# Digital Communication Systems Engineering with Software-Defined Radio

Di Pu, Alexander M. Wyglinski
Worcester Polytechnic Institute

Lecture 24

# Wireless System Evolution

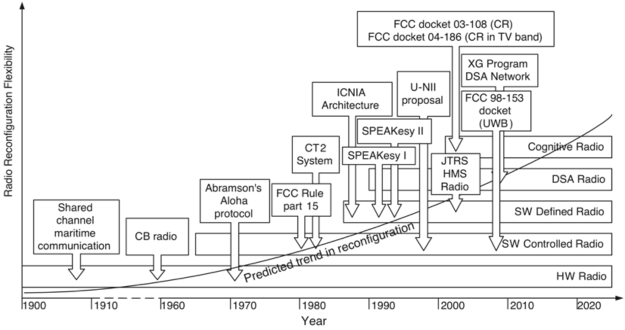


Figure : Depiction of Cognitive Radio History.

P. Pawelczak, R. V. Prasad. "Standardizing Cognitive Radio: IEEE P1900 and IEEE SCC41." in *Cognitive Radio Communications and Networks: Principles and Practice* (A. M. Wyglinski, M. Nekovee, Y. T. Hou (eds.)), Academic Press, 2009.

# Cognitive Radio Definition

- An intelligent wireless communications system
- Based on SDR technology
  - Reconfigurable
  - Agile Functionality
- Aware of its environment
  - RF spectrum occupancy
  - Network traffic
  - Transmission quality
- Learns from its environment and adapts to new scenarios based on previous experiences

# Mitola's Definition

- "wireless personal digital assistants and the related networks were sufficiently computationally intelligent about radio resources, ... to detect user needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs"

J. Mitola III. *Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio*. PhD thesis, Royal Institute of Technology (KTH), Stockholm, Sweden, May 2000.

# Haykin's Definition

- "Inclusive of SDR, [idea] to promote efficient use of spectrum by exploiting the existence of spectrum holes"
- "intelligent wireless communication system (...) that adapt(s) to statistical variations in the input stimuli ... which are highly reliable communication (...); efficient utilization of radio spectrum"

S. Haykin. "Cognitive radio: Brain-empowered wireless communications." *IEEE Journal on Selected Areas in Communications*, vol. 23, pp. 201220, Feb. 2005.

# Standardization Efforts: IEEE SCC 41

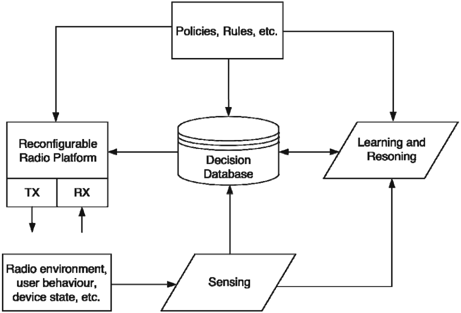


Figure : Schematic of the IEEE SCC41 Cognitive Radio Definition.

P. Pawelczak, R. V. Prasad. "Standardizing Cognitive Radio: IEEE P1900 and IEEE SCC41." in *Cognitive Radio Communications and Networks: Principles and Practice* (A. M. Wyglinski, M. Nekovee, Y. T. Hou (eds.)), Academic Press, 2009.

# Feature Comparison

Table : Comparison of Various Terms Related to Cognitive Radio.

| Aspects | Mitola | Haykin | SDR Forum | FCC | IT |
|---|---|---|---|---|---|
| User Needs | X | | | | |
| Context | X | | | | |
| Intelligence Control | X | X | X | | |
| Radio Spectrum | X | X | X | X | X |
| Spectrum Efficiency | | X | X | X | X |
| Primary Users | | X | X | X | X |
| SDR | X | X | | | |
| Cooperation | | | | X | |
| Reliability | | X | | | |

# How To Construct "Intelligence"?

- Cognitive engine decision making process is highly dependant upon parameters
  - Radio transmission parameters
  - Environmental measurements
  - Performance Objectives
- How can these parameters be related to radio objectives analytically?
  - Engine must understand how parameters affect the environment
  - Multiple parameters must be related to multiple objectives
- Cognitive engine implementations
  - Genetic algorithm based cognitive engine
  - Rule based system cognitive engine
  - Case-Based Reasoning

# Cognitive Radio Parameters

- Radio operating parameters represent the input and output parameters of the cognitive engine
- Recent research has termed the input and output parameters as “knobs” and “dials”
  - Transmission parameters or “Knobs”
    - Parameters that can be modified
  - Environment parameters or “Dials”
    - Parameters that are sensed from the wireless environment
- Parameters selected from various sources
  - General knowledge of field
  - Related research
  - Observation of current publications

# "Knobs" and "Dials"

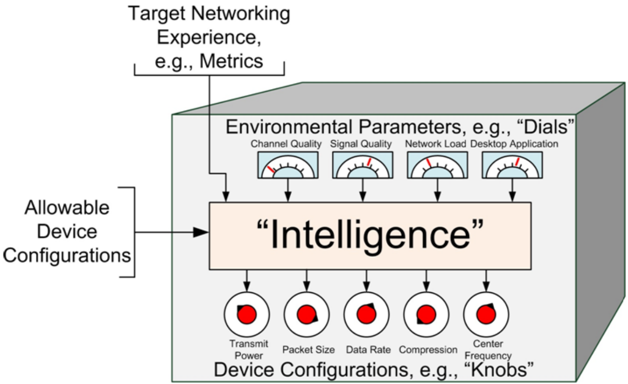


Figure : Schematic of a Cognitive Radio Communication Platform.

# Radio Transmission Parameters

Table : Transmission Parameter List.

| Parameter Name | Description |
|---|---|
| Transmit Power | Raw transmission power |
| Modulation Type | Type of modulation format |
| Modulation Index | Number of symbols for given modulation scheme |
| Bandwidth | Bandwidth of transmission signal in Hertz |
| Channel Coding Rate | Specific rate of coding scheme |
| Frame Size | Size of transmission frame in bytes |
| Time Division Duplexing | Percentage of transmit time |
| Symbol Rate | Number of symbols per second |

T. R. Newman, J. B. Evans, A. M. Wyglinski. "Reconfiguration, Adaptation, and Optimization." in *Cognitive Radio Communications and Networks: Principles and Practice* (A. M. Wyglinski, M. Nekovee, Y. T. Hou (eds.)), Academic Press, 2009.

# Environmental Measurements

Table : Environmentally Sensed Parameter List.

| Parameter Name | Description |
|---|---|
| Path Loss | Amount of signal degradation lost due to the channel path characteristics. |
| Noise Power | Size in decibels of the noise power. |
| Battery Life | Estimated energy left in batteries. |
| Power Consumption | Power consumption of current configuration. |
| Spectrum Information | Spectrum occupancy information. |

T. R. Newman, J. B. Evans, A. M. Wyglinski. "Reconfiguration, Adaptation, and Optimization." in *Cognitive Radio Communications and Networks: Principles and Practice* (A. M. Wyglinski, M. Nekovee, Y. T. Hou (eds.)), Academic Press, 2009.

# Radio Performance Objectives

Table : Cognitive Radio Objectives.

| Objective Name | Description |
|---|---|
| Minimize Bit-Error-Rate | Improve the overall BER of the transmission environment. |
| Maximize Throughput | Increase the overall data throughput transmitted by the radio. |
| Minimize Power Consumption | Decrease the amount of power consumed by the system. |
| Minimize Interference | Reduce the radios interference contributions. |
| Maximize Spectral Efficiency | Maximize the efficient use of the frequency spectrum. |

T. R. Newman, J. B. Evans, A. M. Wyglinski. "Reconfiguration, Adaptation, and Optimization." in *Cognitive Radio Communications and Networks: Principles and Practice* (A. M. Wyglinski, M. Nekovee, Y. T. Hou (eds.)), Academic Press, 2009.

# Multi-objective Fitness Function Construction

- *Weighted sum approach* allows us to combine the single objective functions into one aggregate multiple objective function
- Each objective is multiplied by a weight $w_i$ and summed together to give a single scalar value for approximating the value of a parameter set:

$$\begin{aligned} f_{multicarrier} &= w_1 * (f_{min\_ber}) + w_2 * (f_{max\_tp}) + w_3 * (f_{min\_power}) \\ &+ w_4 * (f_{min\_interference}) + w_5 * (f_{max\_spectralefficiency}) \end{aligned}$$

- Weighting values, $w_1$, $w_2$, $w_3$, $w_4$, and $w_5$ determine the search direction for the algorithm
- Note that because the individual objective functions are normalized they are unitless

# Weighting Selection

Table : Example Weighting Scenarios.

| **Scenario** | **Weight Vector** $[w_1, w_2, w_3, w_4, w_5]$ |
|---|---|
| Low Power Mode (min. power) | [ 0.10, 0.20, 0.45, 0.15, 0.10 ] |
| Emergency Mode (min. BER) | [ 0.50, 0.10, 0.10, 0.10, 0.20 ] |
| DSA Mode (min. interference) | [ 0.10, 0.20, 0.10, 0.50, 0.10 ] |
| Multimedia Mode (max. throughput) | [ 0.15, 0.50, 0.10, 0.15, 0.10 ] |

T. R. Newman, J. B. Evans, A. M. Wyglinski. "Reconfiguration, Adaptation, and Optimization." in *Cognitive Radio Communications and Networks: Principles and Practice* (A. M. Wyglinski, M. Nekovee, Y. T. Hou (eds.)), Academic Press, 2009.

# Minimize BER

For a multi-carrier system with $N$ independent subcarriers, the objective functions are defined as:

$$f_{min\_ber} = 1 - \frac{\log_{10}(0.5)}{\log_{10}(\overline{P_{be}})} ,$$

where $\overline{P_{be}}$ is the average BER over $N$ independent subcarriers

# Maximize Data Throughput

For a multi-carrier system with $N$ independent subcarriers, the objective functions are defined as:

$$f_{max\_tp} = \frac{\sum_{i=1}^{N}\left(\frac{L_i}{L_i + O + H} * (1 - P_{ber_i})^{(L_i+O)} * R_{c_i} * TDD_i\right)}{N},$$

where $L_i$ is the packet length, $O$ and $H$ are static packet overheads for the PHY and MAC layer, $R_{c_i}$ is the coding radio and $TDD_i$ is the time division duplex value for channel $i$

# Minimize Transmission Power

For a multi-carrier system with $N$ independent subcarriers, the objective functions are defined as:

$$
\begin{aligned}
f_{min\_power} \quad = \quad & \Bigg[ 1 - \alpha * \frac{\sum_{i=1}^{N} (P_{max} + B_{max}) - (P_i + B_i)}{N * P_{max} + B_{max}} \\
+ \quad & \beta * \frac{\sum_{i=1}^{N} \log_2(m_{max}) - \log_2(m_i)}{N * \log_2(m_{max})} + \lambda * \frac{\sum_{i=1}^{N} R_{s_{max}} - R_{s_i}}{N * R_{s_{max}}} \Bigg]
\end{aligned}
$$

where $m_i$ is the modulation index used on subcarrier $i$ and $m_{max}$ is the maximum modulation index available, $B_i$ is the bandwidth allocated to channel $i$, and $B_{max}$ and $B_{min}$ are the maximum and minimum bandwidth the radio can transmit over instantaneously

# Minimize Interference

For a multi-carrier system with $N$ independent subcarriers, the objective functions are defined as:

$$f_{min\_interference} = 1 - \frac{\sum_{i=1}^{N}((P_i + B_i + TDD_i) - (P_{min} + B_{min} + 1))}{N * (P_{max} + B_{max} + 100)}$$

# Maximize Spectral Efficiency

For a multi-carrier system with $N$ independent subcarriers, the objective functions are defined as:

$$f_{max\_spectralefficiency} = \frac{\sum_{i=1}^{N} \frac{m_i * R_{s_i} * B_{min}}{B_i * m_{max} * R_{s_{max}}}}{N},$$

where $P_i$ is the transmit power on subcarrier $i$, $N$ is the number of carriers, $P_{max}$ is the maximum possible transmit power for a single subcarrier, and $R_{s_i}$ is the symbol rate on channel $i$ with $R_{s_{max}}$ and $R_{s_{min}}$ are the maximum and minimum symbol rates available

# Cognitive Adaptation Engines

- Expert Systems
  - Non-algorithmic approach
  - Consists of rules created by an expert that govern the operation of the system
  - Consists of *domain expert*, *knowledge engineer*, *knowledge base*, and *working storage*
- Genetic Algorithms
  - Uses evolutionary techniques
  - Transmission parameters represented as chromosomes
  - Small random set of chromosomes selected and assigned fitness scores
  - Evolution ends with a time constraint or a fitness convergence constraint
- Case-based Reasoning
  - History is used to determine best solution
  - Similar cases are retrieved and adapted to the current situation