Scheduling with a Spectrum Server in Cognitive Radio Networks

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Wireless world is not flat!

- Home networking
- TV broadcasting
- Secondary sensors
- Spectrum server

- Multihopping
- Wireless LANs
- AP

- Multaccess/variable rate transmission schemes
- Interference channel / wideband transmissions
- Orthogonal & non-orthogonal multiplexing schemes
What can a Spectrum Policy Server do?

- Spectrum Server facilitates co-existence of heterogeneous set of radios by advising them on several possible issues:
  - Spectrum etiquette
  - Interference information
  - Location specific services
  - Many more things ....
Link scheduling using Spectrum Server

A centralized approach
Transmission mode

Graph of a network with 4 links

Possible transmission modes:

\[
\begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\
0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
\end{pmatrix}
\]

A transmission mode activity

\([1 \ 0 \ 1 \ 0]\)

(one of \(2^4\) possible modes)

\(t_{ij} = 1, \text{ if link } i \text{ is ON in mode } i\)

\(= 0, \text{ otherwise.}\)
Rate Matrices and Time Schedules

- Rate matrix $C$ includes achievable physical layer rates for wide range of phy layer transmission techniques.
- If $c_{ii}$ is the rate of link $i$ in mode $i$, an example rate matrix is:

$$
\begin{bmatrix}
6.6 & 0 & 0.01 & 0 & 0.56 & 0 & 0.01 & 0 & 2.05 & 0 & 0.01 & 0 & 0.49 & 0 & 0.01 \\
0 & 6.6 & 0.06 & 0 & 0 & 1.86 & 0.06 & 0 & 0 & 0.97 & 0.06 & 0 & 0 & 0.77 & 0.06 \\
0 & 0 & 0 & 6.6 & 1.0 & 1.86 & 0.83 & 0 & 0 & 0 & 0 & 0.04 & 0.04 & 0.04 & 0.04 \\
0 & 0 & 0 & 0 & 0 & 0 & 6.65 & 0.32 & 0.05 & 0.04 & 0.40 & 0.19 & 0.05 & 0.04
\end{bmatrix}
$$

- Spectrum server specifies:
  - $x_i = \text{fraction of time mode } i \text{ is ON}$
- Average rate in link $i$ is $r_i = \sum_i c_{ii} x_i$
Duplexing constraints in the rate matrix $C$

- Node B: Link 1 Rx, Link 2 Tx
- $G_{12} = \infty$
- In mode $[1\ 1]$, link 1 gets rate $\varepsilon_0 \approx 0$, $c_0 < 1$

$$C = \begin{bmatrix} 0 & 1 & 0 & \varepsilon_0 \\ 0 & 0 & 1 & c_0 \end{bmatrix}$$

Both links ON: link 1 is useless, link 2 is crummy
Technology Modeling Example
Multiaccess

- Nodes A and B send to D
- D employs joint decoding
  - Modes induced by successive decoding order at C

\[ C = \begin{bmatrix}
0 & 1 & 0 & 0.5 & 1 \\
0 & 0 & 1 & 1 & 0.5
\end{bmatrix} \]

Modes 0 1 2 3 4
What are the performance bounds on wireless networks employing a variety of physical layer strategies?

- Physical links - achievable rates depend on the transmission schemes, signal processing at receiver etc.
- MAC - distributed/centralized schemes to avoid/control interference
- Routing - decision made based on metric specified by application running on the network
Universal cross-layer scheduling framework – Centralized Approach

UTILITIES: Max throughput, max-min fairness, proportional fairness, energy efficiency

Maximize User utilities subject to:

\[ \text{Physical link rates} \begin{pmatrix} c_{11} & \ldots & c_{M1} \\ c_{i1} & \ldots & c_{iM} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_M \end{pmatrix} > \begin{pmatrix} 1 & 0 & \ldots & 0 \\ 1 & 1 & \ddots & \vdots \\ 1 & \ldots & 0 \end{pmatrix} \begin{pmatrix} f_1 \\ \vdots \\ f_M \end{pmatrix} \]

Higher layer flow requirements

PHY rates              >        Sum of flows in the link

MAC schedule

NETWORK routes

TRANSPORT flows
End-to-end flow scheduling

- Two flows: $f_1$ and $f_2$
- Flow constraints: $f_1 \leq \min (r_1, r_2, r_3)$, $f_2 \leq \min (r_4, r_5)$
EXAMPLE 1: Maximizing the sum of flows

Linear Programming formulation

\[ \max \{f >0, x>0\} \quad f_1 + f_2 \]
subject to
\[ f_1 \leq \min (r_1, r_2, r_3), \]
\[ f_2 \leq \min(r_4, r_5), \]
\[ r_i = \sum_j C_{ij} x_j, \quad i=1,2,3,4,5 \]
\[ \sum_j x_j = 1. \]

Scheduler specifies:
(1) \( x^*_j \) - fraction of time subset \( j \) is on
(2) \( f^*_1 \) and \( f^*_2 \)
EXAMPLE 2: Effect of physical layer

- Linear network of nodes spaced equidistant apart
- Two decoding methods at each receiver
  - Gaussian Single user decoding
  - Successive two-user decoding
- Vary distance between adjacent nodes to vary interference
EXAMPLE 2: Effect of physical layer

- Single flow: node 1 to node 5
- Gaussian Single User Decoding at Node 3
- Two User Successive Decoding at Node 3

Several such physical transmission modes possible!
EXAMPLE 2: Effect of physical layer

Simulation results

![Graph showing the effect of physical layer simulation results. The x-axis represents the distance (in meters) between nodes in the network, and the y-axis represents the session rate (bits/sec/Hz). The graph compares Single user decoding, Successive decoding - strong link first, and Successive decoding - weak link first.]
Low-complexity scheduling strategies

- Limitations of centralized scheduling
  - Rate matrix grows exponentially with number of links

- Two low-complexity scheduling algorithms studied
  - Randomized distributed scheduling
  - *Column generation*: centralized low-complexity scheduling schemes to generate good transmission modes
**RDS:** Randomized Distributed Scheduling

- **IDEA:** Link $j$ autonomously transmits with probability $p_j$ in each slot
  - Induces an ergodic transmission schedule

$$ x(p) = \begin{bmatrix} (1-p_1)(1-p_2)\cdots(1-p_L) \\ p_1(1-p_2)\cdots(1-p_L) \\ \vdots \\ (1-p_1)p_2\cdots p_L \\ p_1p_2\cdots p_L \end{bmatrix} $$

  - All links are OFF
  - Only Link 1 is ON
  - All links are ON

- **Rate region of RDS**

$$ \mathcal{R}_L^p := \{(r_1, \ldots, r_L) : r = Cx(p), 0 \leq p \leq 1\} $$
RDS Rate Region: Two Link Low Interference

Case \((\alpha + \beta > 1)\)

\[ \begin{align*}
(0,1) & \\
(0,1) & \\
(\alpha,\beta) & \\
(1,0) & \\
r_2 & \\
r_1 & \\
\end{align*} \]

Same as the centralized case!
RDS Rate Region: Two Link High Interference

Case \((\alpha + \beta \leq 1)\)

\[
C = \begin{pmatrix}
0 & 1 & 0 & \alpha \\
0 & 0 & 1 & \beta
\end{pmatrix}
\]

Strictly smaller than the centralized case
Distributed Schedule Optimization

- For an arbitrary number of links, algorithm achieves any point in RDS rate region in a distributed way
- Algorithm at each link:
  - Measure rate achieved in each slot
  - Increase/decrease transmission probability if achieved rate is lower/higher than desired rate
  - Link \( i \) updates its probability as
    \[
    p_i(n+1) = \frac{r^d_i}{r_i(n)} \cdot p_i(n)
    \]
    \( r_i(n) \) → rate obtained in slot \( n \), \( r^d_i \) → desired rate
- Convergence depends on \( r^d \), \( p(0) \) and structure of rate matrix \( C \)
Column generation

- Centralized scheduling methodology to generate the “good” transmission modes
- Solve the problem with a smaller set of modes
  - provides a lower bound to the maximization program
- Solve the Lagrange dual problem
  - provides an upper bound to the problem
- Iterate until the difference on bounds satisfies a threshold criteria
- Column generation helps in identifying good modes “progressively”
Conclusions

- Hierarchical cognitive radio networks with a spectrum server coordinating the links solves lot of interference issues
- Future multi-radio platform designs could incorporate a local area spectrum server to increase throughput
- **CHALLENGES**: Localization, link gain measurements required by the spectrum server
THANK YOU

http://www.winlab.rutgers.edu/~chandru/research.htm