Cross-layer scheduling of end-to-end flows using a spectrum server

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Talk Outline

- Introduction – Cognitive Radio & Spectrum Server
- Scheduling of variable rate links
- End-to-end scheduling of flows using spectrum server
- Fairness and Max-Min Fair Flows
- Conclusion
The Spectrum Debate

- **What everyone agrees on:**
  - Spectrum use is inefficient
  - FCC licensing has yielded false scarcity

- **Proposed Solutions**
  - Spectrum Property Rights
    - The triumph of economics
  - Open Access (Commons)
    - The triumph of technology
Open Access

- **A Technology Panacea**
  - Agile wideband radios will dynamically share a commons
  - Minor technical rules (power spreading) for transceivers

- **Systems of end-user devices**
  - Spread spectrum, UWB, MIMO, OFDM
  - Short range communications
  - Ad hoc multi-hop mesh networks

- **Evidence: (perceived) success of 802.11 vs. 3G**
Open Access Needs Radio Agility

- Require radios that can:
  - Discover
  - Cooperate
  - Self-Organize into hierarchical networks

- Agility needed at every protocol layer

- But cannot predict environments/applications

  The Answer? “Cognitive Radios”

- Optimization Perspective:
  - Enlarging the space of feasible solutions
    ⇒ improved performance
Cognitive Radio: Modeling Issues

- Heterogeneous PHYs:
  - OFDM, UWB, FH, CDMA
- Is there a control channel?
- What are control actions?
A Simple Spectrum Server

- Spectrum Server tells radios to turn OFF/ON
- Radios use best rate given signal & interference
Simple System Model

- Users share a common frequency band
  - Orthogonal signal dimensions = time slots
  - Time domain scheduling is used for channelization

- Wireless network of \( L \) directed links

- Links follow ON-OFF transmission schedule over time slots
  - Use constant transmission power in the ON state

- Links employ interference-adaptive modulation/coding
  - Link rate in each time slot depends on interference from other active links

- Interference depends on the transmission mode
  - \( \text{mode} \) = subset of links that are ON simultaneously
Transmission modes

Network with $L = 4$ links

Transmission mode matrix $T$: 

$$
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\
0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 \\
0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
\end{bmatrix}
$$

Transmission mode $[1 \ 0 \ 1 \ 0]$ 

(one of $2^4$ possible modes)

$t_{li} = 1$, if active link $l$ is in mode $i$

$= 0$, otherwise.
Transmission Mode ⇒ Data Rate

- **Example: Gaussian Interference, Single User Decoding**
  - Each receiver measures its own SIR $\gamma_{li}$ in every mode $i$:
    \[
    \gamma_{li} = \frac{t_{li} G_{li} P_l}{\sum_{k \in \mathcal{E}, k \neq l} t_{ki} G_{lk} P_k + \sigma_l^2}
    \]
  - Achievable rate at link $l$ in mode $i$ is
    \[
    c_{li} = \log(1 + \gamma_{li})
    \]

- $L \times 2^L$ matrix $C$: column $i$ = rates in mode $i$
**Mode Matrix $\Rightarrow$ Rate Matrix**

Network with 4 links

Transmission mode $[1 \ 0 \ 1 \ 0]$

Rate matrix $C =$

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

- Spectrum server specifies
  \[ x_i = \text{fraction of time mode } i \text{ is ON} \]

- Schedule = Stationary Distribution on Modes

- Average rate in link \( l \) is
  \[ r_l = \sum_{i} C_{li} x_i \]

- In vector form,
  \[ r = Cx \]

- Spectrum server specifies schedule \( x \) to:
  - Maximum sum rate of the network
  - Maximize the common rate on the links
  - Satisfy session flow requests
  - Fair scheduling
Comments on the Model

- Average link data rates \( r = Cx \)

- Any ergodic dynamic spectrum access policy \( \Rightarrow \)
  schedule \( x \)
  average link rates \( r = Cx \)

- Centralized scheduling upperbounds
  distributed/dynamic solutions

- Tx/Rx technology assumptions are embedded in \( C \)
*Technology Modeling Example*

**Duplexing**

- **Duplex 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 $\varepsilon_0 \approx 0$, $c_0 < 1$

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

**Modes**

$0 \ 1 \ 2 \ 3$

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

- Nodes A and B send to D
- D employs joint decoding
  - Mode induced by sender code rates & successive decoding order at D

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

 Modes 0 1 2 3 4
System model for end-to-end flows

- Wireless network with \( N \) nodes and \( L \) links
- \( K \) end-to-end sessions – a session described by an origin-destination (OD) pair
- Set of \( R \) routes in the network
- End-to-end route incidence matrix for each flow \( k \):
  \[
  [A_k]_{lr} = 1, \text{ if link } l \text{ is part of route } r \\
  = 0, \text{ otherwise}
  \]
- Vector \( f_k \) – session \( k \) flows in the \( R \) routes
System model for end-to-end flows

- Aggregate rates through links \[ r = \sum_k A_k f_k \]

- Maximum Sum Utility of the flows:

\[
\begin{align*}
\text{max} & \quad \sum_k U_k(y_k) \\
\text{subject to} & \quad y_k = 1^T f_k, \quad k = 1, \ldots, K, \\
& \quad r = Cx, \\
& \quad r \geq \sum_k A_k f_k, \\
& \quad x \geq 0, \quad 1^T x = 1, \\
& \quad f_k \geq 0, \quad k = 1, \ldots, K.
\end{align*}
\]
Cross Layer Optimization??

- **PHY**: Link rates $c_{ii}$ for each mode $i$
- **MAC**: Schedule $x \Rightarrow$ Link rates $r = Cx$
- **Network**: Routes $A_k$
- **Transport**: Flows $f_k$

$$r = Cx \geq \sum_k A_k f_k$$

**Issues**

- Dual decomposition methods don’t yield distributed solutions.
- $x_i$ is not controlled locally by entity $i$

[Bonald & Proutiere, WP-01]: Flow allocation $f$ drives schedule $x$
Example 1: Max Flow scheduling on a linear network

- One flow, linear network, 5 nodes equally spaced
  - 10 directional links: (1,2), (1,3) … (4,5)
  - 25 useful (half-duplex) transmission modes
  - 8 paths in the network
  - Routes are chosen to maximize the end-to-end flow
Example 1: Max Flow

The graph shows the variation of the sum of flows with distance between nodes in the network. The x-axis represents the distance between nodes in the network, while the y-axis represents the sum rate of the flows in bits/sec/Hz.

- **1 hop flow, high link SNR**: This line indicates a high sum rate of flows for a 1-hop flow with a high link SNR.
- **4 hop flow at low SNR**: This line shows a low sum rate of flows for a 4-hop flow at a low SNR.

Activity of transmission modes provides the routes.
Special Case: Session Flows = Link Rates

- Each flow traverses one link.
- Each link carries one flow.
- $A_k = I$, $f_k = r_k e_k$,
- (Session flow) $y_k = r_k$ (link rate)
Max sum link-rate scheduling

- Each flow traverses one link. Each link carries one flow.

- Objective: To maximize the sum rate in the network with minimum rate constraints on each link

- Optimization problem can be posed as a linear program

\[
\begin{align*}
\text{max} & \quad 1^T r \\
\text{subject to} & \quad r = Cx, \\
& \quad r \geq r_{\text{min}}, \\
& \quad 1^T x = 1, \\
& \quad x \geq 0.
\end{align*}
\]
Example 2

Distance Attenuation ⇒ Link Gain
Maximum sum rate solution

- When $r_{\text{min}} = 0$, the **dominant mode** is always scheduled.

- Dominant mode – the mode corresponding to the maximum column sum in $C$.

- Leads to inherent unfairness in the schedule.
  - links not active in the dominant mode are never scheduled.
Example 2: Dominant mode

Dominant mode: the mode that has maximum sum rate

Dominant mode vector is

\[ [0 \ 1 \ 0 \ 0 \ 1] \]
Maximum Sum rate - solution

- When each component $r_{\text{min}} > 0$, more than one mode is used

- The disadvantaged links are operated for just enough time to satisfy their rate requirement

- Most transmission modes are unused
Example 2: As common $r_{\text{min}}$ increases,

- the sum rate decreases
- Rates of dominant mode links decrease
- Rates of disadvantaged links increase
Max-min fairness

- Flow vector $f$ is max-min fair if $f_i$ cannot be increased while maintaining feasibility without decreasing $f_i'$ for some $i'$ such that $f_i' \leq f_i$

- Example from data networks:

```
Bottleneck 1
C_1 = 3

Bottleneck 2
C_2 = 4
```

MMF Rates:

Flow 1 = 1.5, Flow 2 = 1.5, Flow 3 = 2.5
Max-min flow schedule

- What is the max-min fair flow schedule in our model?

- Step 1: Maximize the minimum flow $y$ using the LP

\[
\begin{align*}
\text{max} & \quad y \\
\text{subject to} & \quad y \leq 1^T f_k, \quad k = 1, \ldots, K, \\
& \quad r = Cx, \\
& \quad r \geq \sum_k A_k f_k, \\
& \quad x \geq 0, \quad 1^T x \leq 1, \\
& \quad f_k \geq 0, \quad k = 1, \ldots, K.
\end{align*}
\]
Max-min fair schedule

- **Theorem**: Non-zero link gains $\Rightarrow$ equal rate flows are max-min fair

- Scheduler timeshares between bottlenecks to equalize the user flow rates
- The shared bandwidth is the bottleneck
Example 3 – Fair scheduling

- Linear network of four nodes, equal link distances
- Fixed Schedule (Equal link rates)
  - MMF rates are \((f_1, f_2, f_3, f_4) = (1/3, 1/3, 1/3, 2/3)\)
- Mode scheduling of links \(\Rightarrow\) equal flows
  - MMF rates are \((f_1, f_2, f_3, f_4) = (0.37, 0.37, 0.37, 0.37)\)
Example 4: Max-min fair flows
(Fixed Mode Schedule)

Spectrum Server Schedule:
Link Rates $r_1 = 10$, $r_2 = 4$

\[
\begin{align*}
    f_1 + f_2 & \leq r_1 \\
    f_2 & \leq r_2
\end{align*}
\]
Max-min fair rates (Example)

\[ f^* = \max \{ \min f : f_1 \geq f, f_2 \geq f \} \]
\[ = (4, 4) \]

\[ r_{MMF} = (6, 4) \]
\[ f_1 + f_2 \leq 10 \]
\[ f_2 \leq 4 \]
MMF rates for the interference model

Rate pair when both links are simultaneously ON
Max-min fair schedules

- “Equal rates are max-min fair” is a property of
  - flexible (centralized) link scheduling
  - Gaussian interference model

- [Radunovic & Le Boudec, Infocom 04]
  - **Solidarity Property**: Decrease in flow $i$ enables strict increase of flow $j$
  - **Solidarity** $\Rightarrow$ equality of max-min fair rates

- **Solidarity** holds for the Gaussian interference model.
Solidarity and the C matrix

- Solidarity depends on the PHY layer (C matrix)
  - In general, Max Common Rate (MCR) ≠ Max Min Fair (MMF) Rate

Interference Model

IT MAC Model
Concluding remarks

- Spectrum server computes schedule – time sharing of transmission modes of the network
- Maximizing common rate over flows gives the max-min fair flows for the interference model
- Centralized scheduler needs to know a lot of information
  - granularity and timeliness of measurements required by the Spectrum Server will be important
- Distributed solutions for finding good PHY layer modes?