Wireless Networking [ET4394]

Cognitive Radio

Przemysław Pawełczak

Learning objectives (LO)

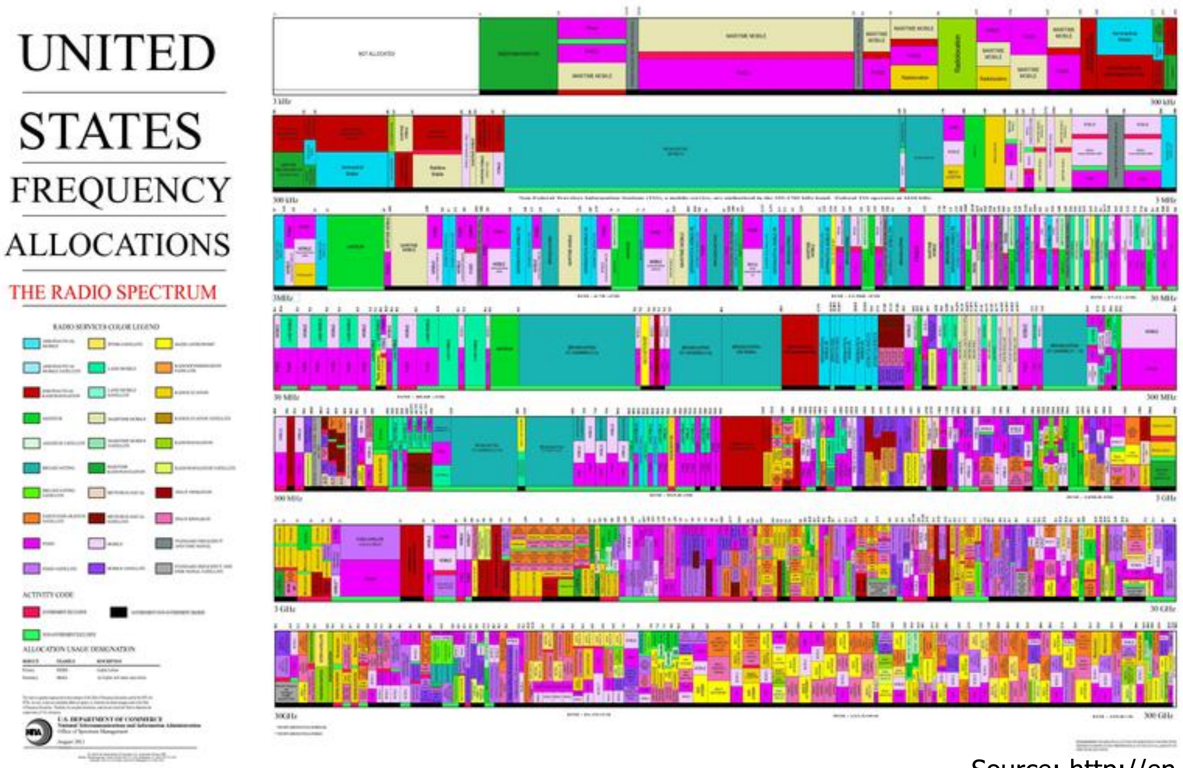
- **LO:** To understand the principles of Cognitive Radio Operation

Literature

- **Overview paper**
  - Y.-C. Liang, K.-C. Chen, G. Y. Li, P. Mähönen, *Cognitive Radio Networking and Communications: An Overview*, IEEE Transactions on Vehicular Technology, vol. 60, no. 7, Sept. 2011
    - http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5783948
- **Book**
  - E. Biglieri, A. J. Goldsmith, L. J. Greenstein, N. B. Mandayam, *Principles of Cognitive Radio*, Cambridge University Press, 2013

The Paradox of Radio Spectrum Regulation

- All spectrum is allocated but most of it is unused



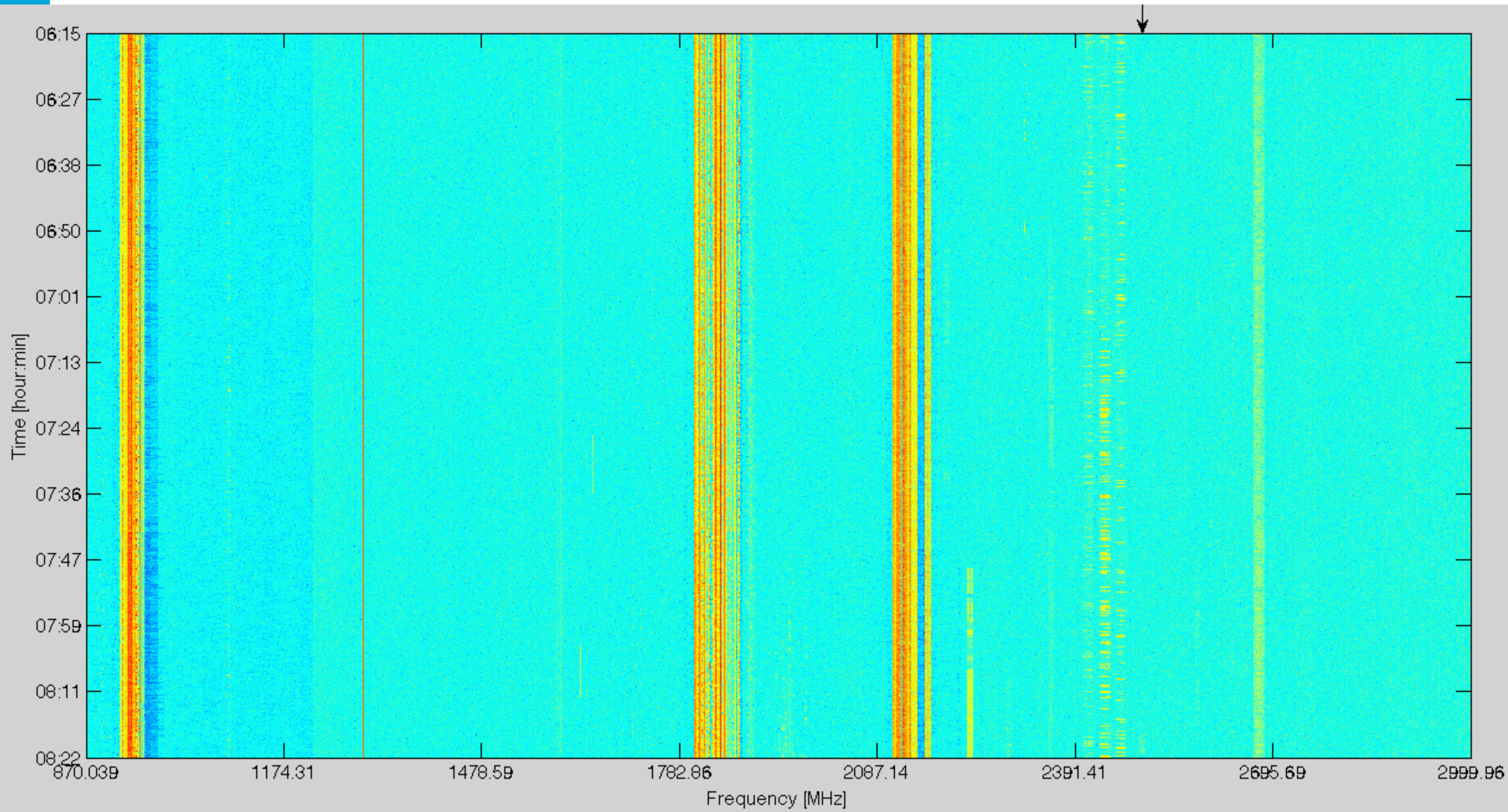
Source: http://en.wikipedia.org/wiki/Frequency_allocation

Real-life Example

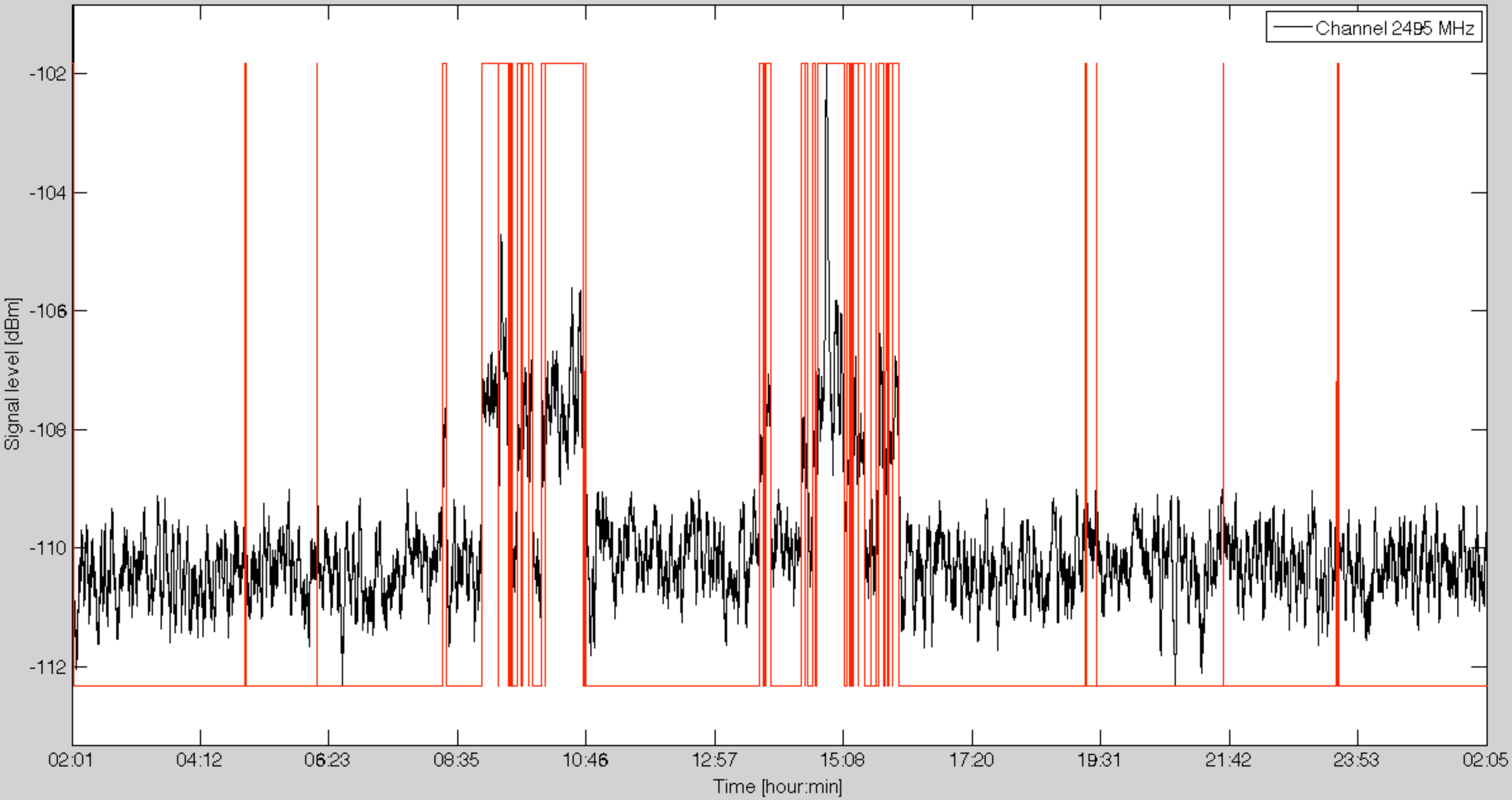
- Queen Beatrix abdication: Amsterdam 30 April 2013
- 3 measurement stations of Agentschap Telekom
  - Bijenkorf, het 'IJ, Rokin
- 24 hour measurement through RFEye stations
  - http://www.crfs.com/products/category/rf-receiver-nodes-bdcs/
- 22 channels granted for TV operation
  - Reuters, NOS, WDR, RTV Noord-Holland, …
- Most dense wireless spectrum utilization in Dutch history

- **Results**
  - 'IJ: 7/22 allocated video signals used =31.8%
  - Bijenkorf: 3/22 allocated video signals used=13.6%
  - Rokin: 7/22 allocated video signals used=31.8%

Real-life Example



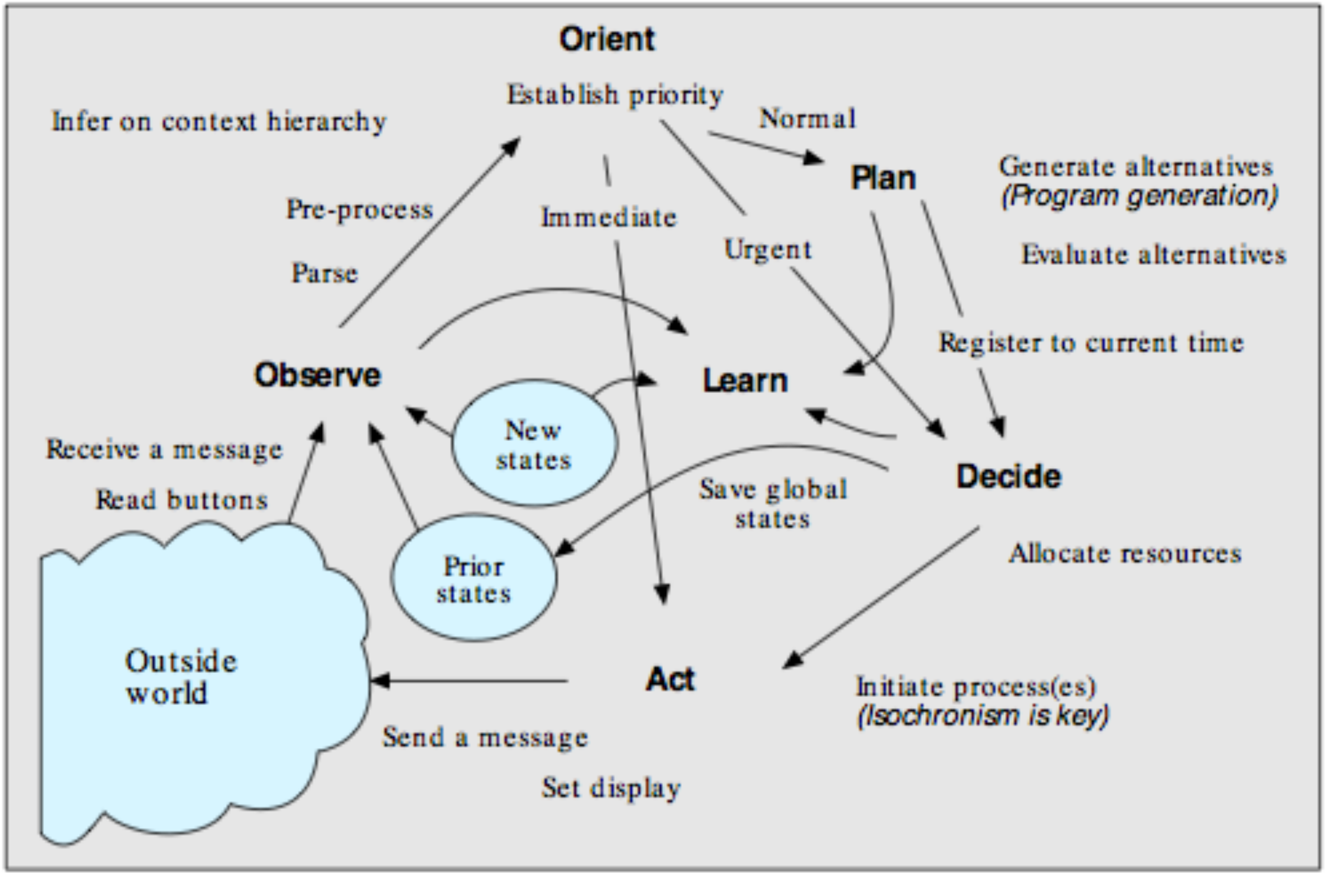
Real-life Example



Cognitive Radio: History

- **Joseph Mitola and Gerald Q. Maguire, Jr.**
  - *Cognitive Radio: Making Software Radios More Personal*, IEEE Personal Communications, Aug. 1999
  - http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=788210
- **Simon Haykin**
  - *Cognitive Radio: Brain-Empowered Wireless Communications*, IEEE Journal on Selected Areas in Communications, vol. 23, no. 2, Feb. 2005
  - http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1391031

Cognitive Radio: Definition



Soure: Joseph Mitola and Gerald Q. Maguire, Jr., Cognitive Radio: Making Software Radios More personal, IEEE Personal Communications, Aug. 1999

Spectrum Sensing

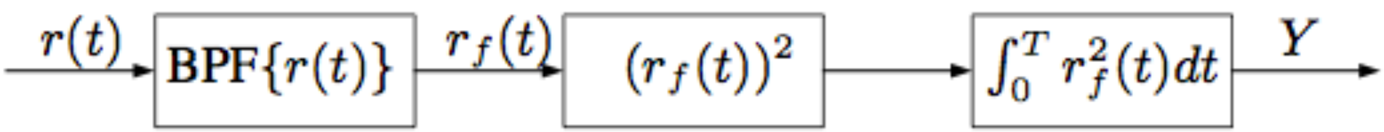
- **Question:** how to find a white space?
- **Answer:** local detection based on signal observation

- **Assumptions**
  - time is slotted
  - r(t): Detected signal has a non-zero carrier
  - n(t): noise is Gaussian with zero mean and unit variance
  - No fading or other signal perturbations

Spectrum Sensing: Energy Detector

- BPF: Band Pass Filter

- t: sample instance time
- r(t): input signal
- $r_f(t)$: filtered input signal
- Y: decision variable



F. E. Visser, G. Janssen, P. Pawełczak, **Multinode Spectrum Sensing Based on Energy Detection for Dynamic Spectrum Access**, Proc. IEEE VTC-Spring 2008
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4525849

Spectrum Sensing: Energy Detector Hypothesis

- Two hypothesis

$$\begin{cases} n(t), & H_0 \\ r(t)+n(t), & H_1 \end{cases}$$

- In distribution

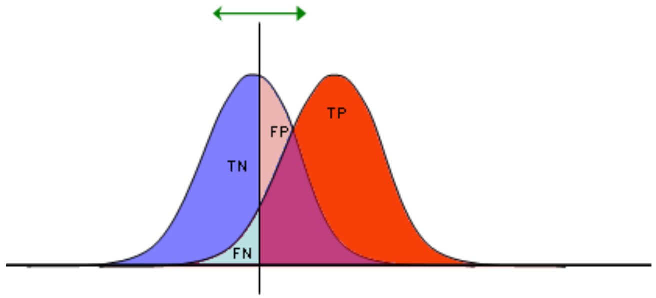
$$Y \sim \begin{cases} \chi^2_{2u}, & \text{under } H_0, \\ \chi^2_{2u}(2\gamma), & \text{under } H_1, \end{cases} \Rightarrow$$

$$P_D = \Pr(Y > \lambda | H_1) = Q_u(\sqrt{2\gamma}, \sqrt{\lambda}),$$

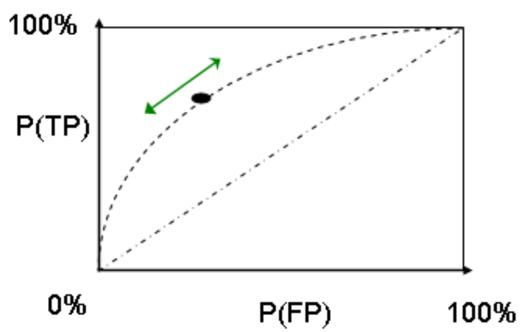
$$P_F = \Pr(Y > \lambda | H_0) = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)},$$

F. E. Visser, G. Janssen, P. Pawełczak, **Multinode Spectrum Sensing Based on Energy Detection for Dynamic Spectrum Access**, Proc. IEEE VTC-Spring 2008
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4525849

Receiver Operating Characteristic (ROC)



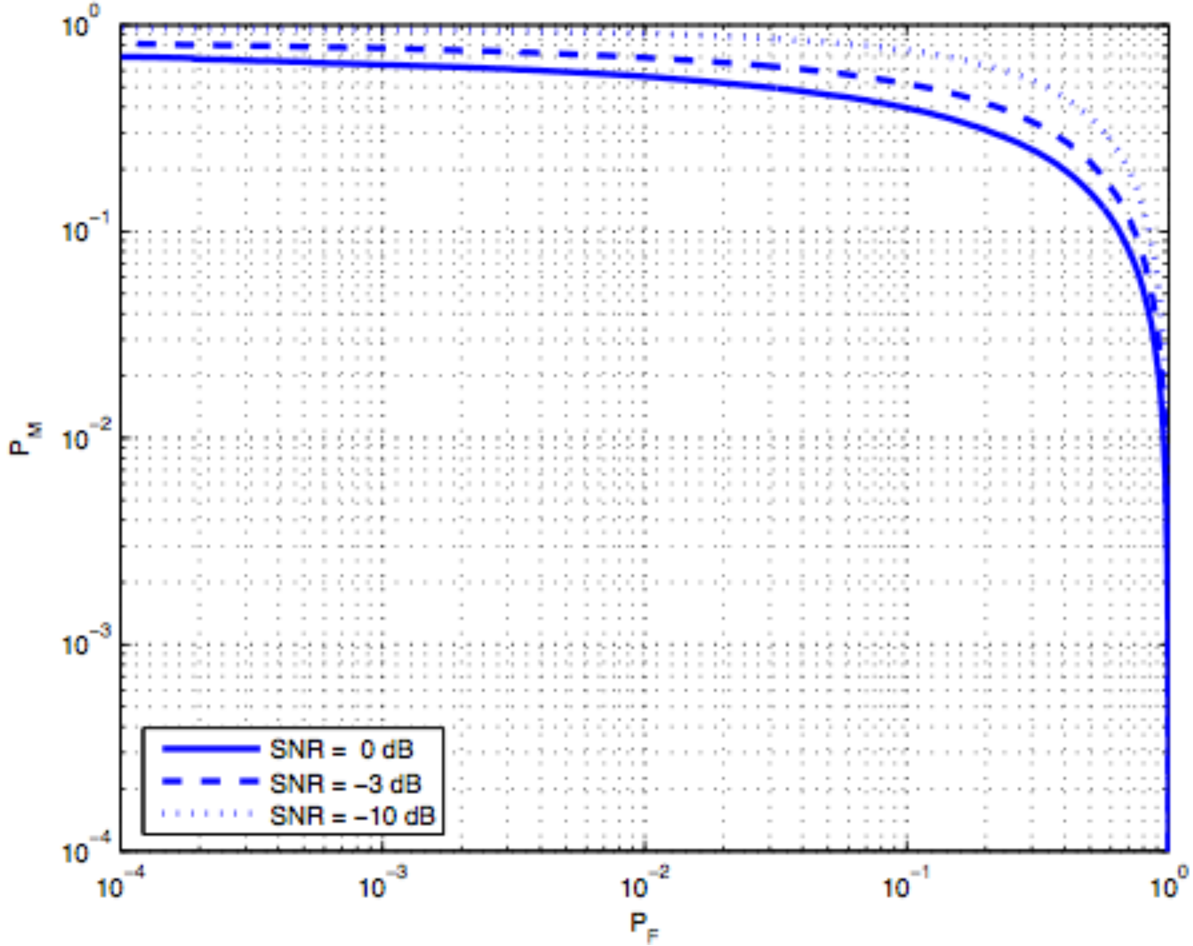
TP	FP
FN	TN
1	1



Source: http://en.wikipedia.org/wiki/Receiver_operating_characteristic

Complementary ROC

F. E. Visser, G. Janssen, P. Pawełczak, **Multinode Spectrum Sensing Based on Energy Detection for Dynamic Spectrum Access**, Proc. IEEE VTC-Spring 2008

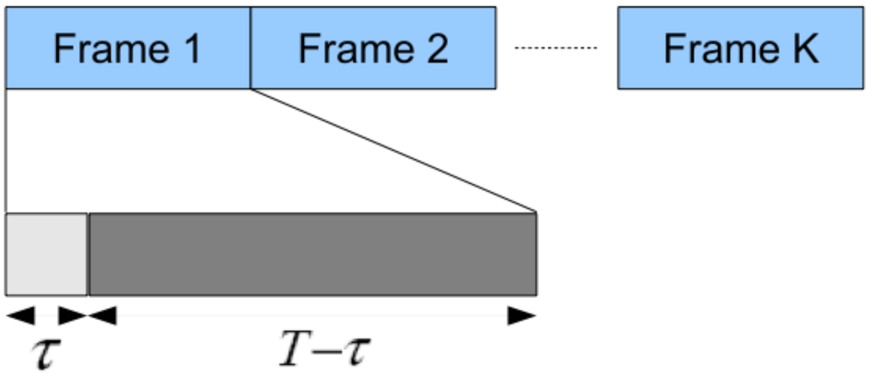


Complementary ROC for Log-Normal+Rayleigh fading at different SNR values for u = 10 and σ_{dB} = 6 dB

Spectrum Sensing: Other methods

- **Cooperative methods**
  - Measurement combining
    - **Hard decision**
      - "k out of n" voting based on local decisions
    - **Soft Decision**
      - Fusion of measurement data (before decision) in a central point
- **Feature detection**
  - Power mask, time-domain features (cyclostationarity), …

Sensing/Throughput Tradeoff



$$R_0(\epsilon,\tau) = \frac{T-\tau}{T} C_0(1 - P_f(\epsilon,\tau))P(\mathcal{H}_0),$$

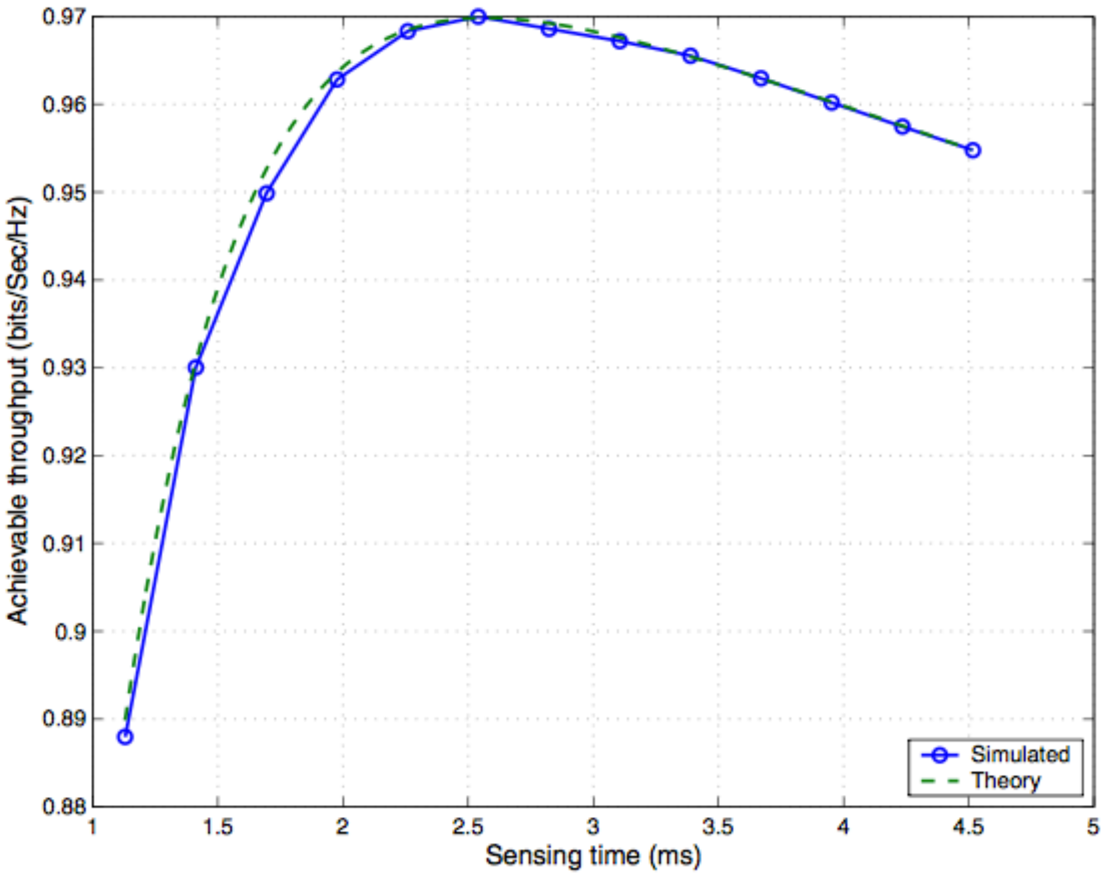
$$R_1(\epsilon,\tau) = \frac{T-\tau}{T} C_1(1 - P_d(\epsilon,\tau))P(\mathcal{H}_1),$$

$$R(\tau) = R_0(\epsilon,\tau) + R_1(\epsilon,\tau).$$

Y.-C. Liang, Y. Zeng, E. C.Y. Peh, A. T. Hoang. **Sensing-Throughput Tradeoff for Cognitive Radio Networks,** IEEE Transactions on Wireless Communications, vol. 7, no. 4, Apr. 2008, http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4489760

Sensing/Throughput Tradeoff

T=100 ms
SNR_P=-15 dB

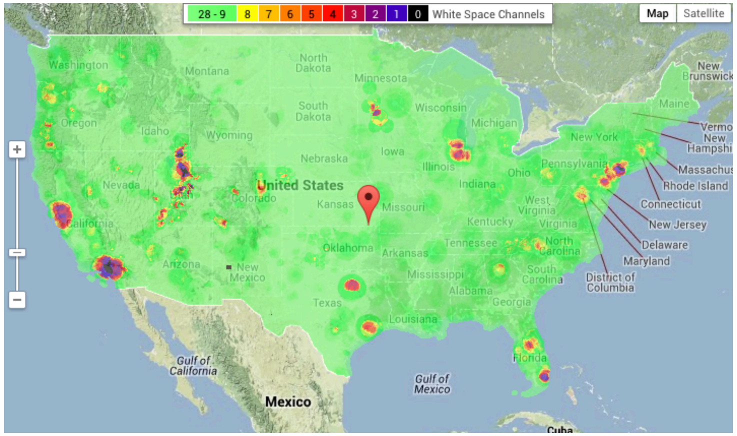


Y.-C. Liang, Y. Zeng, E. C.Y. Peh, A. T. Hoang. **Sensing-Throughput Tradeoff for Cognitive Radio Networks,** IEEE Transactions on Wireless Communications, vol. 7, no. 4, Apr. 2008, http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4489760

Cognitive Radio: Database Approach

- Idea: Search for vacant channels through querying of databases

- **Commercial products**
  - https://www.google.com/get/spectrumdatabase/
  - http://spectrumbridge.com/ProductsServices/WhiteSpacesSolutions/



Source: https://www.google.com/get/spectrumdatabase/channel/

Database Approach—Database Request (Google)

```
{
    "jsonrpc": "2.0",
    "method": "spectrum.paws.init",
    "apiVersion": "v1explorer",
    "params": {
      "type": "INIT_REQ",
      "version": "1.0",
      "deviceDesc": {
        "serialNumber": "your_serial_number",
        "fccId": "your_FCC_ID",
        // ...
      },
      "location": {
        "point": {
          "center": {"latitude": 37.0, "longitude": -101.3}
        }
      }
      "key": "your_API_key"
    },
    "id": "any_string"
  }
```

Source: https://developers.google.com/spectrum/paws/gettingstarted

Database Approach—Database Response (Google)


```
{
 "jsonrpc": "2.0",
 "id": "any_string",
 "result": {
  "type": "AVAIL_SPECTRUM_RESP",
  "version": "1.0",
  "timestamp": "2013-08-31T03:28:08Z",
  "deviceDesc": {
   "serialNumber": "your_serial_number",
   "fccId": "OPS13",
   "fccTvbdDeviceType": "MODE_1"
  },
  "spectrumSchedules": [
   {
    "eventTime": {
     "startTime": "2013-08-31T03:28:08Z",
     "stopTime": "2013-09-02T03:28:08Z"
    },
    ...
```


Source: https://developers.google.com/spectrum/paws/gettingstarted

Database Approach—Database Response (Google) [cont.]


```
"spectra": [
    {
     "bandwidth": 6000000.0,
     "frequencyRanges": [
      {
       "startHz": 5.12E8,
       "stopHz": 5.72E8,
       "maxPowerDBm": 15.99999928972511
      },
     ]
    }
   ]
  }
 ],
 "needsSpectrumReport": false,
 "rulesetInfo": {
  "authority": "US",
  "maxLocationChange": 100.0,
  "maxPollingSecs": 86400,
  "rulesetIds": [
   "FccTvBandWhiteSpace-2010"
]
```


Source: https://developers.google.com/spectrum/paws/gettingstarted

“Cognitive” Radio Standards

- **IEEE SCC41**
  - Definitions, Policy languages, recommended practices, etc.
  - http://grouper.ieee.org/groups/dyspan/index.html
- **IEEE 802.11af**
  - WiFi over TV White Spaces
- **IEEE 802.22**
  - WiMax over TV White Spaces
    - http://en.wikipedia.org/wiki/IEEE_802.22
    - http://www.ieee802.org/22/

“Cognitive” IEEE 802.22

Parameter	IEEE 802.16e	IEEE 802.22-2011	NS-2
Bandwidth	10 MHz	{6, 7, 8} MHz	6 MHz
FFT Size	1024	2048	2048
Frequency/Channels	2.5-2.69 GHz	54-698 MHz	54–698 MHz
Frame size	5 ms	10 ms	10 ms
Duplexing method	TDD	TDD	TDD
Tx/Rx Transit Gap (TTG)	105.7 μs	210, 245, 279.8 μs	210 μs
Rx/Tx Transit Gap (RTG)	60 μs	81.8, 221.7, 350.3 μs	81.8 μs
Modulation types	{16,64}-QAM, QPSK	{16,64}-QAM, QPSK	{16,64}-QAM, QPSK
Coding rates	1/2, 2/3, 3/4, 5/6	1/2, 2/3, 3/4, 5/6	1/2, 2/3, 3/4
Error correction coding	CC, CTC, LDPC	CTC/BTC	No (emulated)
Max power	BS: 43, CPE: 23 dBm	BS/CPE: 36 dBm	BS/CPE: 36 dBm
Assumed noise figure	BS: 4 dB, CPE: 7 dB	BS/CPE: 4-6 dB	BS/CPE: 4 dB
QoS classes	UGS, rtPS, ErtPS, nrtPS, BE	UGS, rtPS, ErtPS, nrtPS, BE	UGS, BE
Cyclic prefix mode	1/4, 1/8, 1/16, 1/32	1/4	1/4
OFDM mapping	Rectangular	DL: vert. UL: horiz.	vert.
Error protection	HARQ	ARQ	ARQ

Source: Pal Grønsund, Przemyslaw Pawelczak, Jihoon Park, Danijela Cabric, **System Level Performance of IEEE 802.22-2011 with Sensing-Based Detection of Wireless Microphones**, IEEE Communications Magazine, vol. 52, no. 2, Jan. 2014
http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6710084

Take-Home Message

- Cognitive Radio is a very exciting and promising topic
- Much research still needs to be done
- Spectrum sensing is quick but unreliable
- Database approach starts to win the market
- Cognitive Standards are already available