Spectrum sensing methods and implementations

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Introduction

spectrum sensing

- electromagnetic field
- wavelengths interesting for radio communications
- 3 kHz – 300 GHz

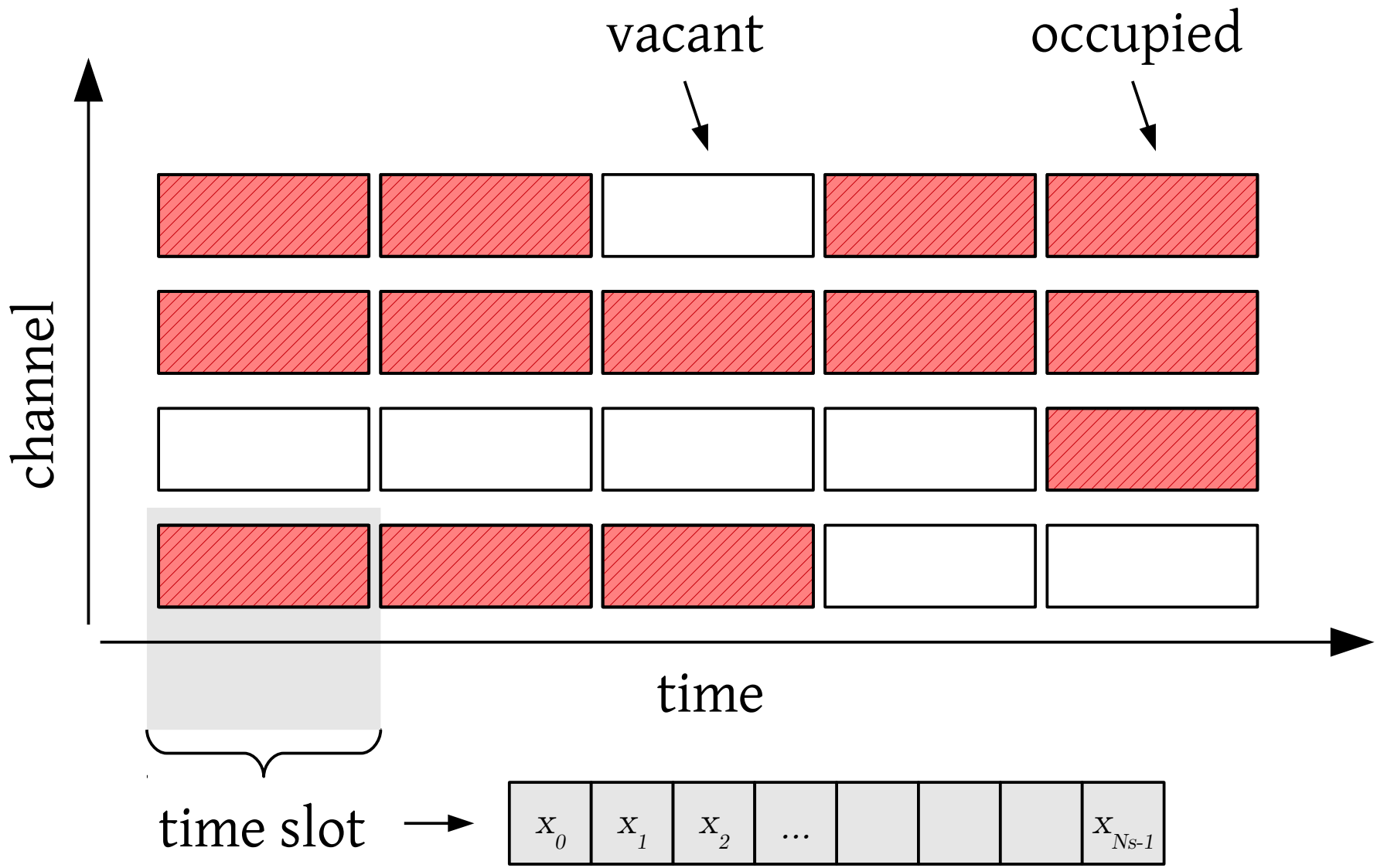
- spectral power density
- signal propagation
- environment characteristics
- detecting users

- single point in space or distributed (cooperative)
- time scale of milliseconds or days
- single channel or multiple channels

Motivation

- S*mart radios* that adapt to their environment
  - demand for bandwidth is growing, spectrum is limited.
  - finding *spectrum opportunities*.
- Transition from static to *dynamic spectrum access*
  - a practical spectrum sensing solution removes the need for centralized geolocation databases.
- Secondary use of *TV whitespaces*
  - *digital dividend* freed a lot of valuable UHF frequencies that can now be used for rural wide-band, sensor networks, etc.

Channel occupancy table



Binary decision

$$\mathcal{H}_0 : x_n = u_n$$

$$\mathcal{H}_1 : x_n = u_n + s_n \qquad n \in [0, N_s - 1]$$

test statistic $\gamma = \gamma(\mathbf{x})$

$$\mathcal{H}_0 \quad \text{if} \quad \gamma(\mathbf{x}) \leq \gamma_0$$

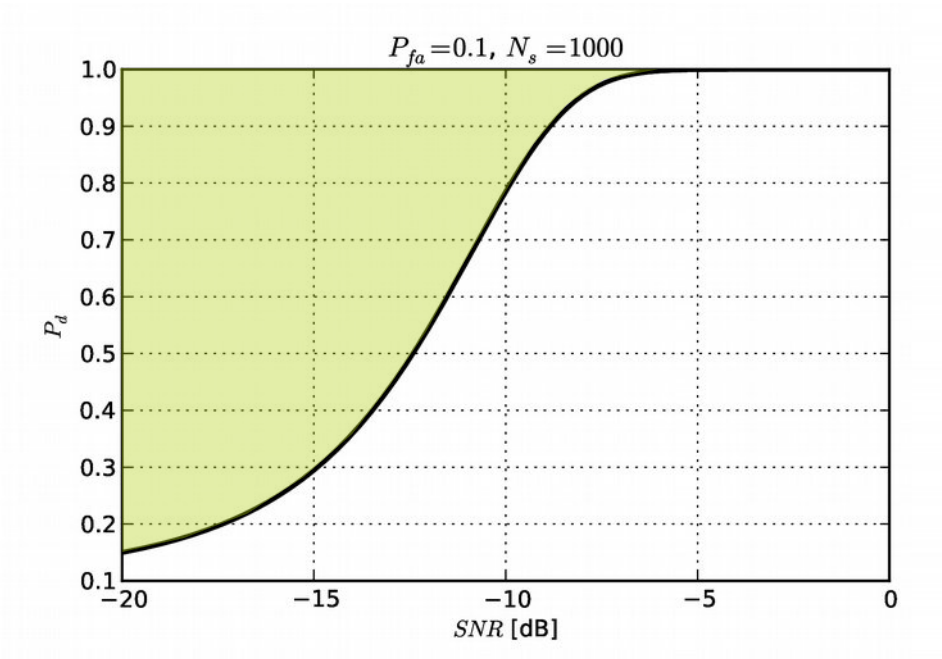
$$\mathcal{H}_1 \quad \text{if} \quad \gamma(\mathbf{x}) > \gamma_0$$

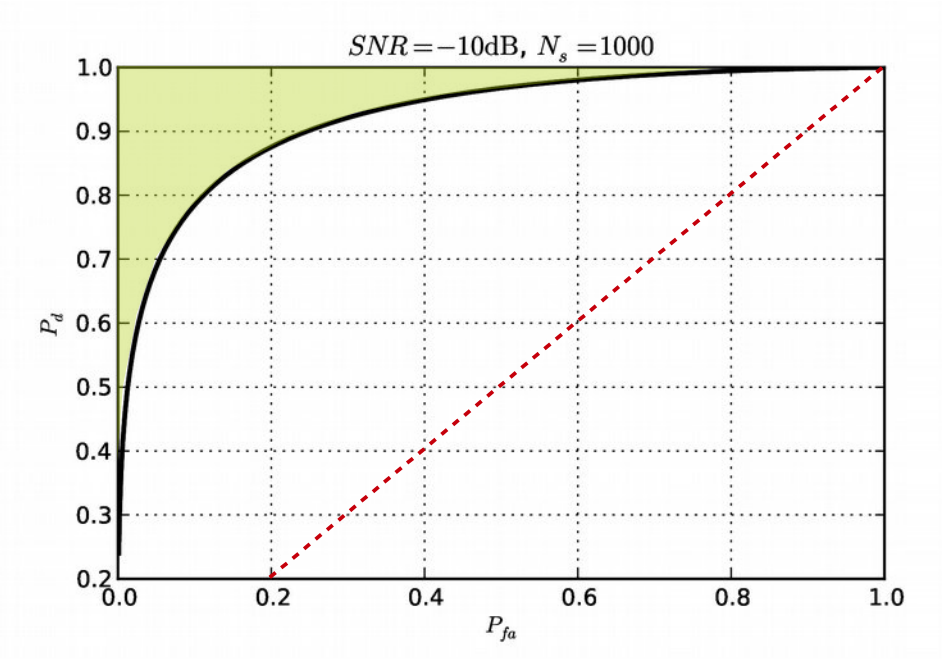
probability of false alarm P_{fa} → probability of detection P_d

Comparing methods

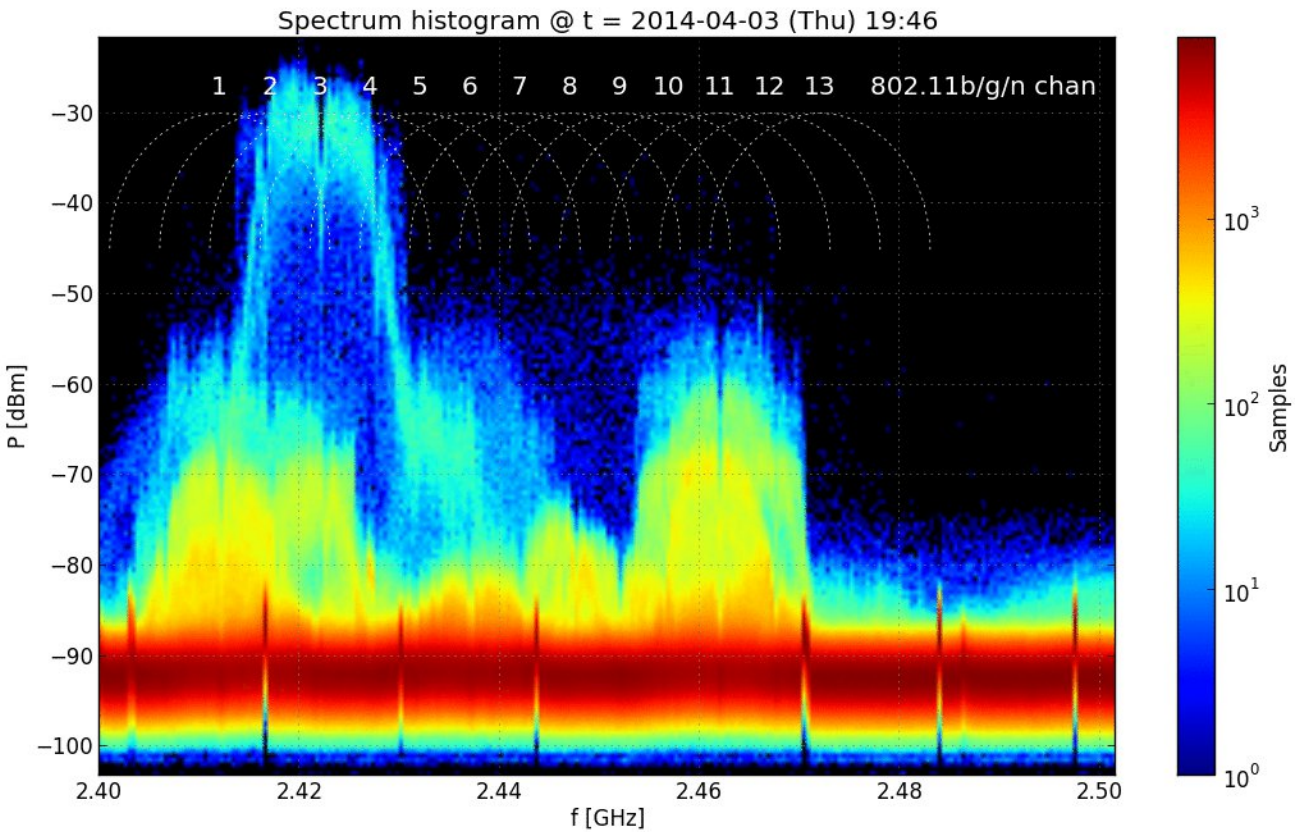
number of samples N_s

signal to noise ratio $SNR = \frac{\frac{1}{N_s}\sum_{n=0}^{N_s} s_n^2}{\sigma_u^2}$





Sensing the spectrum



Sensing methods

method	detected signal property
energy detection	signal energy
covariance methods CAV, CFN, eigenvalue, ...	correlation between samples
cyclostationary detection	stochastic periodicity
matched filter	known waveform

Sensing methods

method

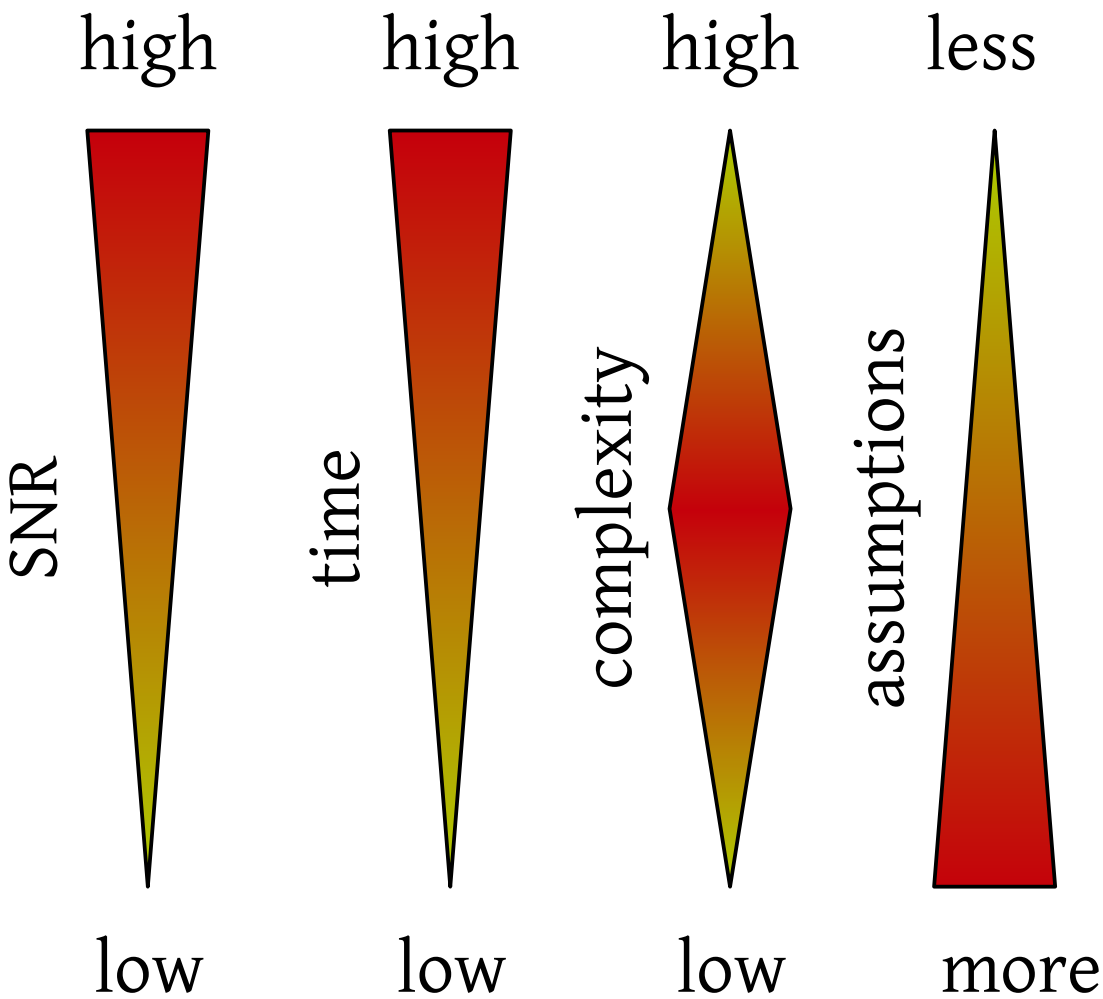
energy detection

covariance methods

CAV, CFN, eigenvalue, ...

cyclostationary detection

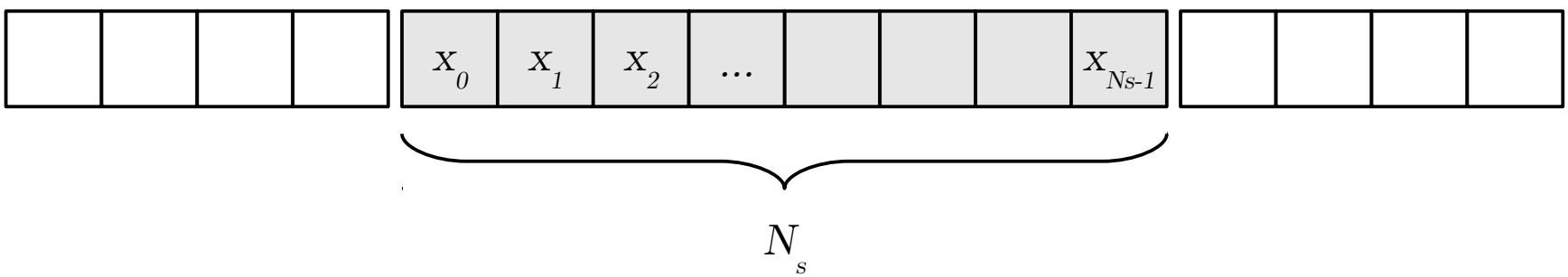
matched filter



Energy detection

test statistic

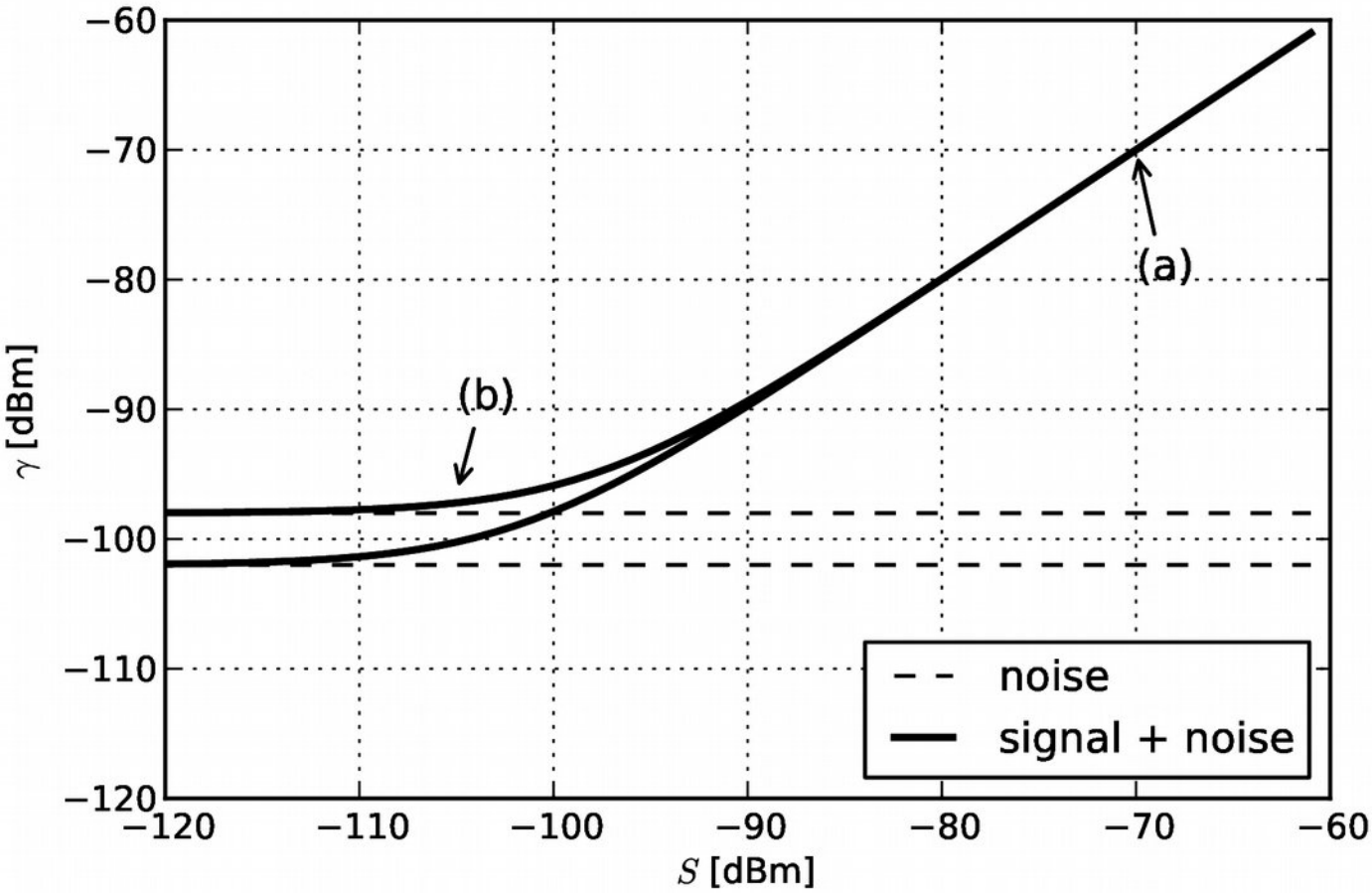
$$\gamma = \sum_{n=0}^{N_s} x_n^2$$



threshold

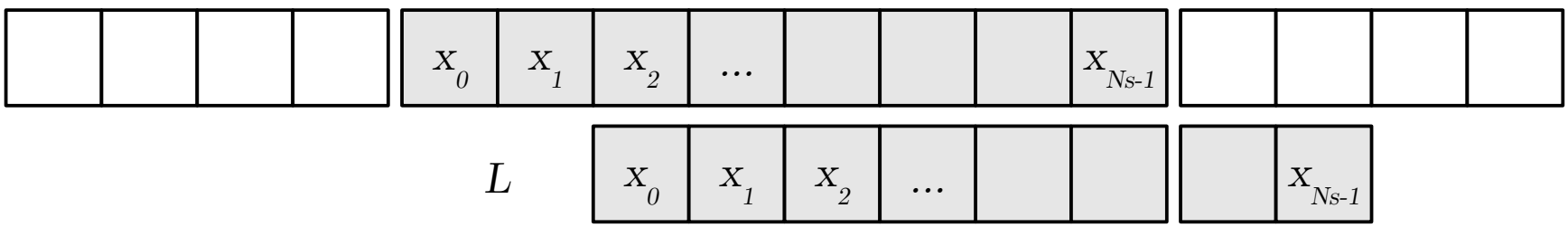
$$\gamma_0 = N_s \sigma_u^2 \left(1 + \frac{\sqrt{2} Q^{-1}(P_{fa})}{\sqrt{N_s}} \right)$$

SNR wall


−60
−70
−80
−90
−100
−110
−120
γ [dBm]
−120
−110
−100
−90
−80
−70
−60
S [dBm]
(a)
(b)
noise
signal + noise

Covariance methods

$$\lambda_l = \frac{1}{N_s} \sum_{n=0}^{N_s-1} x_n \cdot x_{n-l} \qquad l \in [0, L-1]$$



$$\mathbf{R} = [r_{ij}] = \begin{bmatrix} \lambda_0 & \lambda_1 & \dots & \lambda_{L-1} \\ \lambda_1 & \lambda_0 & \dots & \lambda_{L-2} \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_{L-1} & \lambda_{L-2} & \dots & \lambda_0 \end{bmatrix}$$

Covariance Absolute Value

$$T_1 = \frac{1}{L}\sum_{i=1}^{L}\sum_{j=1}^{L}|r_{ij}|$$

$$T_2 = \frac{1}{L}\sum_{i=1}^{L}|r_{ii}|$$

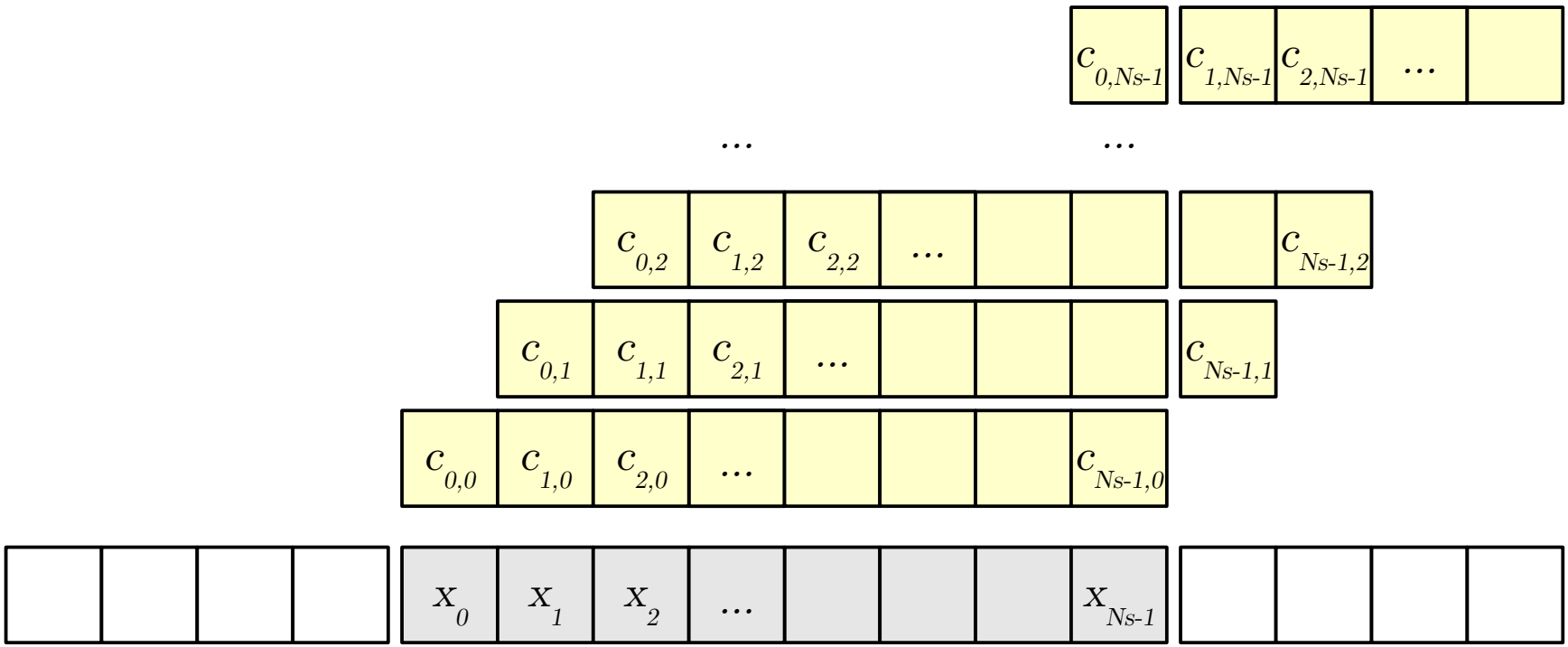
$$\begin{bmatrix} \lambda_0 & \lambda_1 & \cdots & \lambda_{L-1} \\ \lambda_1 & \lambda_0 & \cdots & \lambda_{L-2} \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_{L-1} & \lambda_{L-2} & \cdots & \lambda_0 \end{bmatrix}$$

$$\gamma = \frac{T_1}{T_2}$$

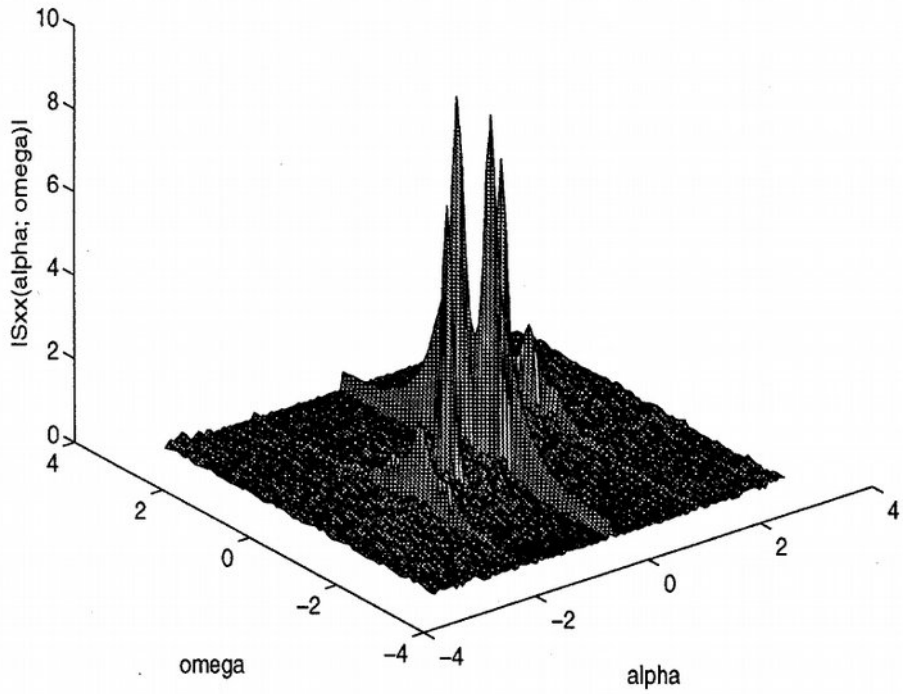
$$\gamma_0 = \frac{1 + (L-1)\sqrt{\frac{2}{N_s \pi}}}{1 - Q^{-1}(P_{fa})\sqrt{\frac{2}{N_s}}}$$

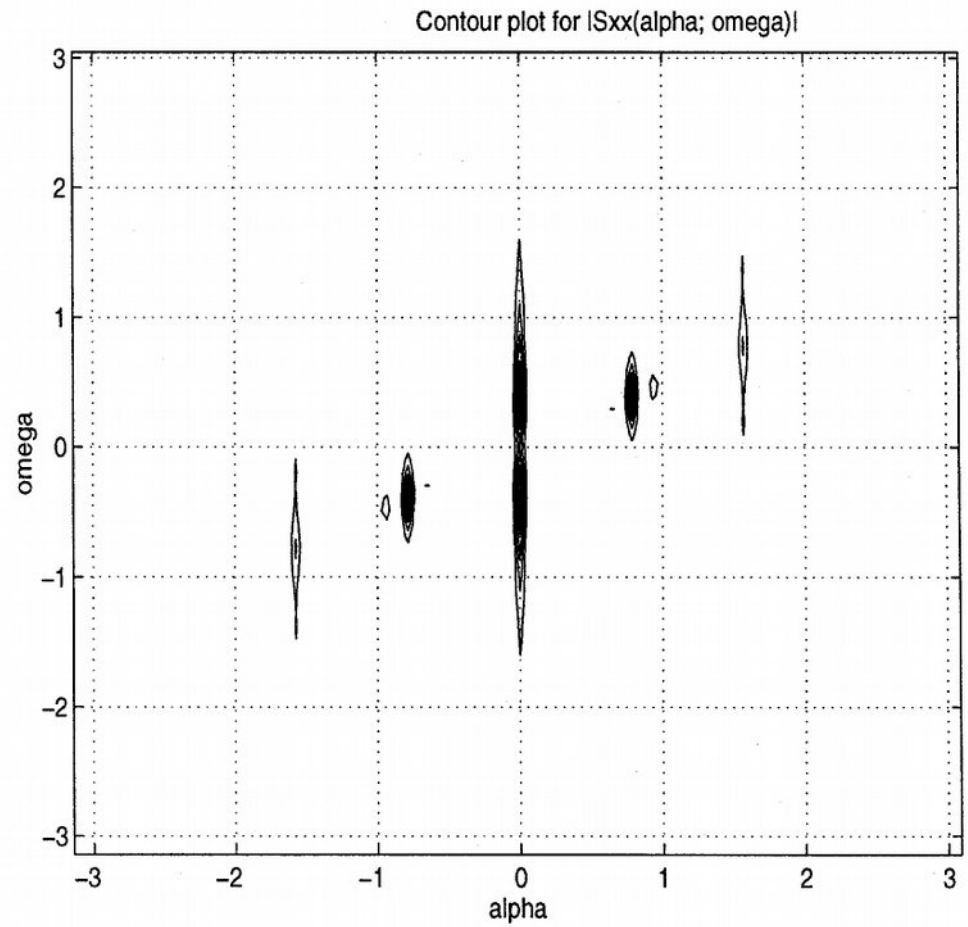
Cyclostationary detection

$$\mu_n = \mu_{n+N_p}$$
$$c_{n,\tau} = c_{n+N_p,\tau}$$



Cyclostationary detection

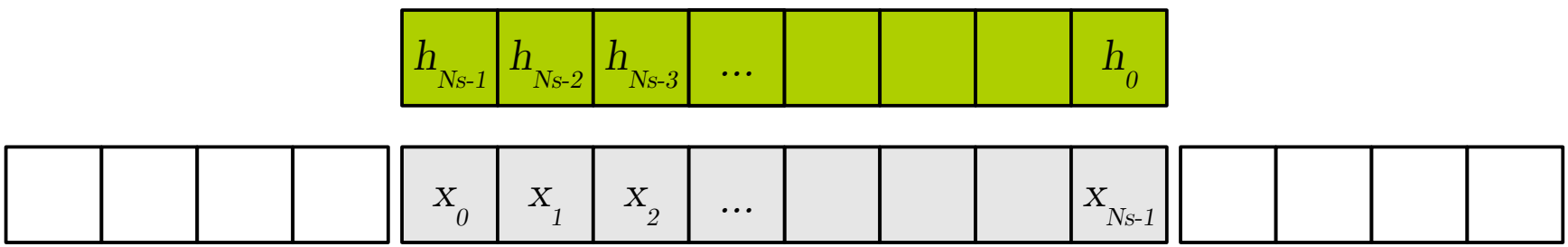




G. B. Giannakis, "Cyclostationary Signal Analysis," in *Digital Signal Processing Handbook* (V. K. Madisetti and D. B. Williams, eds.), CRC Press LLC, 1999.

Matched filter

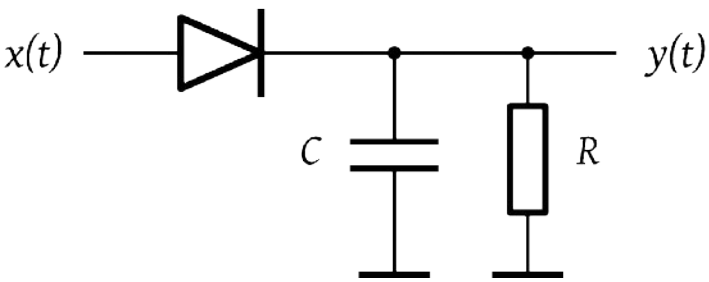
test statistic $$\gamma = \sum_{n=0}^{N_s-1} x_n \cdot h_{N_s-1-n}$$



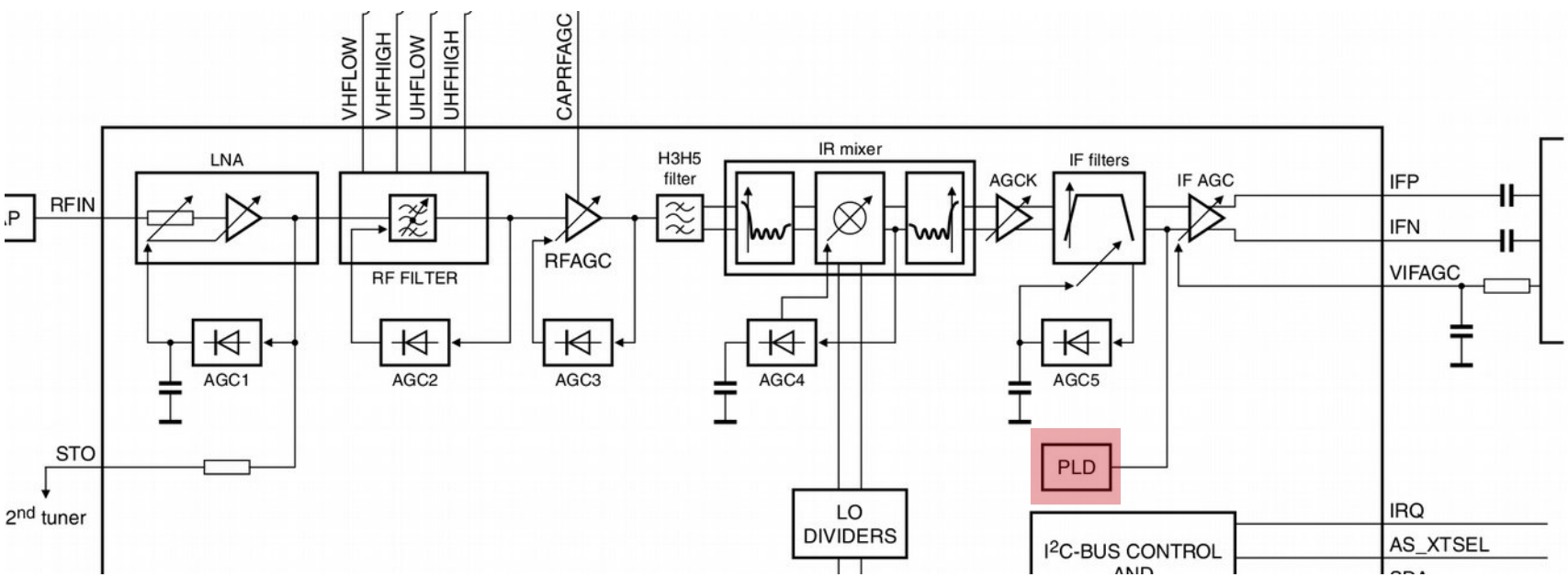
threshold $$\gamma_0 = \sigma_u Q^{-1}(P_{fa}) \sqrt{\sum_{n=0}^{N_s-1} |h_n|}$$

Implementations

Analog



$$\approx \qquad \gamma = \int_0^T x^2(t)\,dt$$



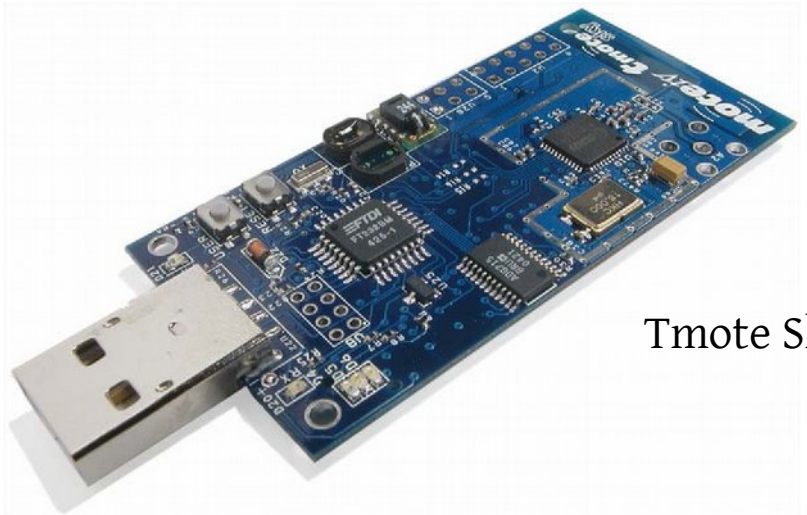
Analog

- Fast Power-Up Time < 1 ms
- Special IEEE 802.15.4-2003 Hardware Support:
  - FCS Computation
  - Clear Channel Assessment
  - Energy Detection / RSSI Computation
  - Automatic CSMA-CA
  - Automatic Frame Retransmission
  - Automatic Frame Acknowledgement
  - Automatic Address Filtering
- Industrial Temperature Range:
  - -40° C to 85° C
- I/O and Packages:
  - 32-pin Low-Profile QFN
  - RoHS/Fully Green
- Compliant to EN 300 328/440, FCC-CFR-47 Part 15, A
- Compliant to IEEE 802.15.4-2003

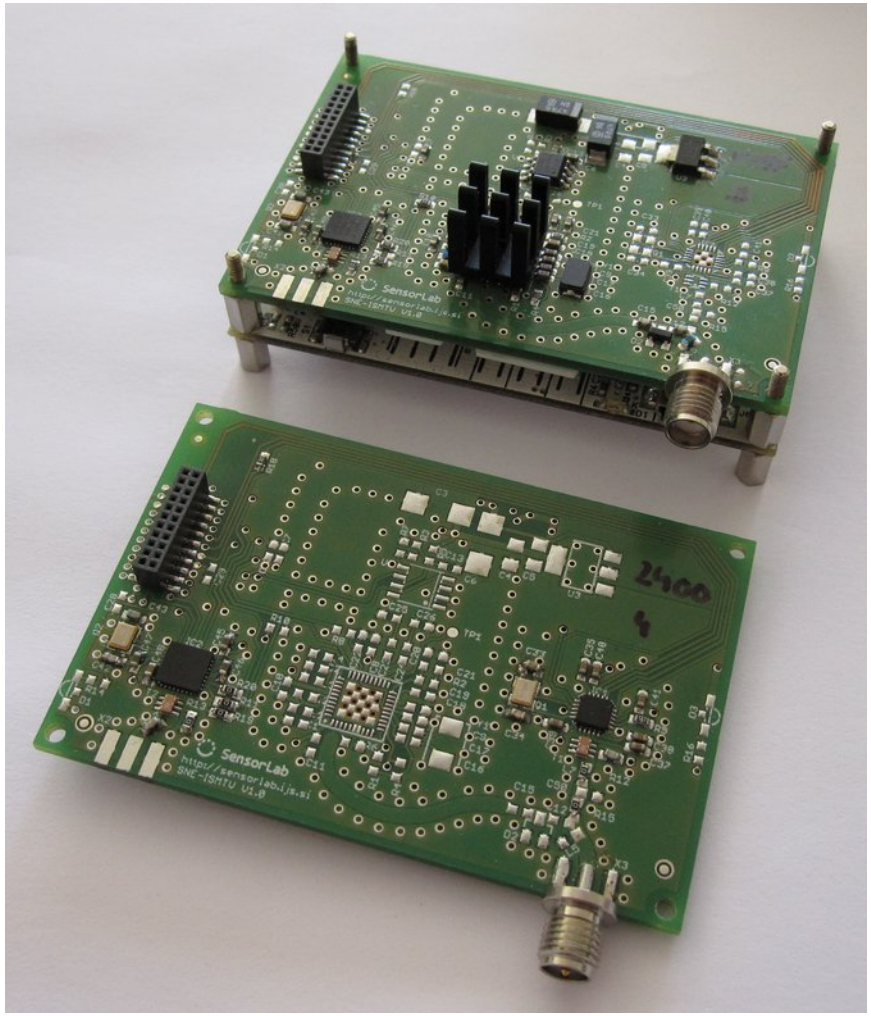
AVR®
Low Power
2.4 GHz
Transceiver
for ZigBee,
IEEE 802.15.4,
6LoWPAN,
RF4CE and ISM
Applications

AT86RF230

Examples



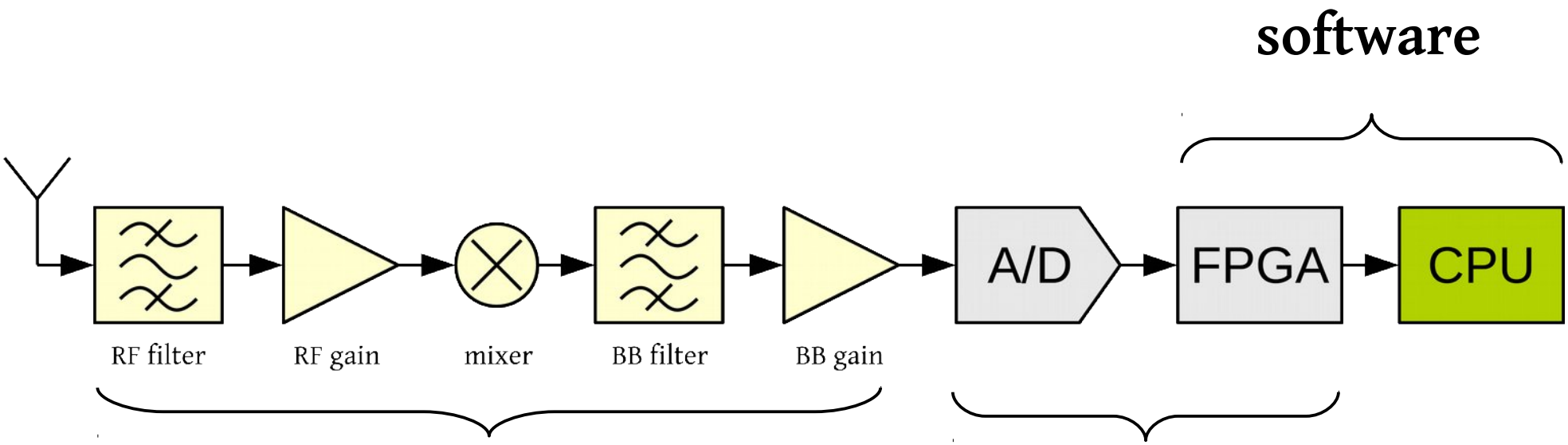
Tmote Sky



M. Zennaro, E. Pietrosemoli, A. Arcia-Moret, C. Mikeka, J. Pinifolo, C. Wang, and S. Song, “TV White Spaces, I presume?,” 2013.

VESNA SNE-ISMTV

Digital



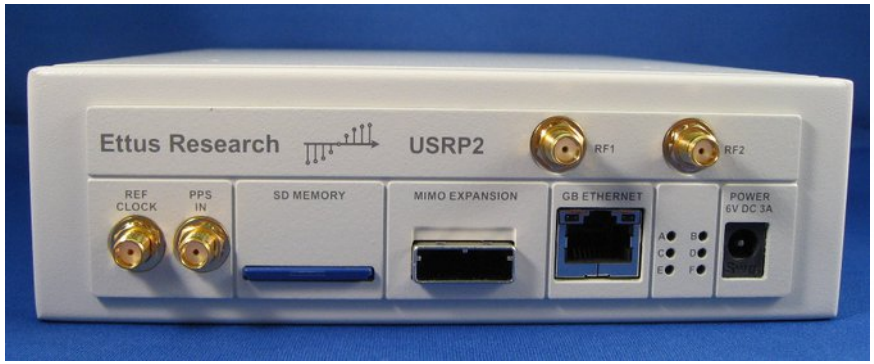
analog front-end

- RF filter
- heterodyne conversion
- antialiasing filter
- gain control

digital front-end

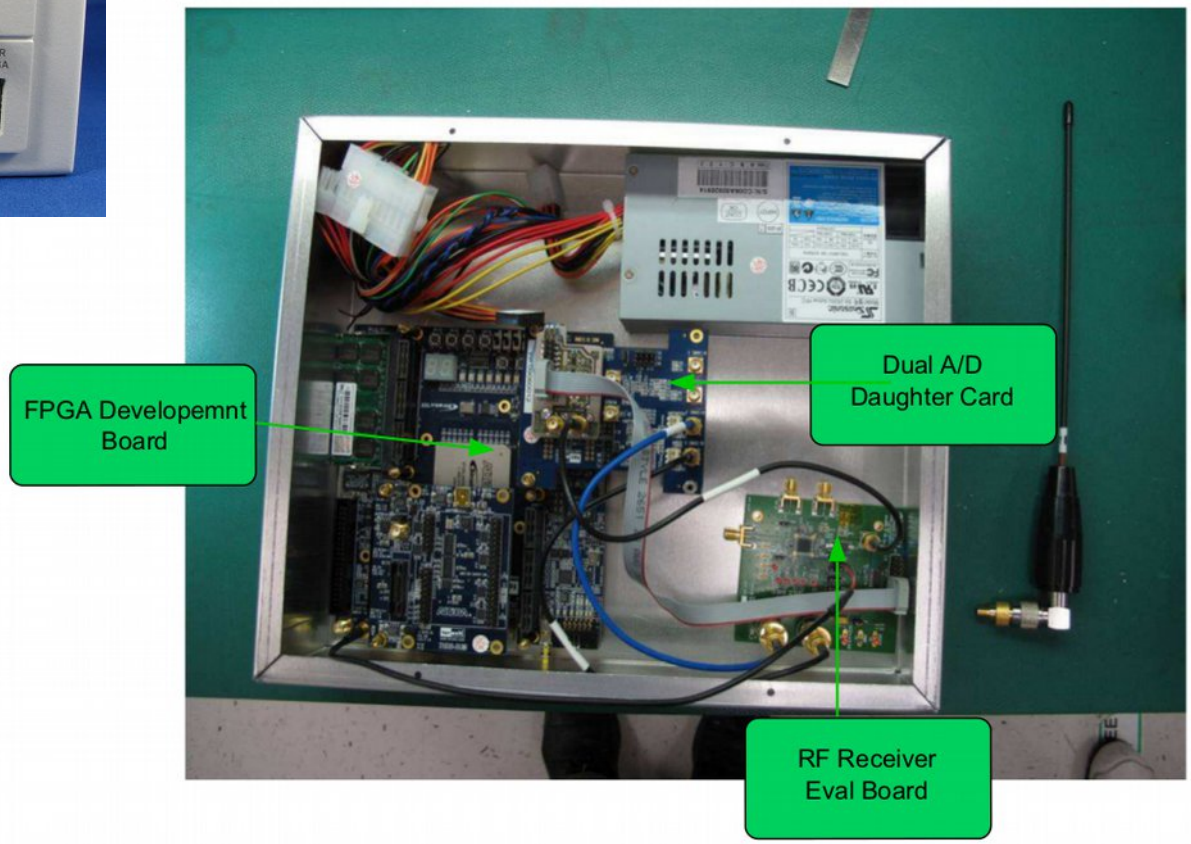
- baseband filter
- decimation
- Fourier transform

Examples



Ettus research USRP

P. V. Wesemael et al., "Interference Robust SDR FE receiver," in *IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pp. 274–275, IEEE, 2012.



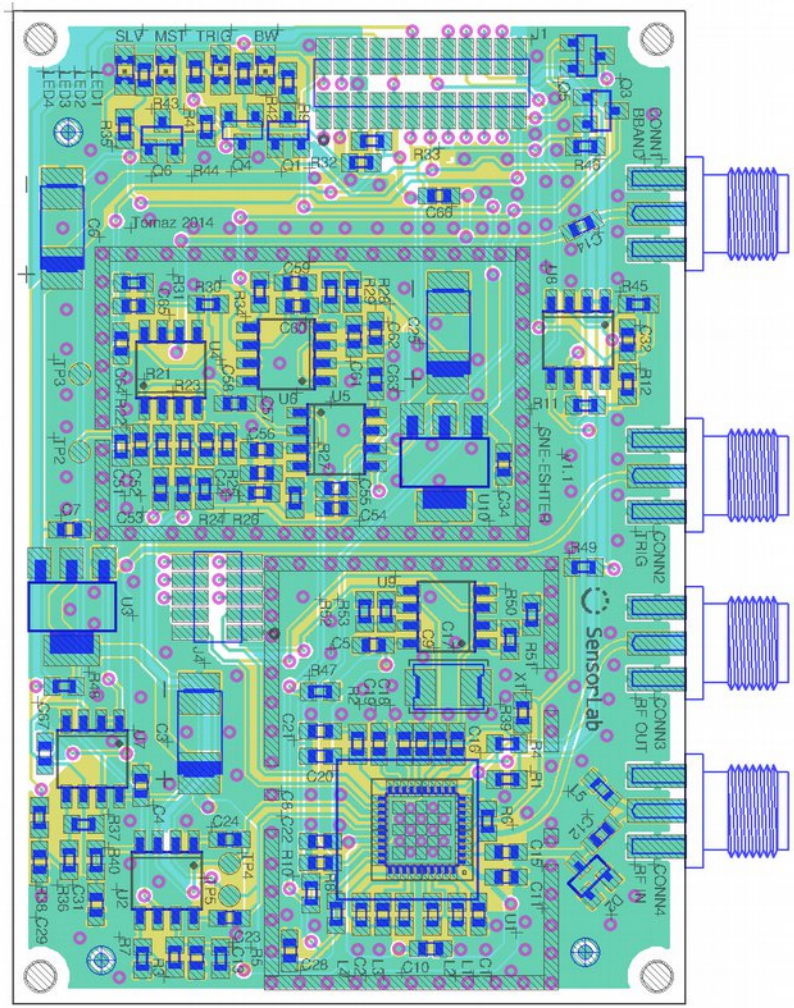
R. Balamurthi, H. Joshi, C. Nguyen, A. K. Sadek, S. J. Shellhammer, and C. Shen, "A TV White Space Spectrum Sensing Prototype," in *IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pp. 297–307, IEEE, 2011.

Conclusions

- Analyses often don't have realistic assumptions
  - e.g. uncorrelated noise, synchronization requirements
- Computational complexity commonly overlooked
  - complexity = battery time, cost
  - developments in covariance methods seem promising.
- Hard to reproduce results in many papers
- Practical experiments
  - still mostly based on energy detection
  - industry prefers heuristical to analytical methods

Further work

- Develop an experimental hardware platform
  - practical experiments with spectrum sensing methods
  - study of effects of engineering constraints
  - sensor networks and other small, embedded systems
  - based on VESNA platform developed at JSI



Questions?

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