Resource Allocation in a Cognitive Digital Home

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Outline

- Wireless Home Networks
- A Cognitive Digital Home
- Joint Channel and Radio Access Technology Allocation
  - Problems
  - Numerical Results
- Conclusion
Wireless Home Networks

Wireless HD video Streaming
Medical Sensor
Wireless web/data
Gaming
Wireless HDTV
Smoke Detector
Smart Fridge
Smart Meter
Occupancy Detector
surveillance camera

Wireless Home Entertainment Networks

Wireless Home Automation Networks

Co2 Detector
Characteristics of Wireless Home Networks

- Multiplicity of Radio Access Technologies (RAT)
  - License-exempt: Wi-Fi, Zigbee, Bluetooth, 60GHz Radio, TV White Space, Cognitive radio, etc.
  - License-regulated: Wimax, Femto-cell, etc.

- Noncontiguous spectrum bands
  - From TV white space up to 60GHz radio bands

- Multiplicity of data services in a home environment
  - Voice over IP, Wireless Gaming, P2P, Video, web/data, etc.

- Degrees of freedom
  - Frequency
  - Power
  - Bandwidth
  - Choice of Radio Access Technology (RAT)
A Cognitive Digital Home (CDH): Architecture

- Maintains the global spectrum availability information
- Makes spectrum access decisions
A Cognitive Digital Home (CDH): Architecture

- Provides end services to users
- Obtains resources from the Genie Node decision
A Cognitive Digital Home (CDH): Architecture

Relay and Wireless Access Devices

Provides relay and wireless access service to service provision devices
A Cognitive Digital Home: **Resources**

- Resources: A 3-tuple of frequency, bandwidth and RAT
- All usable spectrum in home environment
Multi-platform Radio Devices

Multiple RATs on a Multi-platform Radio Device

- Legacy: WiFi, Bluetooth, TV White spaces, etc.
  - Access to limited number of channels in specific spectrum regions
    - Over-crowded spectrum bands

- Cognitive Radio
  - Accesses a channel orthogonally ---- OFDMA (Noncontiguous)
    - Reduce system complexity and signaling overhead
  - Access to all the channels in a CDH
    - Provide channel access flexibility
A Framework for Resource Allocation in a CDH

- Multi-Platform Radios, Genie Node, Sensing Devices (Not currently considered)
Joint Channel and RAT Allocation Problem 1: Max Sum Rate

\[
\max_{L} \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{M}} \sum_{t \in \mathcal{T}} R(k, i, t) l(k, i, t)
\]

subject to

\[
\sum_{i \in \mathcal{M}} \sum_{t \in \mathcal{T}} R(k, i, t) l(k, i, t) \geq R_k^{\min}, \quad \forall k \in \mathcal{K}
\]

\[
P(k, i, t) = P_t, \quad \forall k \in \mathcal{K}, \forall i \in \mathcal{M}, \forall t \in \mathcal{T}
\]

\[
\sum_{i \in \mathcal{M}} \sum_{t \in \mathcal{T}} P(k, i, t) [l(k, i, t)] \leq P_k^{\max}, \quad \forall k \in \mathcal{K}
\]

\[
l(k, i, t) \in \begin{cases} 
\{0, 1\} & \text{if } t = \text{CR}, \forall i \in \mathcal{M}, \forall k \in \mathcal{K} \\
[0, 1] & \text{if } t \neq \text{CR}, \forall i \in \mathcal{M}_t, \forall k \in \mathcal{K} \\
0 & \text{otherwise}
\end{cases}
\]

\[
\sum_{k \in \mathcal{K}} \sum_{t \in \mathcal{T}} l(k, i, t) \leq 1, \quad \forall i \in \mathcal{M}
\]
Joint Channel and RAT Allocation Problem 2: Max Service Capacity

$$\max_L \sum_{k \in \mathcal{K}} \left( \sum_{i \in \mathcal{M}} \sum_{t \in \mathcal{T}} u(R(k, i, t)l(k, i, t) - R_{k_{\text{min}}}) \right)$$

subject to

$$P(k, i, t) = P_t, \quad \forall k \in \mathcal{K}, \forall i \in \mathcal{M}, \forall t \in \mathcal{T}$$

$$\sum_{i \in \mathcal{M}} \sum_{t \in \mathcal{T}} P(k, i, t)[l(k, i, t)] \leq P_{k_{\text{max}}}, \quad \forall k \in \mathcal{K}$$

$$l(k, i, t) \in \begin{cases} 
\{0, 1\} & \text{if } t = \text{CR}, \forall i \in \mathcal{M}, \forall k \in \mathcal{K} \\
[0, 1] & \text{if } t \neq \text{CR}, \forall i \in \mathcal{M}_t, \forall k \in \mathcal{K} \\
0 & \text{otherwise}
\end{cases}$$

$$\sum_{k \in \mathcal{K}} \sum_{t \in \mathcal{T}} l(k, i, t) \leq 1, \forall i \in \mathcal{M}$$

$u(.)$: step function

Transmit power is only determined by RAT

Individual Transmit Power Constraint for each service

Spectrum usage constraint
Joint Channel and RAT Allocation Problem 3: \textit{Max Min Rate}

\[
\begin{align*}
\max_{L} & \quad r \\
\text{subject to} & \quad r \leq \sum_{i \in \mathcal{M}} \sum_{t \in \mathcal{T}} R(k, i, t) l(k, i, t), \forall k \in \mathcal{K} \\
& \quad \sum_{i \in \mathcal{M}} \sum_{t \in \mathcal{T}} P(k, i, t)[l(k, i, t)] \leq P_k^{\max}, \forall k \in \mathcal{K} \\
& \quad \quad l(k, i, t) \in \begin{cases} 
0, 1 & \text{if } t = \text{CR}, \forall i \in \mathcal{M}, \forall k \in \mathcal{K} \\
[0, 1] & \text{if } t \neq \text{CR}, \forall i \in \mathcal{M}_t, \forall k \in \mathcal{K} \\
0 & \text{otherwise}
\end{cases} \\
& \quad \sum_{k \in \mathcal{K}} \sum_{t \in \mathcal{T}} l(k, i, t) \leq 1, \forall i \in \mathcal{M}
\end{align*}
\]
Heuristic Algorithm: *Max Sum Rate & Max Service Capacity*

RAT First Joint Channel and RAT Allocation (RF-JCRA)

- **Stage 1: Minimum Rate Allocation**
  - Allocate resources to meet services’ minimum required rates

- **Stage 2: Marginal Rate Allocation**
  - Allocate marginal resources to maximize the sum rates
Stage 1: Min. Rate Allocation

- Heuristic based on multiple choice knapsack problem

Sort Services according to increasing Average Rx Signal Quality

For current service, check feasibility of best channel with least Tx power RAT

- Go to next Service

Check feasibility in ascending order of RAT Tx Power

- Assign RAT with max. Tx power
- Proceed to next best Channel
Stage 2: Marginal Rate Allocation

- Solution Refinement based on local search in mixed-integer programming
  - improve an identified feasible solution
- Marginal Resource Allocation
  - Water-filling

![Diagram](attachment:image.png)
Numerical Result: Setup

- **Channels:**

<table>
<thead>
<tr>
<th>CH. #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq.(GHz)</td>
<td>2.412</td>
<td>2.437</td>
<td>2.462</td>
<td>2.484</td>
<td>57.1</td>
<td>57.2</td>
<td>57.3</td>
</tr>
<tr>
<td>Bandwidth(MHz)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

- Wi-Fi operates on the first 4 channels
- CR operates on all the channels
- RATs employ constant transmit power on each channel

<table>
<thead>
<tr>
<th>RAT</th>
<th>Bluetooth</th>
<th>Wi-Fi</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power(mW)</td>
<td>10</td>
<td>30</td>
<td>60</td>
</tr>
</tbody>
</table>
Numerical Result 1: (An exemplary CDH)

- 4 services, A (gaming controlling), B (Wireless Internet), C (gaming video) and D (Wireless HDTV)

- Constraints

<table>
<thead>
<tr>
<th>Service</th>
<th>Gaming Controlling (A)</th>
<th>Wireless Internet (B)</th>
<th>Gaming Video (C)</th>
<th>Wireless HDTV (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate Req. (Mbps)</td>
<td>1</td>
<td>10</td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>Max. Device Transmit Power (Mw)</td>
<td>10</td>
<td>30</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>Accessible Channels</td>
<td>1~4</td>
<td>1~4</td>
<td>1~7</td>
<td>1~7</td>
</tr>
<tr>
<td>Link length (m)</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

- Results

<table>
<thead>
<tr>
<th>CH. &amp; RAT</th>
<th>1~4 (BT)</th>
<th>1 (WiFi)</th>
<th>1,2 (WiFi)</th>
<th>2<del>4 (WiFi), 5</del>7 (CR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved Rates (Mbps)</td>
<td>1</td>
<td>13</td>
<td>26</td>
<td>71</td>
</tr>
</tbody>
</table>
Numerical Result 2: $\textbf{Max Sum Rate}$

- **RAT:** CR and Wi-Fi
- **Link Distances:** Uniformly generated in 5~10m
- **Service Power Constraints vector:** [100 200 300 400] mW
- **Rate Constraints:** 15Mbps for each service

$$P = \left( \sum_{t \in T_C} |\mathcal{K}| + \sum_{t \in T_L} \sum_{i=1}^{|\mathcal{K}|} \binom{|\mathcal{K}|}{i} \right)|\mathcal{M}|$$

- **Optimal:** $O(|\mathcal{K}| |\mathcal{M}| P)$
- **RF-JCRA:** $O\left(|\mathcal{K}| |\mathcal{M}|^2 |\mathcal{T}|\right)$
Numerical Result 3: *Max Service Capacity*

![Graph showing the relationship between the number of satisfied services and the number of services.](image)

- RF-JCRA 1 Channel
- Optimal 1 Channel
- RF-JCRA 2 Channels
- Optimal 2 Channels
- RF-JCRA 3 Channels
- Optimal 3 Channels
- RF-JCRA 4 Channels
- Optimal 4 Channels
Conclusion

- Proposed a novel framework for resource allocation in wireless home networks: CDH
  - Radio access technology as a new dimension of allocation
- Proposed efficient algorithms for 3 joint channel and RAT allocation problems in CDH
- Future work: Decentralized algorithms
Q&A

Thanks!