Chapter 7

Reconfiguration, adaptation, and optimization
Outline

- Introduction
- Operating Parameters
  - Transmission Parameters
  - Environmental Parameters
- Parameter Relationships
  - Individual Performance Objectives
  - Multiple Performance Objectives
- Cognitive Adaptation Engines
  - Expert Systems
  - Genetic Algorithms
  - Case-Based Reasoning Systems
Introduction

- 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
Radio Transmission Parameters

- **Transmission Parameters**
  - **Controllable system parameters.**
  - Used to alter the operating state of the radio in order achieve specific performance objectives

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit power</td>
<td>Raw transmission power</td>
</tr>
<tr>
<td>Modulation type</td>
<td>Type of modulation format</td>
</tr>
<tr>
<td>Modulation index</td>
<td>Number of symbols for given modulation scheme</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Bandwidth of transmission signal in Hertz</td>
</tr>
<tr>
<td>Channel coding rate</td>
<td>Specific rate of coding scheme</td>
</tr>
<tr>
<td>Frame size</td>
<td>Size of transmission frame in bytes</td>
</tr>
<tr>
<td>Time division duplexing</td>
<td>Percentage of transmit time</td>
</tr>
<tr>
<td>Symbol rate</td>
<td>Number of symbols per second</td>
</tr>
</tbody>
</table>
Environmental Measurements

- Represent the current state of the wireless environment.
- Used to model the current wireless channel environment.
- Two measurement parameter categories
  - Direct Parameters
  - Trigger Parameters

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path loss</td>
<td>Amount of signal degradation lost due to the channel path characteristics</td>
</tr>
<tr>
<td>Noise power</td>
<td>Size in decibels of the noise power</td>
</tr>
<tr>
<td>Battery life</td>
<td>Estimated energy left in batteries</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Power consumption of current configuration</td>
</tr>
<tr>
<td>Spectrum information</td>
<td>Spectrum occupancy information</td>
</tr>
</tbody>
</table>
Radio Performance Objectives

- Radio operates using combinations of performance objectives
- Direct the solution of the cognitive engine
- Multiple objectives create conflicting solutions

Table 7.3: Cognitive Radio Objectives

<table>
<thead>
<tr>
<th>Objective Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize bit error rate</td>
<td>Improve the overall BER of the transmission environment</td>
</tr>
<tr>
<td>Maximize throughput</td>
<td>Increase the overall data throughput transmitted by the radio</td>
</tr>
<tr>
<td>Minimize power consumption</td>
<td>Decrease the amount of power consumed by the system</td>
</tr>
<tr>
<td>Minimize interference</td>
<td>Reduce the radios interference contributions</td>
</tr>
<tr>
<td>Maximize spectral efficiency</td>
<td>Maximize the efficient use of the frequency spectrum</td>
</tr>
</tbody>
</table>
Parameter Relationships

- Minimize BER
- Maximize Throughput
- Minimize Power
- Transmit Power
- Symbol Rate
- Frame Size
- Modulation Index
- Bandwidth
- Modulation Type
- Coding Rate
- TDD
- Minimize Spectral Interference
- Minimize Spectral Efficiency
Fitness Function: Minimize BER

- **Objective:** minimize bit-error-rate
  - Useful in situations with guaranteed communication requirements
    - Emergency radio situations
  - Probability of bit error depends upon both modulation, channel type, signal power, and noise power.
  - Normalization is needed to keep fitness linear and between 0 and 1.
  - Multiple channel systems use average BER over all channels.

\[
f_{\text{min\_ber}} = 1 - \frac{\log_{10}(0.5)}{\log_{10}(P_b)}
\]
Fitness Function: Minimize BER

- Probability of Bit Error in AWGN Channel

**BPSK:**

\[ P_b = Q\left(\sqrt{\gamma}\right) \]

**M-QAM:**

\[ P_b = \frac{4}{\log_2(M)} \left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\frac{3 \log_2(M) \gamma}{M - 1}\right) \]

**M-PSK:**

\[ P_b = \frac{2}{\log_2(M)} Q\left(\sqrt{2 \log_2(m) \gamma \sin\left(\frac{\pi}{m}\right)}\right) \]

- Raleigh and Rician fading closed form channel models shown in appendix.
Fitness Function: Minimize BER

BER curves for uncoded M-QAM transmissions
Fitness Function: Minimize Power Consumption

- **Objective:** minimize power consumption
  - Useful for strict power requirement systems
    - Mobile / embedded environments
  - Several factors contribute to power consumption
    - General wireless transmission
    - Complexity of modulation and low level digital processing
  - Consumption ratio depends on system hardware

\[
f_{\text{min\_power}} = 1 - \left[ \alpha \left( \frac{P_{\text{max}} + B_{\text{max}}}{P_{\text{max}} + B_{\text{max}}} - (P + B) \right) + \beta \log_2(m_{\text{max}}) - \log_2(m) + \lambda \frac{R_{\text{s\_MAX}} - R_s}{R_{\text{s\_MAX}}} \right]
\]

“Cognitive Radio Communications and Networks: Principles and Practice”
Fitness Function: Maximize Throughput

- Objective: maximize throughput
  - Measure of goodput to the receiving system
  - Useful for multimedia applications
    - Video / Audio streaming
  - Complex relationship between the BER and the frame size (L)
  - Goodput also takes into account MAC layer overhead (H) and PHY layer overhead (O).

\[ f_{\text{max \_throughput}} = \frac{L}{L + O + H} \times (1 - P_{\text{ber}})^{(L+O)} \times R_c \times TDD \]
Fitness Function: Maximize Throughput

Goodput versus frame size for varying bit error rates

- $10^{-5}$
- $10^{-4}$
- $5 \times 10^{-4}$
- $10^{-3}$
- $5 \times 10^{-3}$

MTU (bytes) vs. Goodput (normalized to $R_c$)
Fitness Function: Minimize Spectral Interference

- Useful in situations with strict interference requirements
  - Primary / secondary user bands
- Function assumes no information about other users
  - Strictly tries to minimize interference contributions
- Minimize power and bandwidth

\[ f_{\text{min\_interference}} = 1 - \frac{(P + B + TDD) - (P_{\text{min}} + B_{\text{min}} + 1)}{P_{\text{max}} + B_{\text{max}} + 100} \]
Fitness Function: Maximize Spectral Efficiency

- Useful for situations where limited spectrum is available but high throughput is needed
- Maximizing the amount of information over a given bandwidth
- Measure of how efficient a given band of frequency is utilized by physical layer

\[ f_{\text{max_spectral_efficiency}} = \frac{m \cdot R_s}{m_{\text{max}} \cdot R_{s_{\text{max}}}} = \frac{m \cdot R_s \cdot B_{\text{min}}}{B \cdot m_{\text{max}} \cdot R_{s_{\text{max}}} \cdot B_{\text{min}}} \]
Fitness Function Construction

- Weighted sum of N objectives
  \[ f(x) = \sum_{i=1}^{N} w_i f_i(x) \]

- Must satisfy following constraints
  \[ 0 \leq w_i \leq 1 \text{ for } i = 1,2,...,n \]
  \[ w_1 + w_2 + ... + w_n = 1 \]

- Resulting in the aggregate fitness function
  \[ f_{\text{multi}} = w_1 * (f_{\text{ber}}) + w_2 * (f_{\text{power}}) + w_3 * (f_{\text{tp}}) + w_4 * (f_{\text{si}}) + w_5 * (f_{\text{se}}) \]
Parameter Relationships

- How does the cognitive engine select a set of transmission parameters when multiple competing objectives are present?
  - Globally optimize the operating parameters

- Multiple objective optimization techniques
  - Exact Methods – Perfect solutions
    - Pure random search
    - Successive approximation
    - Bayesian search algorithms
  - Heuristic Methods – Sub-optimal solutions
    - Simulated annealing
    - Neural networks
    - Evolution strategies

- Combinations
  - Case-based Reasoning w/ GA
Optimization Techniques

- Exact Methods
  - Advantages
    - Exact optimal solution can be found
  - Disadvantages
    - Typically requires at least first derivative of a complex equation
    - Time complexity (pure random)

- Heuristic Methods
  - Advantages
    - Lower complexity than exact methods – less resource usage
    - Increased flexibility with regards to changes in the fitness equation
  - Disadvantages
    - Sub-optimal solutions
Expert Systems - Exact

- Primary goal: Quick solutions
- Non-algorithmic approach
- Consists of rules created by an expert that govern the operation of the system
- Consists of the following system components:
  - Domain expert
    - Defines the real world rules
    - Example: If frequency of interest in use, alter frequency by x amount.
  - Knowledge engineer
  - Knowledge base
    - Database of rules
    - Example: Battery life = 95%, Freq. 5.279 GHz = occupied, Current SNR = 4 dBm
Expert System Results

- Primary research results
  - Memory usage much smaller than expected
  - Bin size
    - Rules created to match against ranges
    - Explore different bin sizes and their affects
  - Optimality of output
    - Increasing bin size created more approximation error
    - Increasing bin size reduces the number of rules needed

Example CLIPS rule:

```
(defule cognitive_rule_13
  (and (noise_power ?channel_num ?noise_power&: (>= ?noise_power - 115.5))
    (noise_power ?channel_num ?noise_power&: (< ?noise_power - 114.5))
    (and (path_loss ?channel_num ?path_loss&: (>= ?path_loss 86.5))
      (path_loss ?channel_num ?path_loss&: (< ?path_loss 87.5)))
    (scenario ?channel_num power_mode)
  =>
    (assert (channel ?channel_num 14 2 2 psk 1500 1.00 125000 25)))
```

<table>
<thead>
<tr>
<th>Bin Size</th>
<th>Power Scenario</th>
<th>Emergency Scenario</th>
<th>Multimedia Scenario</th>
<th>DSA Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 dB</td>
<td>0.9785</td>
<td>0.9416</td>
<td>0.9247</td>
<td>0.9414</td>
</tr>
<tr>
<td>1.5 dB</td>
<td>0.9475</td>
<td>0.9202</td>
<td>0.8960</td>
<td>0.9201</td>
</tr>
<tr>
<td>2.0 dB</td>
<td>0.9224</td>
<td>0.9007</td>
<td>0.8607</td>
<td>0.8998</td>
</tr>
<tr>
<td>2.5 dB</td>
<td>0.8994</td>
<td>0.8745</td>
<td>0.7778</td>
<td>0.8647</td>
</tr>
</tbody>
</table>

"Cognitive Radio Communications and Networks: Principles and Practice"
Results Comparison

- **Rule-Based System**
  - Optimality constant independent of number of channels
  - Very small execution time

- **Genetic Algorithm**
  - Strengths lie in the flexibility
  - Environment can not be modeled offline for every scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>GA: Single Channel</th>
<th>GA: 16 Channel</th>
<th>RBS: 1.0 dBm</th>
<th>RBS: 2.5 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize Power</td>
<td>0.973</td>
<td>0.882</td>
<td>0.9785</td>
<td>0.8994</td>
</tr>
<tr>
<td>Emergency</td>
<td>0.992</td>
<td>0.793</td>
<td>0.9416</td>
<td>0.8747</td>
</tr>
<tr>
<td>DSA</td>
<td>0.966</td>
<td>0.869</td>
<td>0.9414</td>
<td>0.8647</td>
</tr>
<tr>
<td>Multimedia</td>
<td>0.920</td>
<td>0.680</td>
<td>0.9247</td>
<td>0.7778</td>
</tr>
</tbody>
</table>

"Cognitive Radio Communications and Networks: Principles and Practice"  
Results Comparison

- How do these results compare to adaptable systems in operation today?
  - GSM power control: 800 - 1500 times per second (.6 – 1.25 ms)
  - WCDMA bandwidth allocations: 100 times per second (10 ms)
  - UMTS link adaptation: 500 times per second (2 ms)
  - Quickest GA adaptation: 24 times per second (43 ms)

- Cognitive engine techniques are adapting 8 parameters instead of a single parameter

- Typical power control and bandwidth allocation algorithms are simple step up or down functions

- Time depends heavily on hardware platform
Genetic Algorithms - Heuristic

- Genetic algorithm uses evolutionary techniques
  - Transmission parameters represented as chromosomes
  - Binary strings
  - Small random set of chromosomes selected and assigned fitness scores
  - Fitness scores determines the probability of the following actions:
    - Crossover - Combination with other high scoring chromosomes
    - Mutation - Random bit mutation
  - Evolution ends with a time constraint or a fitness convergence constraint

“Cognitive Radio Communications and Networks: Principles and Practice”
Genetic Algorithm Simulation Results

- Low Power Scenario
  - Emphasis on minimizing power
- Increase in channels cause increase in TpG and optimal generation
- Processing requirement increased with channel increase
  - Optimal fitness decreases

<table>
<thead>
<tr>
<th>Number of Channels</th>
<th>Optimal Generation</th>
<th>Optimal Fitness</th>
<th>Time per Generations (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>77</td>
<td>0.981</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>789</td>
<td>0.904</td>
<td>3.9</td>
</tr>
<tr>
<td>8</td>
<td>845</td>
<td>0.886</td>
<td>7.7</td>
</tr>
<tr>
<td>16</td>
<td>892</td>
<td>0.831</td>
<td>17.6</td>
</tr>
</tbody>
</table>

"Cognitive Radio Communications and Networks: Principles and Practice"
Genetic Algorithm Simulation Results

- **DSA Scenario**
  - Emphasis on minimize interference contributions

- **Similar complexity trend as low power scenario**
  - Increase channels = increased complexity

<table>
<thead>
<tr>
<th>Number of Channels</th>
<th>Optimal Generation</th>
<th>Optimal Fitness</th>
<th>Time per Generations (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>163</td>
<td>0.966</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>897</td>
<td>0.940</td>
<td>4.2</td>
</tr>
<tr>
<td>8</td>
<td>953</td>
<td>0.918</td>
<td>9.3</td>
</tr>
<tr>
<td>16</td>
<td>932</td>
<td>0.870</td>
<td>16.3</td>
</tr>
</tbody>
</table>

“Cognitive Radio Communications and Networks: Principles and Practice”
Genetic Algorithm Results

- Primary research results
  - Convergence time
    - Time per generation increases linearly with number of channels
  - Optimality of output
    - Decreases with increase in system complexity
- Genetic Algorithm Averaged Results
  - 1% of optimal fitness results also shown

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>184</td>
<td>40</td>
<td>0.965</td>
<td>1.08</td>
<td>199</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>795</td>
<td>229</td>
<td>0.856</td>
<td>4.13</td>
<td>3283</td>
<td>945</td>
</tr>
<tr>
<td>8</td>
<td>924</td>
<td>458</td>
<td>0.844</td>
<td>8.50</td>
<td>7854</td>
<td>3893</td>
</tr>
<tr>
<td>16</td>
<td>950</td>
<td>587</td>
<td>0.795</td>
<td>16.83</td>
<td>10939</td>
<td>9879</td>
</tr>
</tbody>
</table>

"Cognitive Radio Communications and Networks: Principles and Practice"
Case-Based Reasoning

- History is used to determine best solution
- Similar cases are retrieved and adapted to the current situation
- Similarity function measures the similarities between previous cases and current situation.
- Fitness functions are used to determine “best” previous case.

“Cognitive Radio Communications and Networks: Principles and Practice”
Chapter 7 Summary

- Cognition within a radio is much more than a flexible parameters
- Intelligence is the ability to make decisions when many apparent options are available
- Several cognition algorithms have been studied
  - Expert Systems, Genetic Algorithms, Case-based Reasoning
- Fitness functions must be carefully designed to accurately reflect the tradeoffs between parameters