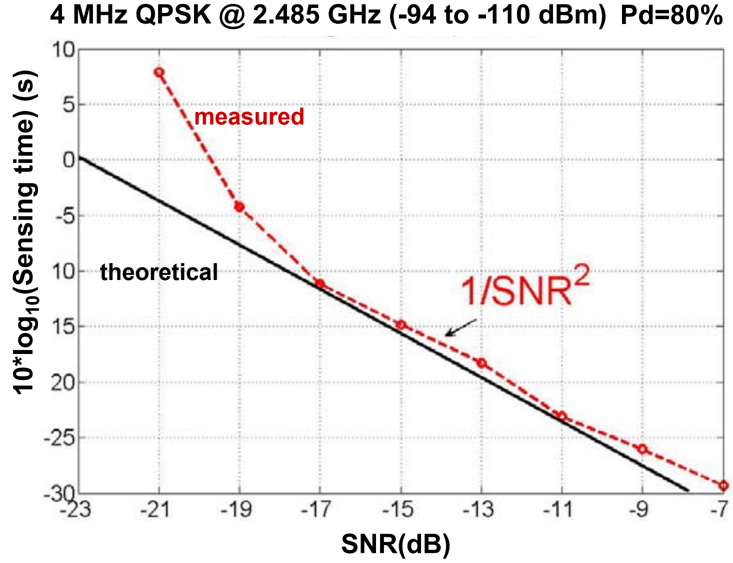


BEE2 platform

Reconfigurable wireless modem

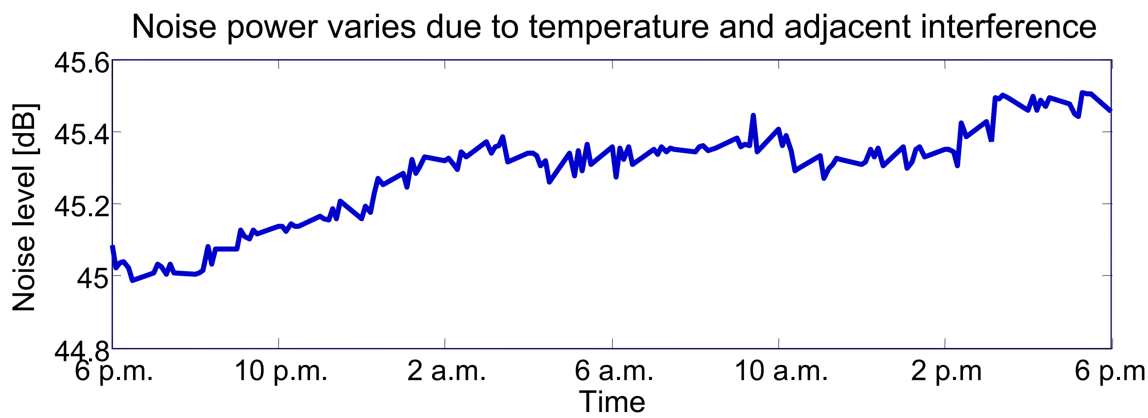
Energy Detection: Sensing Time vs. SNR

4 MHz QPSK @ 2.485 GHz (-94 to -110 dBm) Pd=80% Pfa=10%



- **Theoretical prediction:**
  - Implies if we allow N to be large, arbitrarily weak signals can be detected
- **Experimental result:**
  - Below -21 dB detection is not possible regardless of sensing time duration

Why Does Energy Detection Break Down?



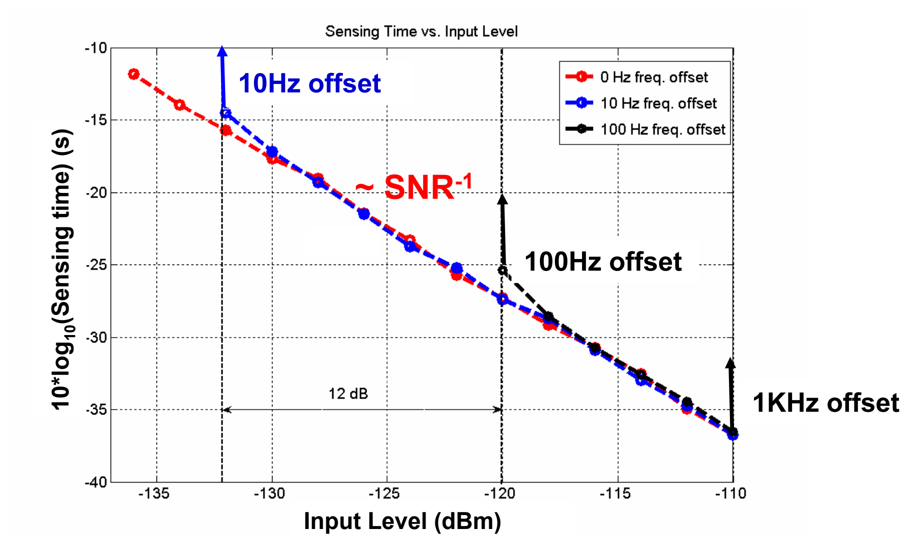
- **Theoretical assumption that noise is Gaussian and stationary fails in negative SNR**
- **Threshold *T* set based on estimated noise power**

  if $S + N_{actual} < T\,(N_{actual} + x)$ **then detection becomes impossible**
- **Estimation error *x* sets sensing SNR limit (0.03 dB -> SNR_{min}-21 dB)**

$$SNR_{min} = 10\log_{10}[10^{(x/10)}-1]\ dB$$

Sahai, Tandra [2005]

Correlator-based Pilot Detection

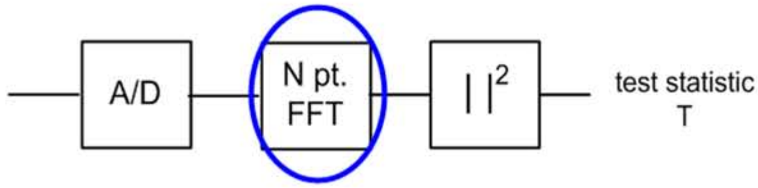


- **Ideal radio (0 Hz freq. offset): Very weak signal detection possible**
- **Practical radio (offsets in the order of KHz)**
  - Signal detection below -110 dBm not possible (802.22 requires -122 dBm)

  Can we design pilot detection that relaxes frequency offset requirements?

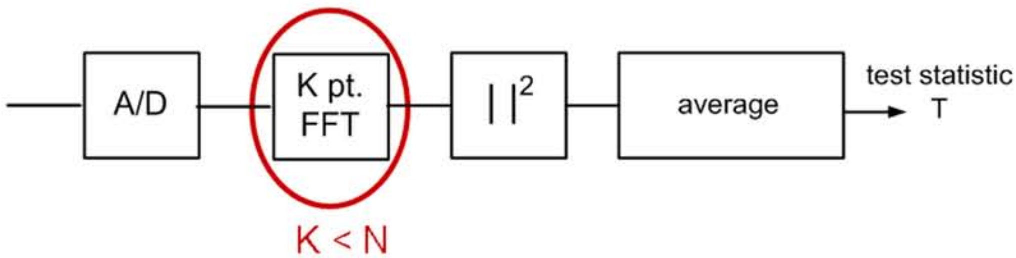
FFT-based Pilot Detector

Optimal detector is N pt FFT



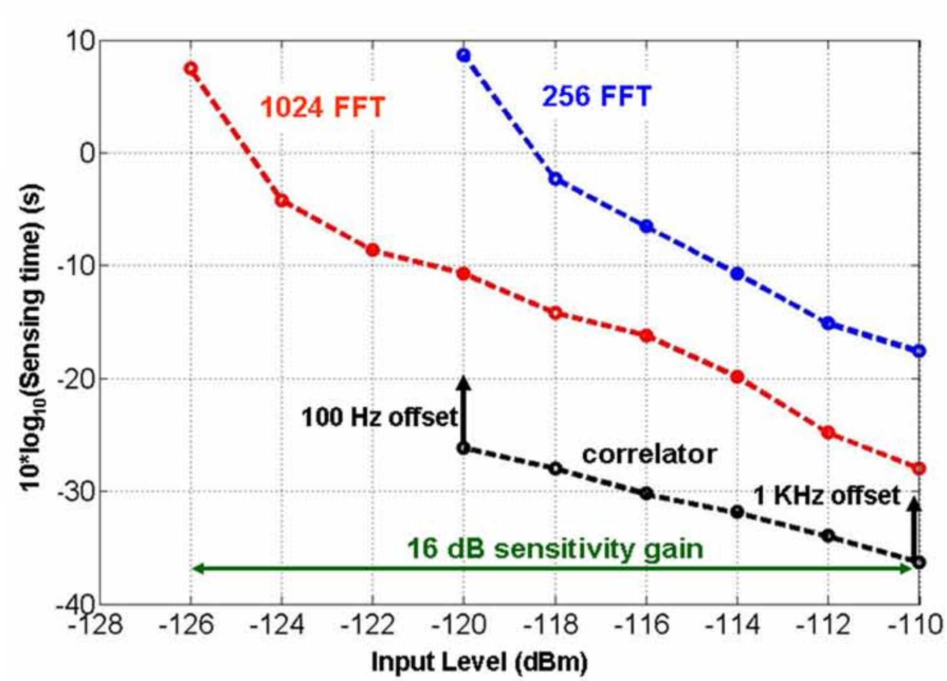
- Can handle offsets ~ Hz but complexity increases

Partial coherent pilot detector



- Partial coherent processing gain proportional to K
- The required K can be determined analytically for max freq. offset.

Partial Coherent Pilot Detection



Practical radio (1KHz offset): Partial coherence provides 16 dB sensitivity gain

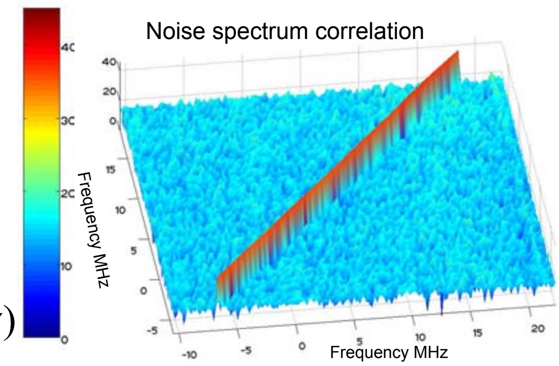
Feature Detection

- Feature is a known statistical property

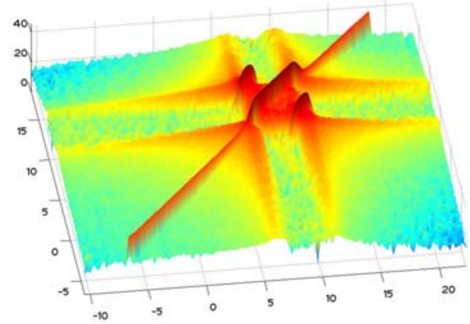
$$S_x(\alpha, f) = E\{X(f)X^*(f+\alpha)\}$$

- Signal and noise features separated
- Sensor estimates features for a finite number of FFT averages

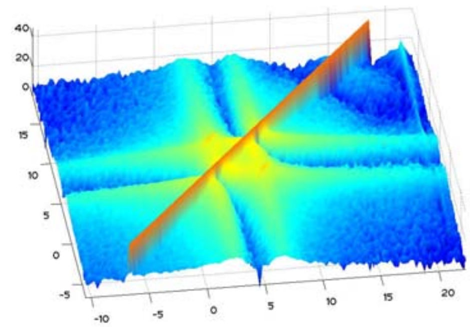
$$\widetilde{S}_x(\alpha, f) = \frac{1}{N}\sum_{i=1}^{N} X(i,f)X^*(i,f+\alpha)$$



(10,000 spectral avgs) SNR≈0 dB



(500,000 spectral avgs) SNR≈-15 dB



Feature Detection under Clock Offset

Time offset modifies Fourier transform

$$\bar{x}(t) = x(t-t_0) \xrightarrow{F} \bar{X}(f) = X(f)e^{-j2\pi f t_0}$$

Constant timing offset and ideal SCF

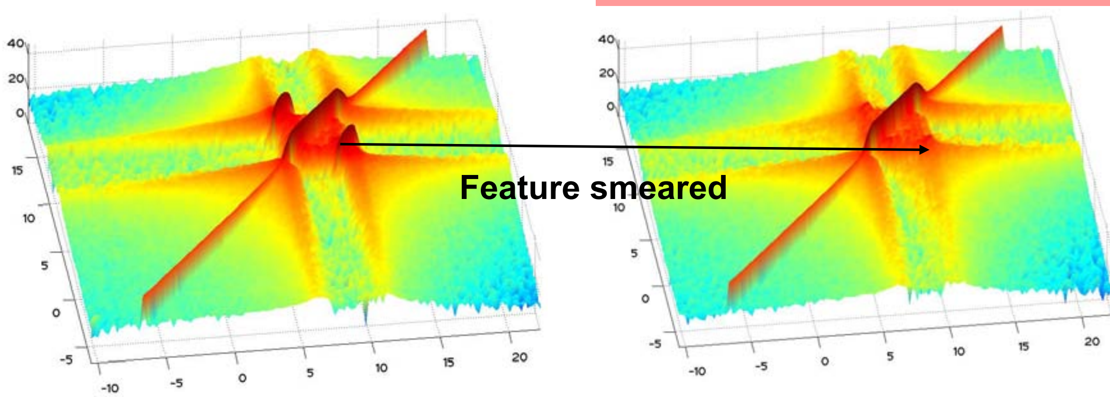
$$S_{\bar{x}}(\alpha, f) = S_x(\alpha, f)e^{-j2\pi\alpha t_0}$$

Clock offset and estimated SCF

$$\widetilde{S}_{\bar{x}}(\alpha, f) = \widetilde{S}_x(\alpha, f)\sum_{i=1}^{N} e^{-j2\pi\alpha t_i}$$

Perfect sampling

100 Hz sampling clock offset (25 ppm)



Partial Coherent Feature Detector

For a fixed number of spectral averages N

$$\tilde{S}_{\bar{x}}(\alpha, f) = \tilde{S}_x(\alpha, f)\frac{\sin(2\pi\frac{\delta}{\alpha}N_{FFT}N/2)}{\sin(2\pi\frac{\delta}{\alpha}N_{FFT}/2)}e^{-j2\pi\frac{\delta}{\alpha}N_{FFT}(N+1)/2}$$

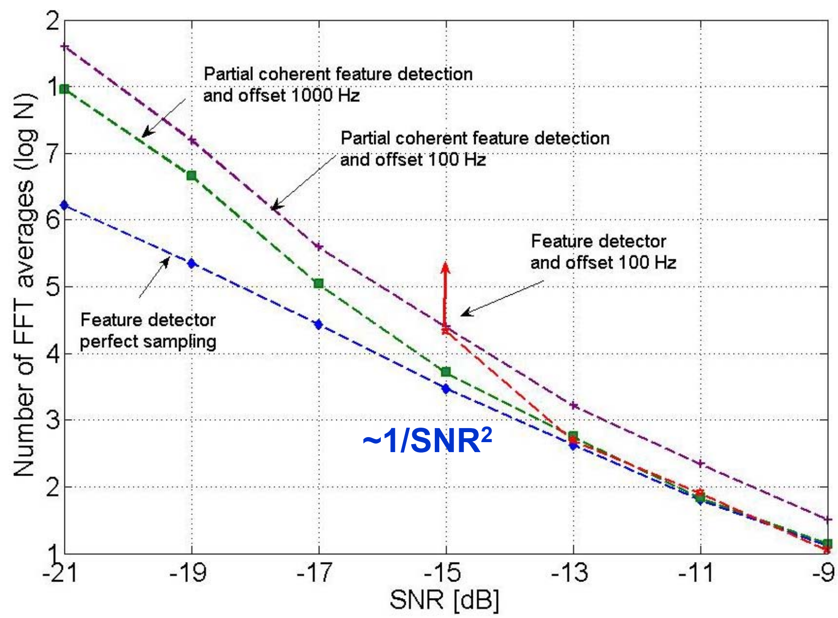
Feature are cancelled if $NN_{FFT} > \frac{\alpha}{\delta}$ where δ is a clock sampling offset

Proposed feature detector exploits partial coherent gain
and overcomes the sampling offset problem:

$$\tilde{S}_x(\alpha, f)' = \frac{1}{T_{FFT}}\sum_{m=1}^{M_2}\left|\underbrace{\sum_{k=1}^{M_1} X(k+mM_2, f)X(k+mM_2, f+\alpha)^*}\right|$$

M_1 determines coherent processing gain,
chosen based on maximum sampling clock offset

Feature Detector: Sensing Time vs. SNR

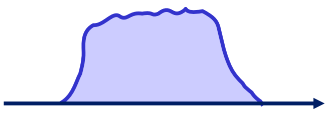


Sampling offsets can be overcome with partial coherent feature processing

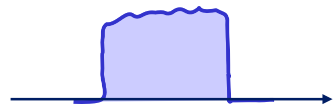
Feature Energy

Feature gain depends on spectral redundancy in pulse shaping filter *Q(f)*

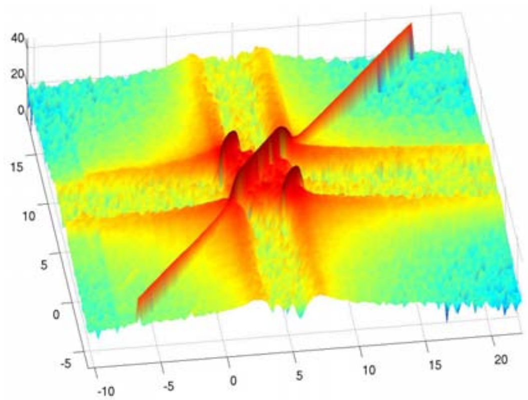
$$S_x(\alpha, f) = \frac{1}{2T_s} Q(f + \frac{\alpha}{2}) Q(f - \frac{\alpha}{2})^* \text{ for } \alpha = 1/T_s$$



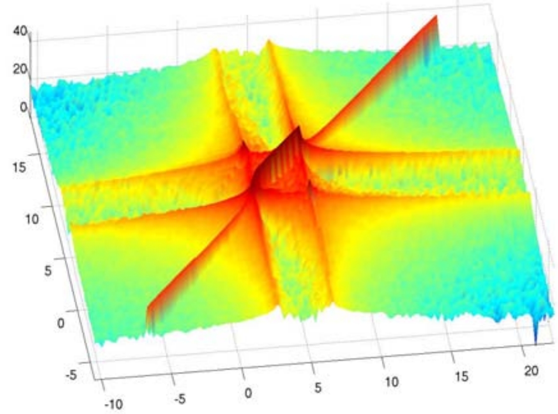
$$\frac{1-\beta}{2T_s} < f < \frac{1+\beta}{2T_s}$$



Pulse shaping filter with roll-off β = 0.5

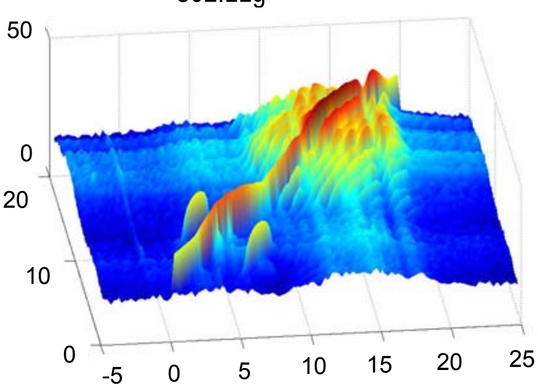


Pulse shaping filter with roll-off β = 0.01

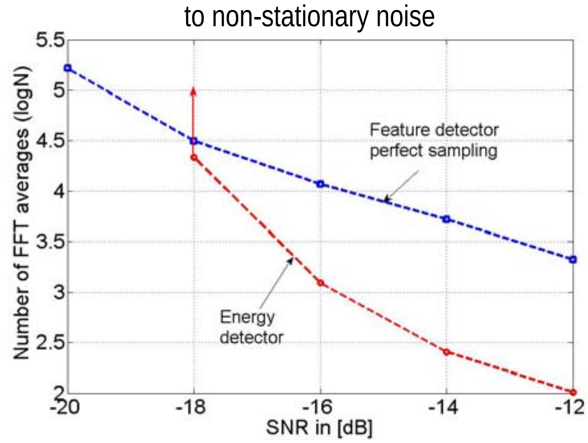


Advantages of Feature Detectors

Strong adjacent band primary user 802.11g



Feature detector robust to non-stationary noise



Energy detector

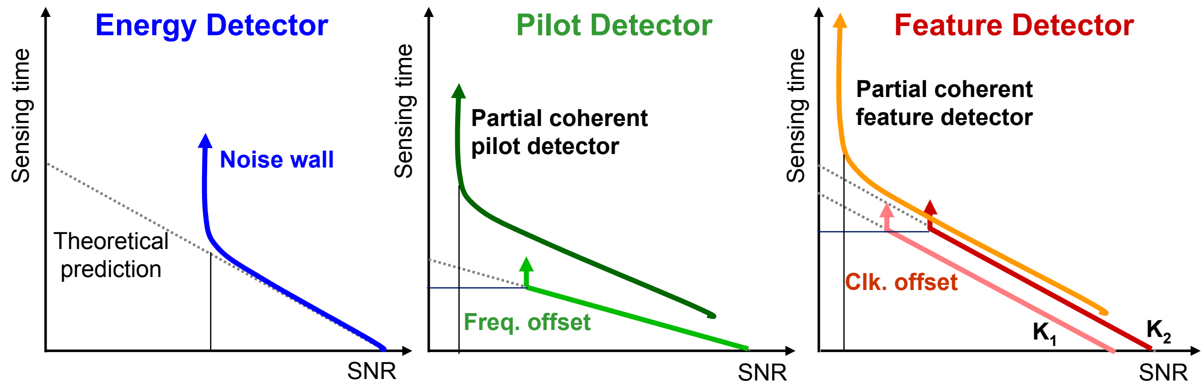
$$PG_{ED} \sim \frac{SNR_{in}\sqrt{N}}{\sqrt{1 + x(1+N)}}$$

Feature detector

$$PG_{FD} \sim \frac{K_{\alpha} SNR_{in}\sqrt{N}}{\sqrt{1 + x}}$$

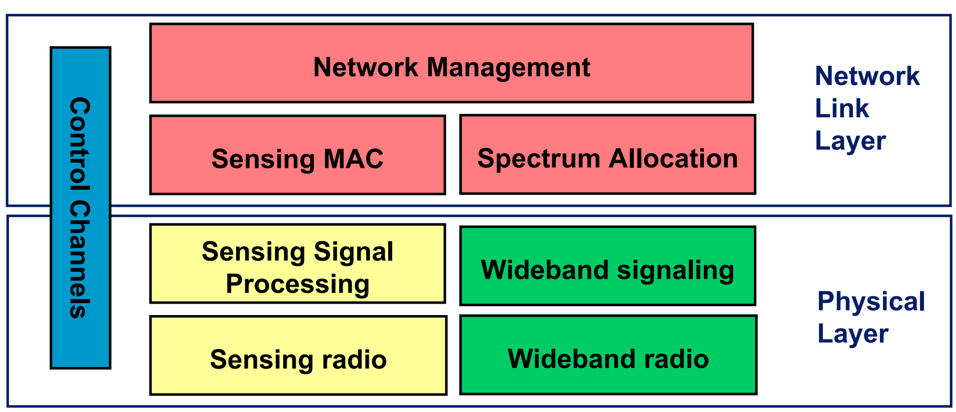
PG - Processing gain   x – adjacent band leakage

Choosing the Right Spectrum Sensor



N~1/SNR^2	N~1/(p*SNR)	N~K/SNR^2
Noise wall	Freq. offset ~ 0.01 ppm	Clk offset ~ 1 ppm
Noise estimation	Partial coherent pilot processing	Partial coherent feature processing
18 mult, 320Kb BRAM 10, 353 slices	40 mult, 64Kb BRAM 22,683 slices	82 mult, 3200Kb BRAM 21, 200 slices
Coarse sensing candidate band selection	Fine sensing if pilots/preambles available	Fine sensing with increased sensitivity

Cross Layer Design for Spectrum Sensing



- **Sensing radio:**
  - Improving radio sensitivity and dynamic range using multiple antenr
  - Use of spatial filtering for blocker suppression
- **Sensing MAC:**
  - Network cooperation for sensing and sensing protocols
  - Use of control channels for network management