Coexistence/Interference Management in Heterogeneous Networks

Farzad Hessar
University of Washington
February 2014
Outline

• Introduction to TV White Space
• SpecObs Framework
• Capacity Consideration in TVWS Networks
• Resource Allocation in Cellular TVWS Networks
• Future Directions
  ➢ TVWS Network Design
  ➢ Radio Environment Map
  ➢ White Space Availability in Radar Band
Intro. TV White Space

![Supply-Demand curve for wireless access](image-url)
Possible Solutions

• More Licensed Spectrum: \( C = BW \times \log_2(1 + SNR) \)
  ➢ Scarce resource
  ➢ Extremely expensive
  ➢ Not feasible beyond 60 GHz

• Higher Spectrum Efficiency
  ➢ PHY and MAC improvements
  ➢ MIMO with large #of TX/RX antennas
Possible Solutions ctd.

• Smaller Cell Size
  - Infrastructure and operational cost
  - Backhaul requirements
  - Site limitation in urban areas

• Unlicensed Spectrum
  - Licensed spectrum is underutilized
  - Low spectral efficiency and large guard bands
  - Current unlicensed bands (ISM) are highly saturated
Unlicensed Spectrum Access

• Basic Idea:

“Spectrum holes must be detected”
Spectrum Hole Detection

• Spectrum Sensing
  - Hidden terminal problem
  - Signal shadowing and fading
  - Spread spectrum users
  - Complexity

• Primary User Modeling
  - Prior information about PU
  - Predictable behavior in time / space
PU Activity Modeling

- Stationary PU → Estimating coverage area
- Time Varying Interference
TV White Space Spectrum

- FCC has opened TV band spectrum for unlicensed use subject to no harmful interference to licensed TV entities
- TV Channel between 2 - 51 except 37
- Channel bandwidth = 6 MHz
- Total potential bandwidth = 294 MHz

<table>
<thead>
<tr>
<th>Low VHF</th>
<th>High VHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 3 4 5 6</td>
<td>7 8 9 10 11 12 13</td>
</tr>
<tr>
<td>54 MHz 88 MHz</td>
<td>174 MHz 216 MHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 15 16 17 18 ..... 47 48 49 50 51</td>
</tr>
<tr>
<td>470 MHz ..... 698 MHz</td>
</tr>
</tbody>
</table>
TVWS-based Secondary Network

Channel Query
Free Channel
Query Packet
Allocation Packet
Intelligent Spectrum Manager
Radio Device

IP Network
SpecObserve
Server
Spectrum Database

Secondary TVWS Networks
Outline

- Introduction to TV White Space
- SpecObs Framework
- Capacity Consideration in TVWS Networks
- Resource Allocation in Cellular TVWS Networks
- Future Directions
  - TVWS Network Design
  - Radio Environment Map
  - White Space Availability in Radar Band
SpecObs Framework

• SpecObs: http://specobs.ee.washington.edu
• Implements DBA for TVWS spectrum
  ✓ FCC regulation
  ✓ All licensed TV entities considered
  ✓ Noise floor / Capacity estimation
  ✓ Resource (channel) allocation among SU devices
SpecObs Structure ctd.
TVWS Messaging

- Query WS List
- Register for Best Channel
- Setup Network

HTTP GET [location]
HTTP Response
HTTP REQ. [Duration]
HTTP Response

SpecObs Server

WS List, QS, Tech. Req.
[22, 27, 32, 42, 46, 47]
[-90,-110,-103,-45,-98,-76] dBm

Query: update registered devices
ACK

DB
SpecObs Web Interface

The protection regions of each TV channel are displayed on the map. Please choose one of the TV channels you want to see. You can also clear the displayed protection regions on the map by clicking the "Clear All" button.

Protection Region  Transmitter  FCC Curve  Channel 19  9 services are selected  ...
Outline

• Introduction to TV White Space
• SpecObs Framework
• **Capacity Consideration in TVWS Networks**
• Resource Allocation in Cellular TVWS Networks
• Future Directions
  ➢ White Space Availability in Radar Band
  ➢ Radio Environment Map
  ➢ TVWS Network Design
Capacity Considerations in TVWS

• Basic question: *How much TV white space spectrum does exist?*
  ✓ How many channel are available?
  ✓ What is channel quality?
  ✓ Spatial variation?
  ✓ FCC rules
  ✓ PU network parameters

• *What are the main trade-off in network design?*
  ✓ SU network parameters
Secondary Network Architecture

PR – Primary Receiver
PT – Primary Transmitter
SC – Secondary Cell

$\theta$
Capacity Formulation

• Set of available channels at cell A:

\[ \Upsilon(A, \Gamma_A) = \{ c_i : \text{Channel } c_i \text{ is available at cell } A \text{ with parameter } \Gamma_A \} \]

• Capacity for an available channel:

\[ C_{cell} = W_0 \log_2(1 + \text{SINR}) \]

• $W_0 = 6 \text{ MHz}$

• Capture spatial variation:

\[ W(Q_T, \Gamma) = \begin{cases} 
W_0 & Q_T \notin \Omega \text{ and } \Gamma \not\in \text{FCC rules} \\
0 & Q_T \in \Omega \text{ or } \Gamma \not\in \text{FCC rules}
\end{cases} \]
Capacity Formulation ctd.

- Channel availability probability: 
  \[ p(\Gamma) = Pr[Q_T \notin \Omega] \]
  \[ p(\Gamma) = \frac{1}{A} \int_A \frac{W(Q_T, \Gamma)}{W_0} dQ_T \]

- Average cell capacity (per channel):
  \[ \overline{C_{cell}}(\Gamma) = p(\Gamma)W_0 \int_A \frac{\log_2(1 + \text{SINR}(Q_R))}{A} dQ_R \]

- Total Capacity:
  \[ \overline{C_{cell, total}}(\Gamma) = \sum_{c_i \in \Gamma(\text{cell}, \Gamma_{cell})} p(\Gamma, c_i)W_0 \int_A \frac{\log_2(1 + \text{SINR}(Q_R, c_i))}{A} dQ_R \]
Channel Availability Determination

- Permissible channels:
  - Fixed TVBD: \(\{2: 51\}\{3,4,37\}\)
  - Portable TVBD: \(\{21: 51\}\{37\}\)

- Power Limit
  - Fixed TVBD: Maximum of 36 dBm
  - Portable TVBD: Maximum of 20 dBm

- Antenna Height:
  - Fixed TVBD: Height < 30-m, HAAT < 250-m
  - Portable TVBD: Height < 3-m
Channel Availability Determination

• Interference Protection:

• Other protected entities
  • PLMRS / CMRS
  • Radio Astronomy Sites
  • Wireless microphones

• Aggregating all FCC rules defines list of available channels $\gamma(A, \Gamma_A)$
Interference Model

- Primary to Secondary Interference

\[
I_{P2S}(QR) = \sum_{i=1}^{N} (1 - \eta) \frac{P_i G_i}{L_{TV}(d_i)} G_r + \sum_{j=1}^{M} \eta \frac{P_j G_j}{L_{TV}(d_j)} G_r
\]
Interference Model ctd.

- The reference amplitude is the total transmitter output power, including the pilot signal.
- The flat portion or "head" of an ideal 8-VSB signal is -10.63 dB ref in amplitude in a 500 kHz bandwidth.
- The mask commences 1/2 Resolution Bandwidth from the Channel's Edge.
- Emission amplitudes are referenced to a 500 kHz bandwidth and shall be less than the limit lines.
- 6.000 000 MHz.
Interference Model ctd.

- **Secondary to Secondary Interference**
  - \( K = i^2 + ij + j^2 \)
  - \( D = \sqrt{3K} r_{cell} \)
  - \( I_{i,j} = P_{sec,TX} G_{sec}^2 L_{sec}(D_{i,j}) \)

\[
I_{S2S} = P_{sec,TX} G_{sec}^2 K_I \sum_{i=0}^{\infty} \sum_{j=i, j\neq 0}^{\infty} L_{sec}(D_{i,j})
\]
Capacity re-defined

\[
\overline{C}_{\text{cell}}(\Gamma) = \frac{p(\Gamma)}{K} W_0 \int_{Q_R} \log_2 \left( 1 + \frac{P_{\text{sec}} / L_{\text{sec}}}{N_0 W_0 + I_{P2S}(Q_R) + I_{S2S}} \right) dQ_R
\]
Numerical Calculation

- Protected Regions – Channel 13
Channel Availability Statistics

<table>
<thead>
<tr>
<th>Device Type</th>
<th>LVHF (2:6)</th>
<th>HVHF (7:13)</th>
<th>UHF (14:51\37)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Available</td>
<td>2.36</td>
<td>2.59</td>
<td>21.77</td>
<td>26.73</td>
</tr>
<tr>
<td>Fixed Devices</td>
<td>2.36</td>
<td>2.59</td>
<td>15.2</td>
<td>20.17</td>
</tr>
<tr>
<td>Portable/Personal</td>
<td>0</td>
<td>0</td>
<td>18.79</td>
<td>18.79</td>
</tr>
<tr>
<td>Reserved (Microphone)</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Busy Channels by TV</td>
<td>0.45</td>
<td>2.22</td>
<td>10.43</td>
<td>13.11</td>
</tr>
<tr>
<td>Unused Channels</td>
<td>2.18</td>
<td>2.19</td>
<td>4.67</td>
<td>9.05</td>
</tr>
<tr>
<td>Channel Utilization Factor</td>
<td>56%</td>
<td>68.7%</td>
<td>87.4%</td>
<td>81.5%</td>
</tr>
</tbody>
</table>

![Graph showing population density vs. channel availability]
Num. Results – Noise Floor
Practical Trade-offs

- Link Capacity vs. TVBD Power
Practical Trade-offs ctd.

- Link Capacity vs. TVBD Antenna Height
Practical Trade-offs ctd.

- Link Capacity vs. Cell Size

![Graph showing link capacity versus cell size for different channels and K values.](image-url)
Practical Trade-offs ctd.

- Capacity Per Stationary User:
- Capacity Per Mobile User:
Outline

• Introduction to TV White Space
• SpecObs Framework
• Capacity Consideration in TVWS Networks

Resource Allocation in Cellular TVWS Networks

• Future Directions
  ➢ White Space Availability in Radar Band
  ➢ Radio Environment Map
  ➢ TVWS Network Design
Problem Definition

Basic Question:
How do we assign resources (channels) to secondary users in TVWS?

Why is it important? Why not setup as WiFi network?

Secondary network in TVWS are managed by DBA.

Facts about TVWS:
- Number of available channels are spatially variant
- Channel numbers vary with location of the receiver
- Quality of channels are spatially varying
Problem Definition ctd.

• Available number of channels in Los Angeles area:
Secondary Cellular Network
Channel Allocation in Cellular Networks

• Regular Cellular Networks
  • Same set of channels are available every where
  • No quality difference among channels
  • Main traffic type is voice
  • Main goal is to color the graph based on number of users.
Channel Allocation in TVWS

Some Definitions

• All permissible channels: \( C = \{2,3, \ldots, 36,38, \ldots, 51\} \)
• Available channels at cell \( A_i \): \( \mathcal{Y}(A_i) \subseteq C \)
• For \( c \in \mathcal{Y}(A_i) \) specify \( \gamma_{i,P}(c) \) as the interference level. It includes co/adjacent channel pollution from primary.
• A min. of one channels must be assigned to each cell
Formulate Channel Allocation

- **Problem formulation 1**: For a set of N cells \( \{A_0, ..., A_{N-1}\} \), with channel set \( \{\Upsilon(A_0), ..., \Upsilon(A_{N-1})\} \) a channel selection function \( f \) is desired \( f: \Upsilon(A_i) \rightarrow C_i \subseteq \Upsilon(A_i) \) so that:

\[
f_{opt} = \arg \max_f \sum_{i=0}^{N-1} |C_i|
\]

Subject to:

\[
C_i \subset \Upsilon(A_i), \ \forall i \in [0, ..., N - 1]
\]

\[
C_i \neq \emptyset
\]

\[
\sum_{j=0}^{N-1} \gamma_{i,j}(c) + \gamma_{i,P}(c) + \sigma_n^2 \leq \gamma_t, \ \forall c \in C_i
\]
Formulate Channel Allocation

- Pros and Cons for problem formulation
  - Threshold $\gamma_t$ must be optimally found
  - Maximizing total number of channels does not necessarily maximizes capacity
  - Objective function and Constraints are linear
  - Standard solver tools exist
Formulate Channel Allocation

- **Problem formulation 2**: For a set of N cells \( \{ A_0, \ldots, A_{N-1} \} \), with channel set \( \{ \Upsilon(A_0), \ldots, \Upsilon(A_{N-1}) \} \) a channel selection function \( f \) is desired \( f: \Upsilon(A_i) \rightarrow C_i \in \Upsilon(A_i) \) so that:

\[
 f_{opt} = \arg \max_f \sum_{i=0}^{N-1} \sum_{c \in C_i} \log_2 (1 + SINR(c))
\]

\[
 SINR(c) = \frac{P}{\sum_{j=0}^{N-1} \gamma_{i,j}(c) + \gamma_{i,P}(c) + \sigma^2_n}
\]

- Subject to:

\[
 C_i \subset \Upsilon(A_i), \ \forall i \in [0, \ldots, N - 1]
\]

\[
 C_i \neq \emptyset
\]
Formulate Channel Allocation

- Pros and Cons for Problem formulation-2
  - No threshold selection is required
  - Maximizing capacity is guaranteed
  - Objective function is nonlinear
  - Standard solver tools do not exist
• Suboptimal Greedy Algorithm for Problem 1
Algorithm 1: Greedy algorithm for problem 1

Data: $G(V, E), \{\mathcal{Y}(V)\}$  \hspace{1cm} \triangleright \text{interference graph, channel availability vectors}

Result: $\{C(v) : \forall v_i \in V\}$

1. Function GreedyAssign()
   2. while $\bigcup_{v_i \in V} \mathcal{Y}(v_i) \neq \emptyset$ do
      3. $v_{cur} \leftarrow \text{select } v \in V \text{ with } \min |C(v)| \text{ and } \min |\mathcal{Y}(v)| \neq 0$ \hspace{1cm} \triangleright \text{current cell}
      4. $c_{\text{min}} \leftarrow \text{select } c \in \mathcal{Y}(v_{cur}) \text{ with } \min \text{ InterferingNodes}(v_{cur}, c)$ \hspace{1cm} \triangleright \text{assign selected channel to current cell}
      5. $C(v_{cur}) \leftarrow C(v_{cur}) \cup c_{\text{min}}$
      6. $\mathcal{Y}(v_{cur}) \leftarrow \mathcal{Y}(v_{cur}) \setminus \{c_{\text{min}}\}$ \hspace{1cm} \triangleright \text{remove selected channel from set of available channels}
      7. UpdateChannels($c_{\text{min}}, v_{cur}$)
   8. end while
9. return

10. Function InterferingNodes($v_{cur}, c$)
11. $V_n \leftarrow \text{set of neighbors of } v_{cur}$
12. $V_{shrd}(c) \leftarrow \{v \in V_n : c \in \mathcal{Y}(v)\}$
13. $V_{own}(c) \leftarrow \{v \in V_n : c \in C(v)\} \cup \{v_{cur}\}$
14. count $\leftarrow \text{number of } v \in V_{shrd}(c) \text{ for which } \text{TotalInterference}(c, v) > \gamma_t$
15. return count
Greedy – Problem 1 ctd.

16 Function UpdateChannels(c, v_{cur})
17 \quad V_n \leftarrow \text{set of neighbors of } v_{cur}; V_{shrd}(c) \leftarrow \{v \in V_n : c \in \mathcal{Y}(v)\};
18 \quad V_{own}(c) \leftarrow \{v \in V_n : c \in C(v)\}
19 \quad \textbf{forall the } v \in V_{shrd}(c) \textbf{ do}
20 \quad \quad V_{own}(c) \leftarrow V_{own}(c) \cup \{v\}
21 \quad \quad \textbf{if } \text{TotalInterference}(c, V_{own}(c)) > \gamma_t \textbf{ then}
22 \quad \quad \quad \mathcal{Y}(v) \leftarrow \mathcal{Y}(v) \setminus \{c\}
23 \quad \quad \quad \text{end if}
24 \quad \quad V_{own}(c) \leftarrow V_{own}(c) \setminus \{v\}
25 \quad \textbf{end forall}
26 \quad \text{return}
Optimal – Problem 1 ctd.

- Channel availability vector $A_i^{C \times 1} \in \{0,1\}^{C \times 1}$
- Channel assignment vector $L_i^{C \times 1} \in \{0,1\}^{C \times 1}$

\[
A = \begin{bmatrix}
A_0 \\
A_1 \\
\vdots \\
A_{N-1}
\end{bmatrix}, \quad L = \begin{bmatrix}
L_0 \\
L_1 \\
\vdots \\
L_{N-1}
\end{bmatrix}
\]
Optimal – Problem 1 ctd.

- Integer Linear Programming:

\[
\text{max} \ 1^T \mathcal{L}
\]

Subject to:

\[
\mathcal{L}^T \mathcal{A}^e = 0
\]

\[
\sum_{j=0}^{\lfloor |C| - 1 \rfloor} \mathcal{L}(|C| + j) > 0, \quad i = 0, 1, ..., N - 1
\]

\[
\sum_{j=0}^{N-1} \mathcal{L}(j|C| + k) \gamma_{i,j}(c^k) + \gamma_{i,P}(c^k) + \sigma_i^2 \leq \gamma_{it} + [1 - \mathcal{L}(i|C| + k)] \Lambda
\]
NLIP Solution – Problem 2

- Non-linear IP:

$$\max_{\mathcal{L}} f_{\text{obj}}(\mathcal{L})$$

Subject to:

$$\mathcal{L}^T \mathbb{A}^c = 0$$

$$\sum_{j=0}^{N-1} \mathcal{L}(|\mathcal{C}|i + j) > 0, \quad i = 0, 1, \ldots, N - 1$$

$$f_{\text{obj}}(\mathcal{L}) = B^{1 \times N|\mathcal{C}|} \mathcal{L}$$

$$B(i|\mathcal{C}|+k) = \log_2 \left( \frac{P}{\sum_{j=0}^{N-1} \mathcal{L}(j|\mathcal{C}|+k) \gamma_{i,j}(c_k) + \gamma_{i,P}(c_k) + \sigma_n^2} + 1 \right)$$

$$i, k = 0, \ldots, N - 1$$
Greedy – Problem 2

Algorithm 2: Greedy algorithm for problem 2

| Data: \( G(V, E), \{\Upsilon(V)\} \) | \( \triangleright \) interference graph, channel availability vectors |
|\ Result: \( \{C(v) : \forall v_i \in V\} \) |

```
24 Function TotalThroughput(c, V)
25     Input: V: Set of nodes, c: specific channel
26     \( f \leftarrow 0 \)
27     \textbf{for all the} \( v_i \in V \text{ do} \) \( \triangleright \) Assume \( c \) is assigned to all nodes in \( V \)
28         \( I \leftarrow \gamma_{i,P}(c) + \sum_{v_j \in V \setminus \{v_i\}} \gamma_{i,j}(c) \)
29         \( f \leftarrow f + \log_2 \left(1 + \frac{P}{I + \sigma_n^2}\right)\)
30     \textbf{end for all}
31     \textbf{return } f

32 Function RemoveNeighbors(c)
33     \( D_1 \leftarrow \{v|c_i \in C(v)\}; D_2 \leftarrow \{v|c_i \in \Upsilon(v)\} \)
34     \textbf{for all the} \( v_j \in D_2 \text{ do} \)
35         \textbf{if TotalThroughput}(c, D_1 \cup v_j) < TotalThroughput(c, D_1) \text{ then} \)
36             \( \Upsilon(v_j) \leftarrow \Upsilon(v_j) \setminus c_{\max} \)
37         \textbf{end if}
38     \textbf{end for all}
39     \textbf{for all} \textbf{if TotalThroughput}(c_i, D_1) > f_{\max} \text{ then} \)
40         \( f_{\max} \leftarrow \text{TotalThroughput}(c_i, D_1); c_{\max} \leftarrow c_i \)
41     \textbf{end if}
42     \textbf{end for all}
43     \textbf{return} c_{\max}
```
Numerical Results

![Diagram of network nodes and channels]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes $</td>
<td>V</td>
</tr>
<tr>
<td>Number of channels $</td>
<td>C</td>
</tr>
<tr>
<td>Available channels $\gamma(\nu)$</td>
<td>$\sim U[3, 5]$</td>
</tr>
<tr>
<td>Primary Interference $\gamma_{i,P}(\cdot)$</td>
<td>$\sim U[0.0, 0.1]$</td>
</tr>
<tr>
<td>Secondary User’s Power</td>
<td>1.0</td>
</tr>
<tr>
<td>Mutual Interference $\gamma_{i,j}$</td>
<td>$\propto \frac{P}{d_{i,j}^2}$</td>
</tr>
<tr>
<td>Noise Power $\sigma_n^2$</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Numerical Results
Numerical Results ctd.

- **Problem 1 vs. Problem 2**

<table>
<thead>
<tr>
<th>Method</th>
<th>Norm. No. Assigned Channels</th>
<th>Norm. Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greedy Prob. 2 with IQP</td>
<td>0.534</td>
<td>0.976</td>
</tr>
<tr>
<td>Greedy Prob. 2 with Heuristic</td>
<td>0.546</td>
<td>0.973</td>
</tr>
<tr>
<td>ILP Prob. 1</td>
<td>0.5</td>
<td>1.005</td>
</tr>
<tr>
<td>Greedy Prob. 1</td>
<td>0.57</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Outline

• Introduction to TV White Space
• SpecObs Framework
• Capacity Consideration in TVWS Networks
• Resource Allocation in Cellular TVWS Networks
• Future Directions
  ➢ TVWS Network Design
  ➢ Radio Environment Map
  ➢ White Space Availability in Radar Band
TVWS Network Design

- Campus Wide TVWS Network as proof of concept

Outcomes:
- An Operational Parallel Wireless Network
- A Test-bed for Evaluation of TVWS Network Quality
TVWS Network Design

- **Hardware**

  - **HOST PC**
  - **TCP/IP**
  - **MAC**

  - **Altera Cyclone IV FPGA**
    - Baseband IEEE 802.11 PHY Processing

  - **Super-heterodyne Transceiver**
    - BW: 28 MHz
    - Freq. Span: 300 MHz – 3.8 GHz
TVWS Network Design

- Experiment Design
  - Measure indoor/outdoor primary to secondary interference level
  - Evaluate TV band channel characteristics, such as delay/power profile, fading, etc.
  - Evaluating achievable throughput per available channel using IEEE 802.11 standard
  - Testing interference management and channel allocation algorithms
Radio Environment Map

- Use TVBD as spectrum sensors
- Aggregate sensing data in the central database
- Perform Krigging (spatial interpolation) to estimate signal strength at unknown locations
- Outcomes
  - More accurate estimation of noise floor in the environment
  - Protection of PU receivers at the edge of coverage area
  - High performance interference managements between SU devices
WS Opportunity in other bands

- Radar band
  - 1.7 GHz of spectrum from 225MHz to 3.7 GHz
  - 1.1 out of 1.7 GHz is for fixed non-military radars
  - Slowly varying in time (compared to scheduling time scale of LTE/WiFi systems)
  - Coexistence with LTE/WiFi systems is possible

How much information about Radar systems is needed?
What PHY/MAC layer changes are necessary?
Publications and Patents

Thank You

Question?