Coexistence/Interference Management in Heterogeneous Networks

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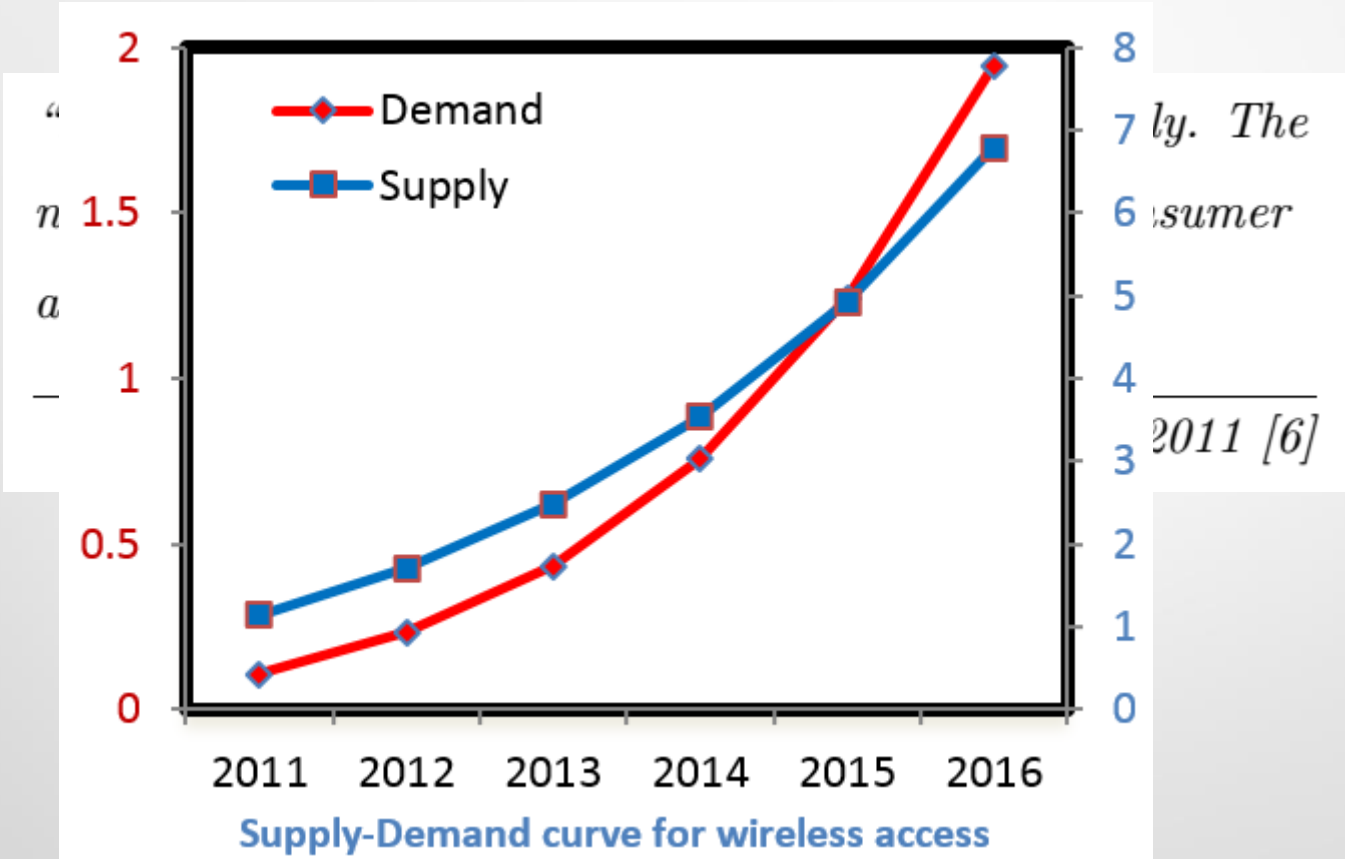
Outline

- 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



Possible Solutions

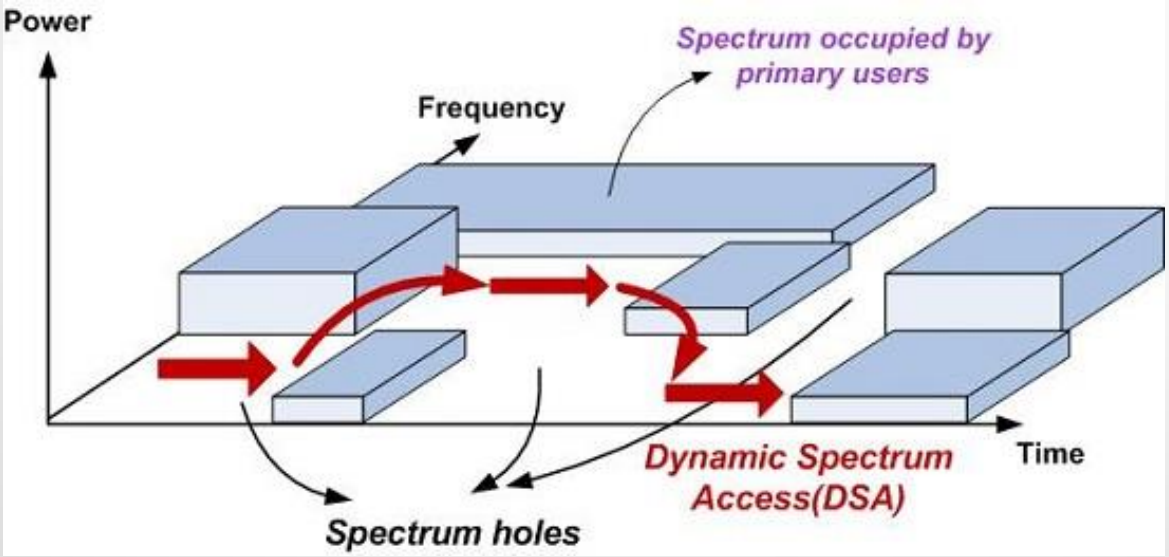
- More Licensed Spectrum: $C = \mathrm{BW} \times \log_2(1 + SNR)$
  - Scarce resource
  - Extremely expensive
  - Not feasible beyond 60 GHz
- Higher Spectrum Efficiency
  - PHY and MAC improvements
  - MIMO with large #of TX/RX antennas

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:



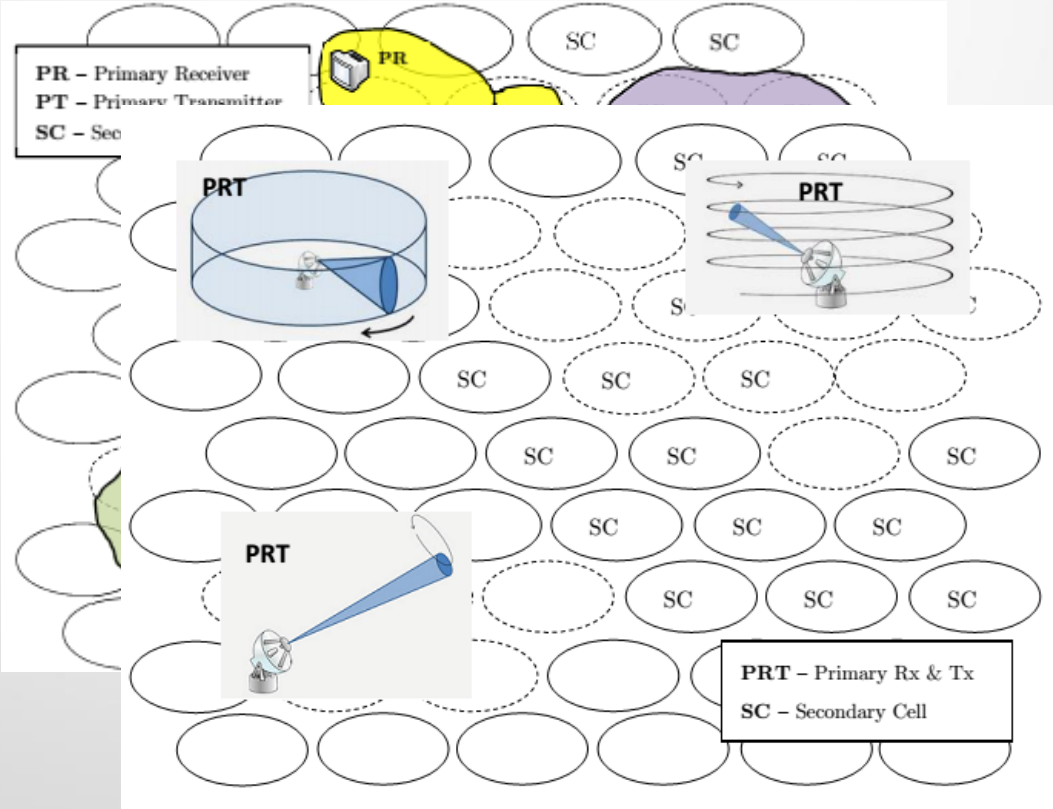
"Spectrum holes must be detected"

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

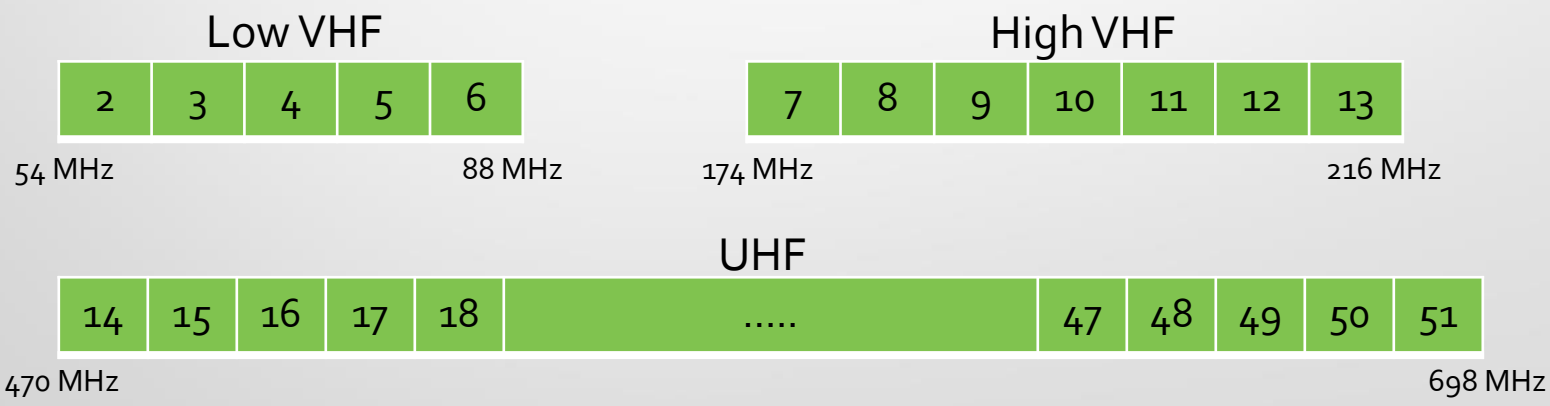
PU Activity Modeling

- Stationary PU → Estimating coverage area
- Time Varying Interference

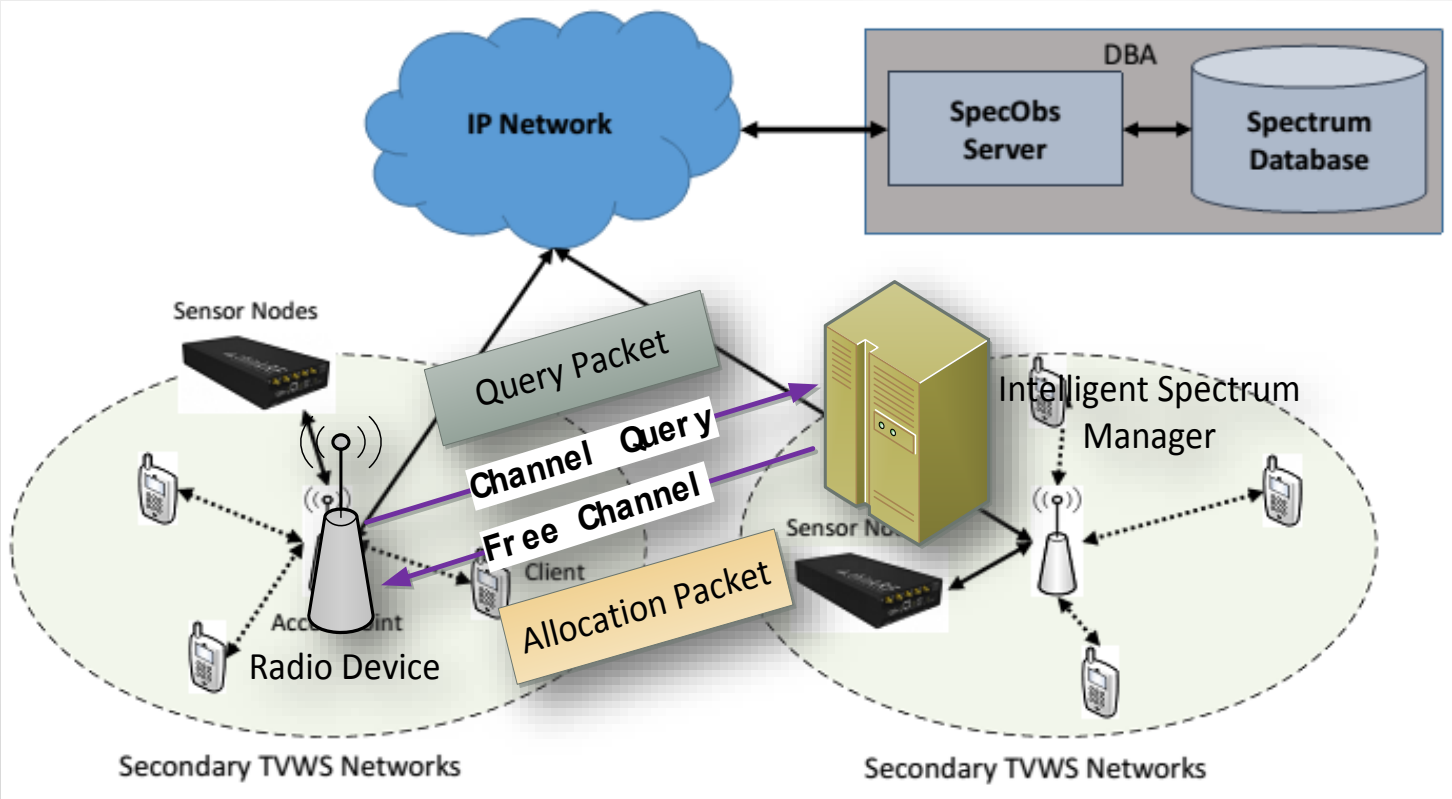


TV White Space Spectrum

- 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



TVWS-based Secondary Network



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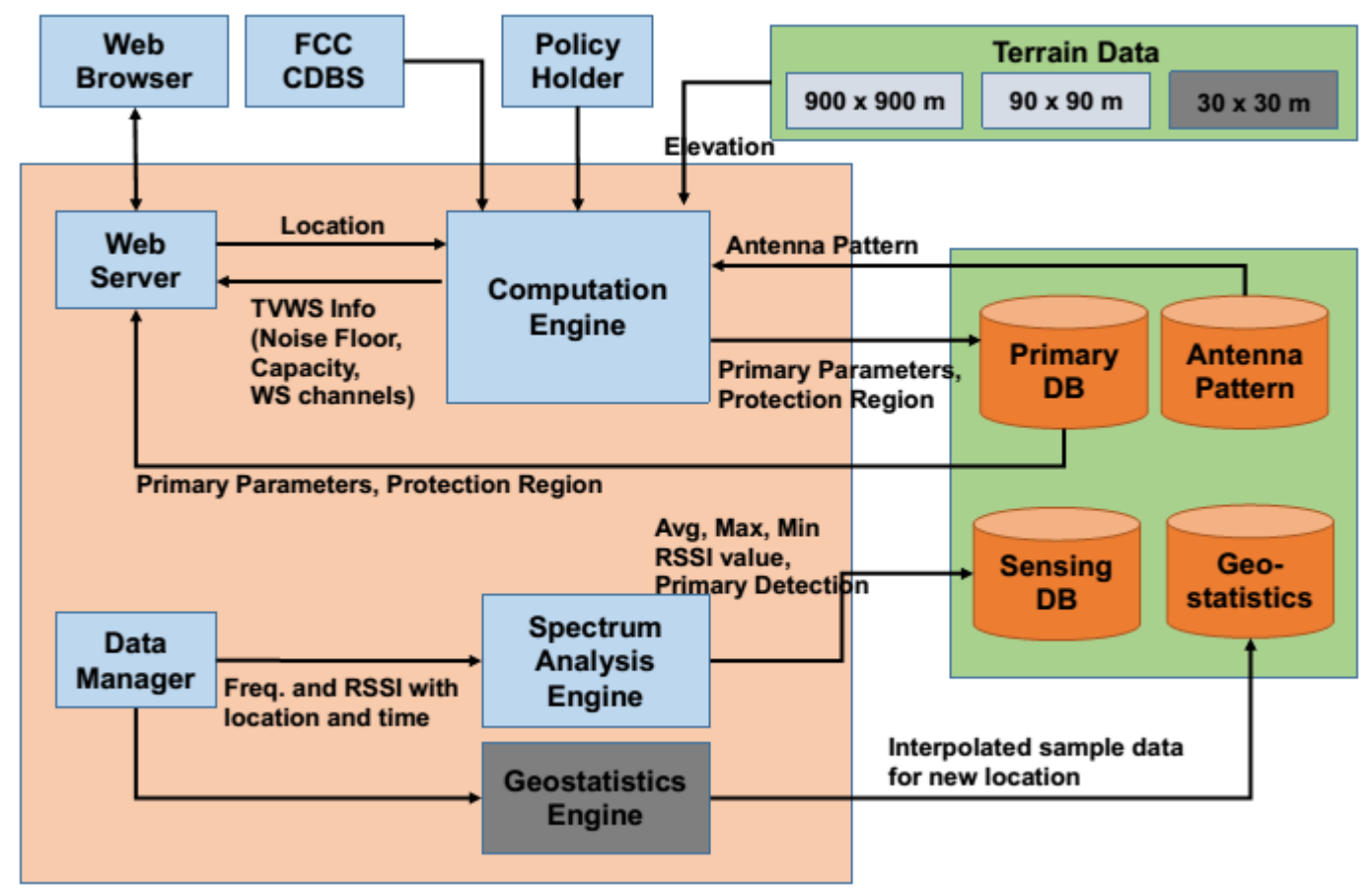
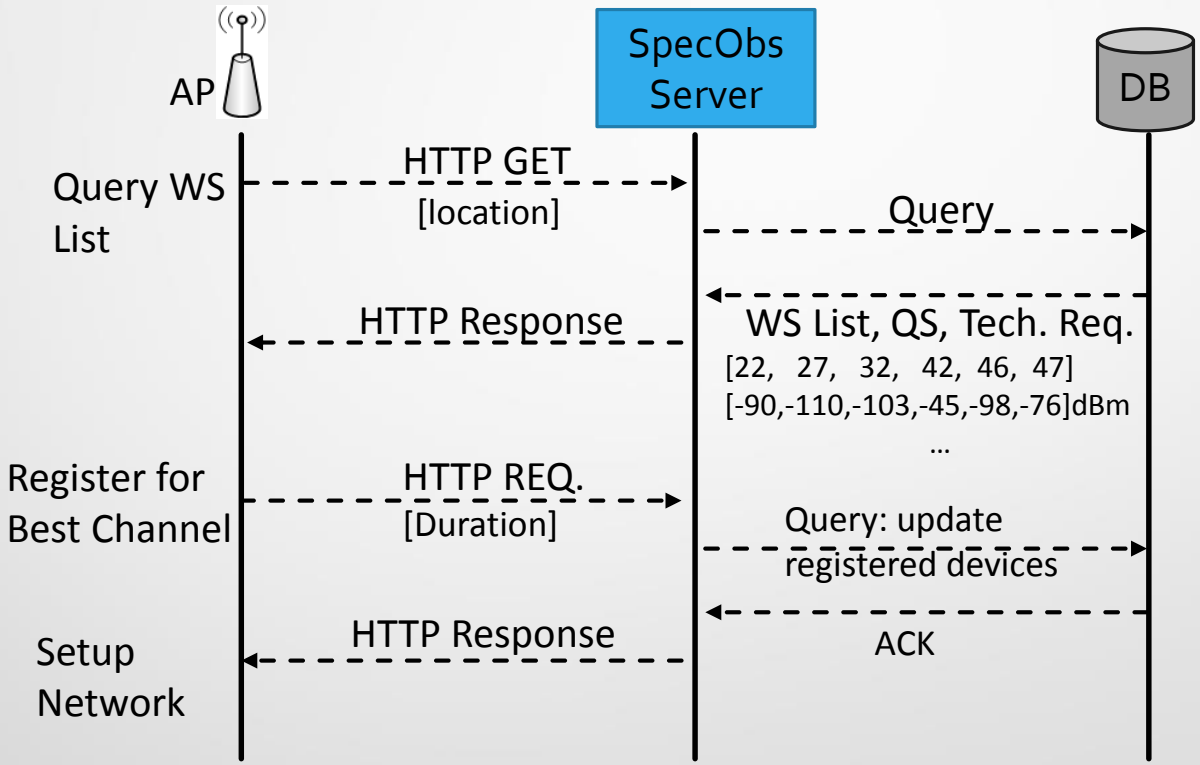
SpecObs Framework

- 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



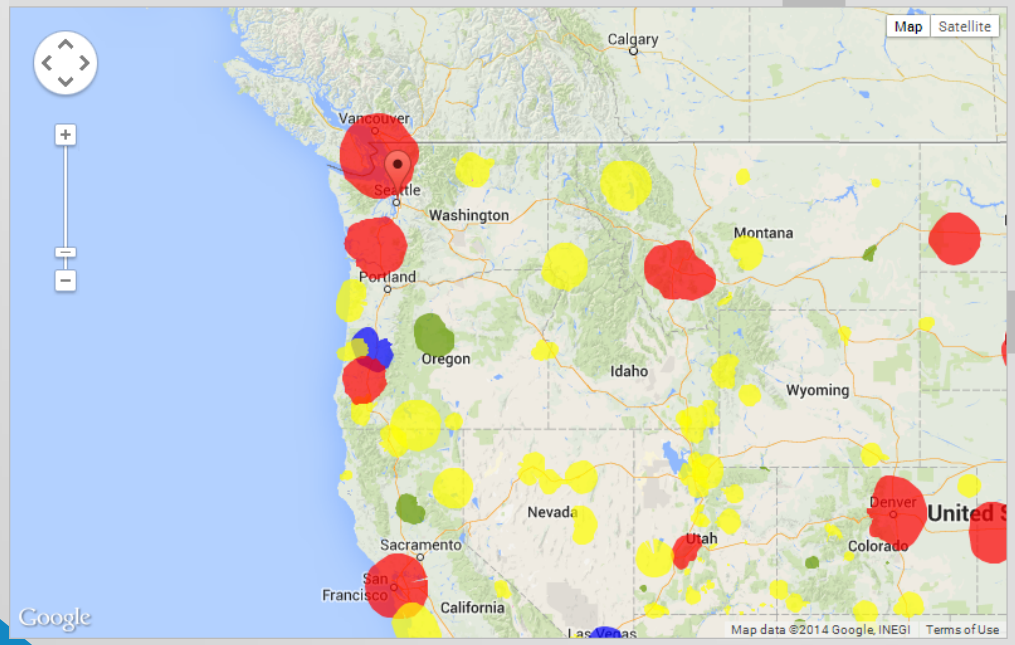
SpecObs Web Interface

specobs.ee.washington.edu

Start | Location | Protection Region | Capacity in Color Map | Contact Us

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 | View | Clear All



Summary | Fixed | Portable | Channel Detail

Portable TVWS Device

Channel Number	Max Power (mW)	Noise Floor (dBm)	Capacity (Mbps)
21	40	-71.03	44.93
23	40	-71.2	44.88
28	40	-105.86	112.95
29	100	-95.07	99.2
30	40	-81.1	63.24
32	40	-76.27	53.27
34	40	-77.96	56.26
41	40	-79.28	57.72
43	40	-62.54	24.54
45	40	-62.79	24.71
49	40	-77.03	51.98
Total			633.68

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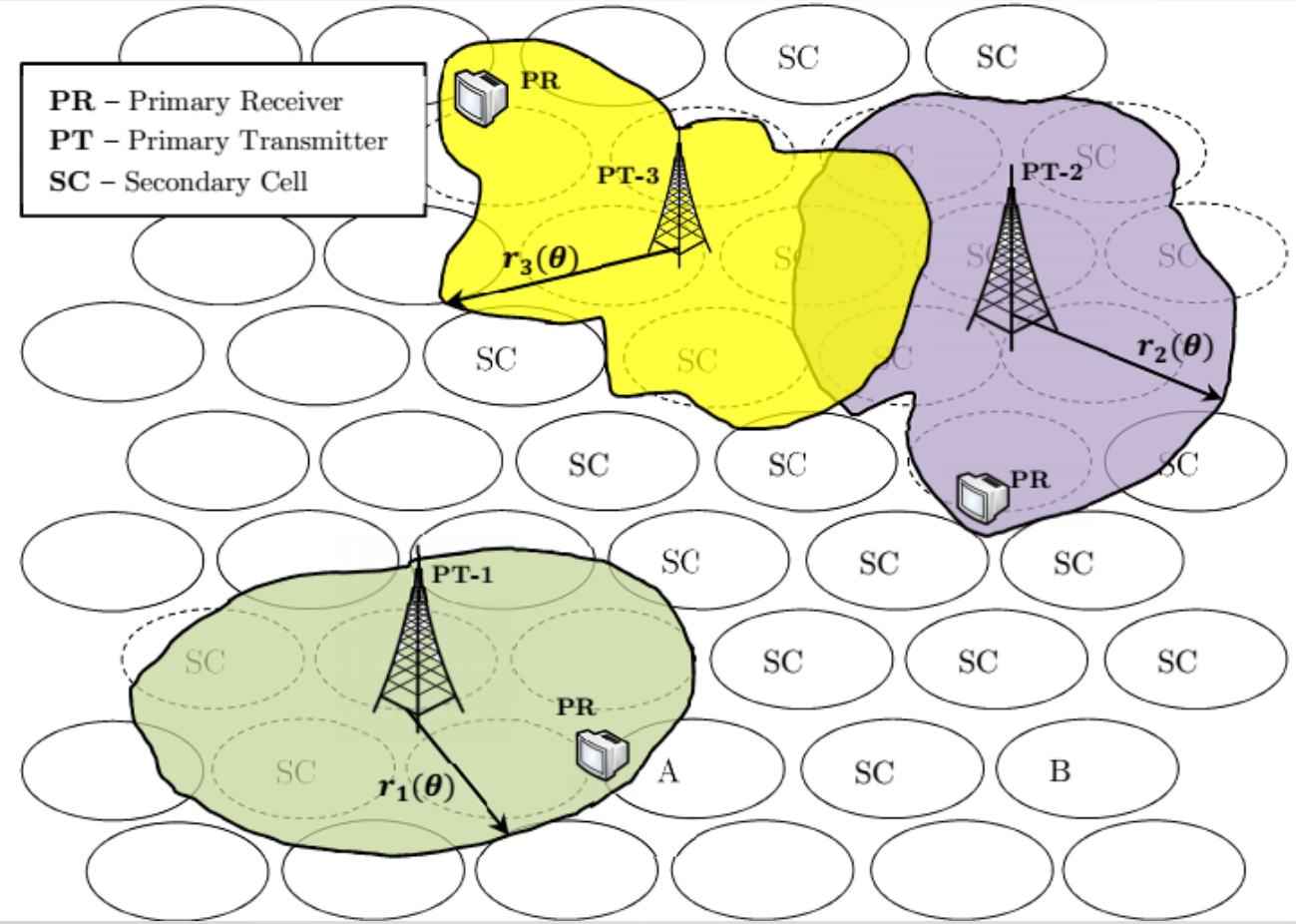
Capacity Considerations in TVWS

- 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



Capacity Formulation

- Set of available channels at cell A:

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

- Capacity for an available channel:

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

- $W_0 = 6$ MHz
- Capture spatial variation:

$$W(Q_T, \Gamma) = \begin{cases} W_0 & Q_T \notin \Omega \text{ and } \Gamma \vdash \text{FCC rules} \\ 0 & Q_T \in \Omega \text{ or } \Gamma \nvdash \text{FCC rules} \end{cases}$$

Capacity Formulation ctd.

- Channel availability probability: $p(\Gamma) = Pr[Q_T \notin \Omega]$

$$p(\Gamma) = \frac{1}{\mathcal{A}} \int_{\mathcal{A}} \frac{W(Q_T, \Gamma)}{W_0} dQ_T$$

- Average cell capacity (per channel):

$$\overline{C_{cell}}(\Gamma) = p(\Gamma) W_0 \int_{\mathcal{A}} \frac{\log_2(1 + \mathrm{SINR}(Q_R))}{\mathcal{A}} dQ_R$$

- Total Capacity:

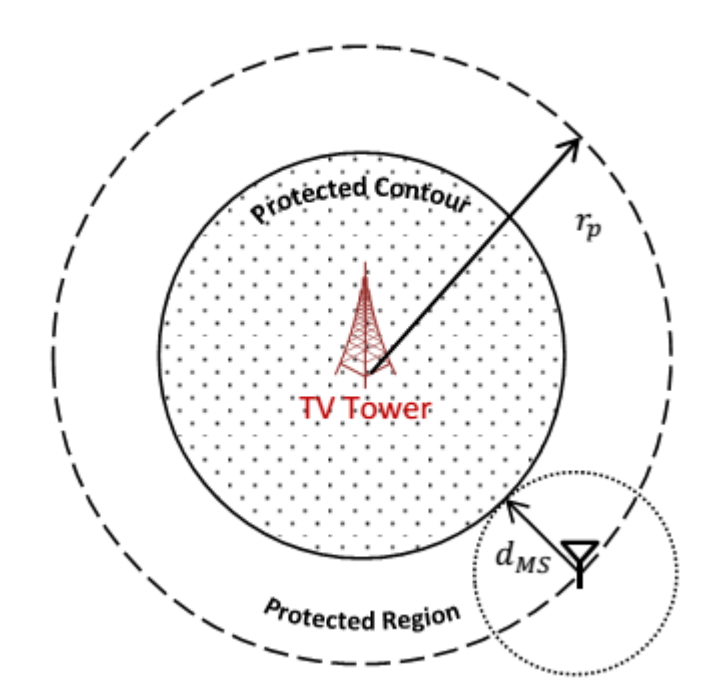
$$\overline{C_{cell,total}}(\Gamma) = \sum_{c_i \in \Upsilon(cell, \Gamma_{cell})} p(\Gamma, c_i) W_0 \int_{\mathcal{A}} \frac{\log_2(1 + \mathrm{SINR}(Q_R, c_i))}{\mathcal{A}} dQ_R$$

Channel Availability Determination

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

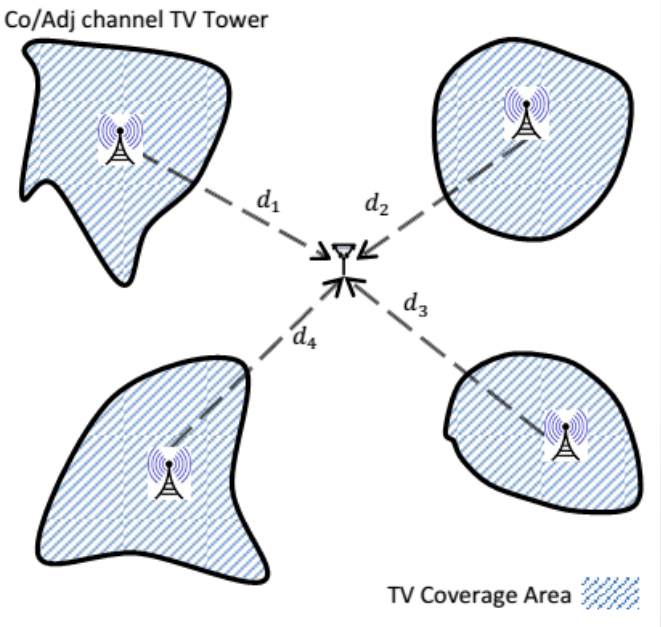


- Other protected entities
  - PLMRS / CMRS
  - Radio Astronomy Sites
  - Wireless microphones
- Aggregating all FCC rules defines list of available channels $\Upsilon(A, \Gamma_A)$

Interference Model

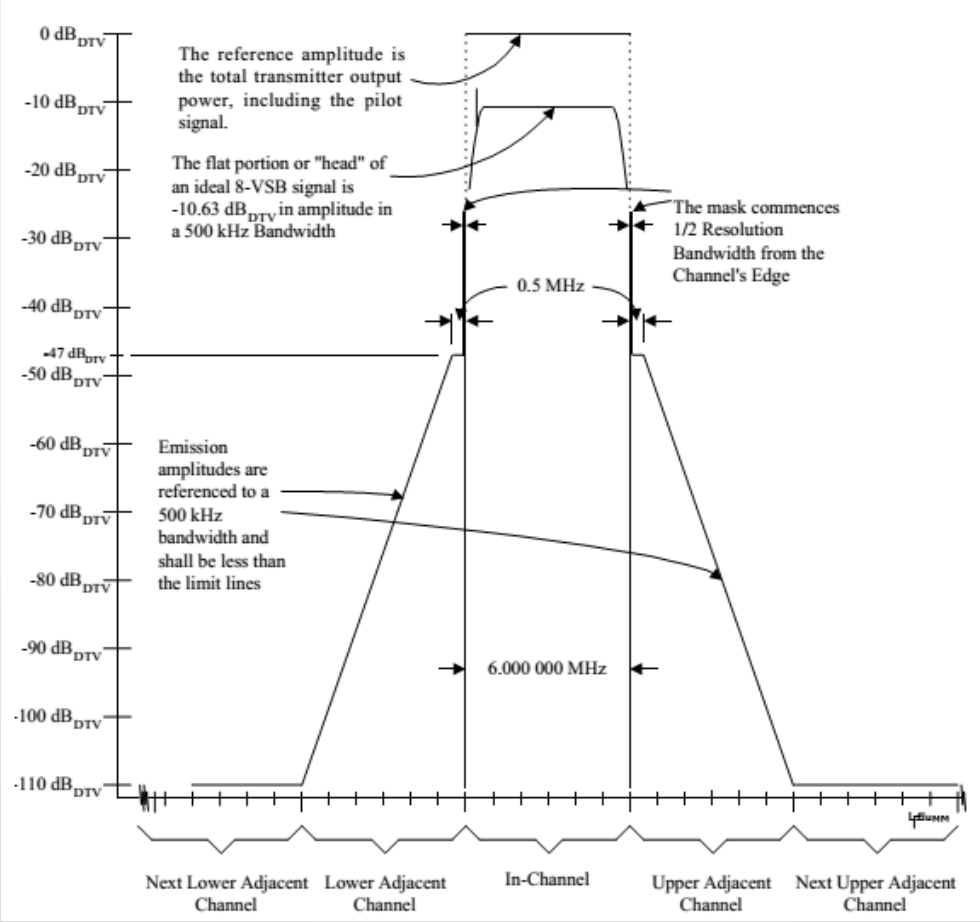
- *Primary to Secondary Interference*

$$\mathrm{SINR}(Q_R) = \frac{P_{secRX}(Q_R)}{N_0 W + I(Q_R)}$$



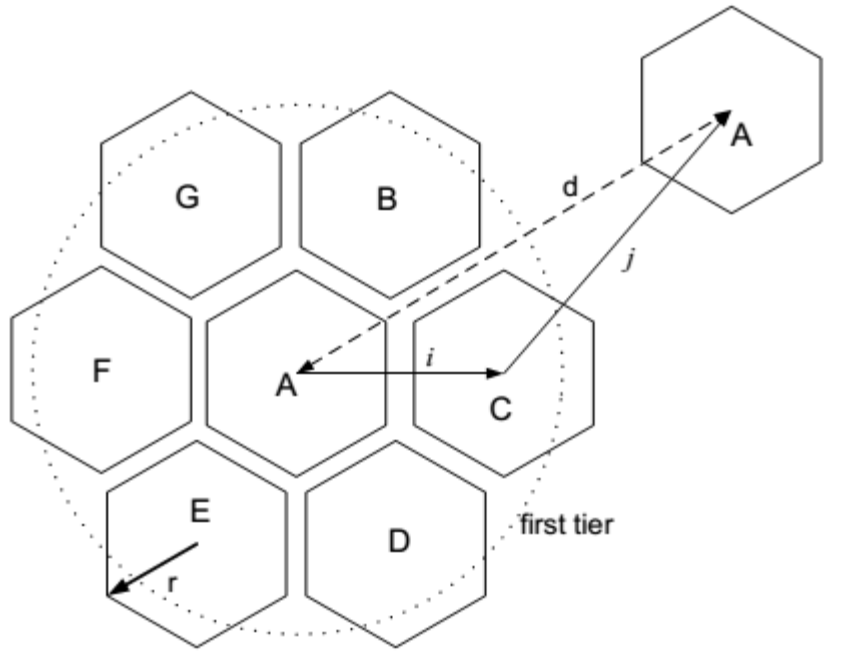
$$I_{P2S}(Q_R) = \sum_{i=1}^{N} (1-\eta) \frac{P_i G_i}{L_{TV}(d_i)} G_r + \sum_{j=1}^{M} \eta \frac{P_j G_j}{L_{TV}(d_j)} G_r$$

Interference Model ctd.



Interference Model ctd.

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



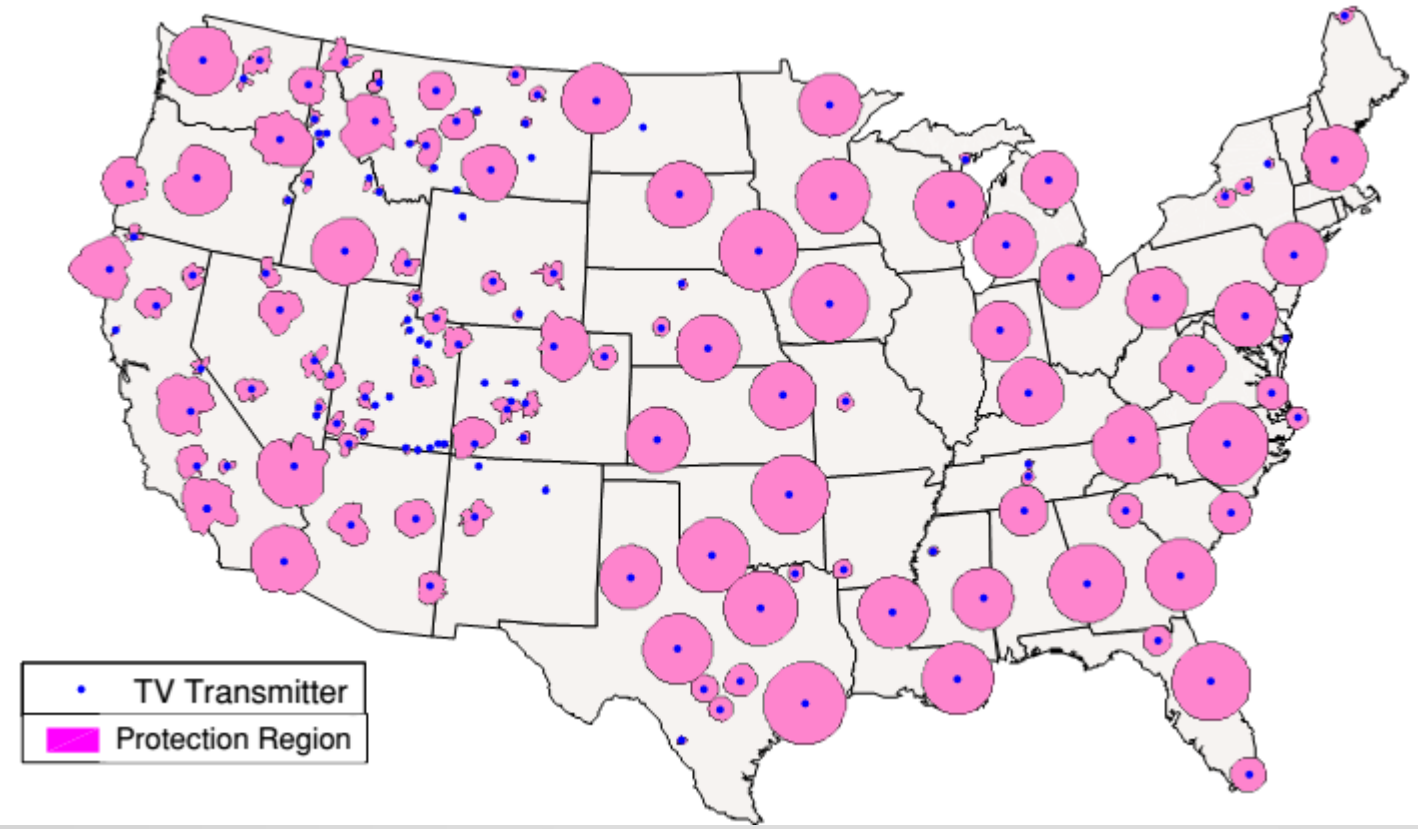
$$I_{S2S} = P_{sec,TX} G_{sec}^2 K_I \sum_{i=0}^{\infty} \sum_{j=i, j \neq 0}^{\infty} L_{sec}(D_{i,j})$$

Capacity re-defined

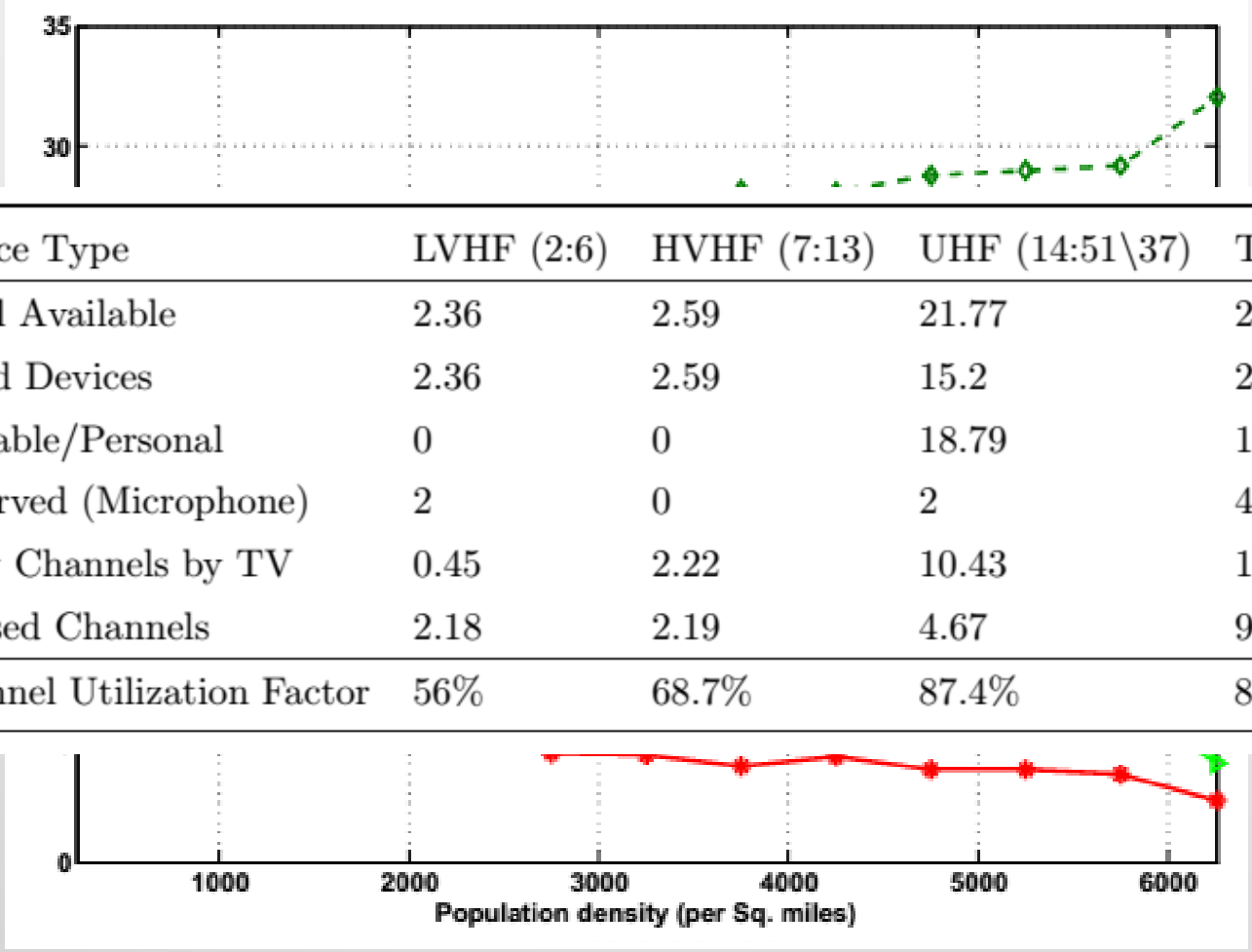
$$\overline{C_{cell}}(\Gamma) = \frac{p(\Gamma)}{K} W_0 \int_{Q_R} \log_2 \left(1 + \frac{P_{sec}/L_{sec}}{N_0 W_0 + I_{P2S}(Q_R) + I_{S2S}}\right) dQ_R$$

Numerical Calculation

- Protected Regions – Channel 13

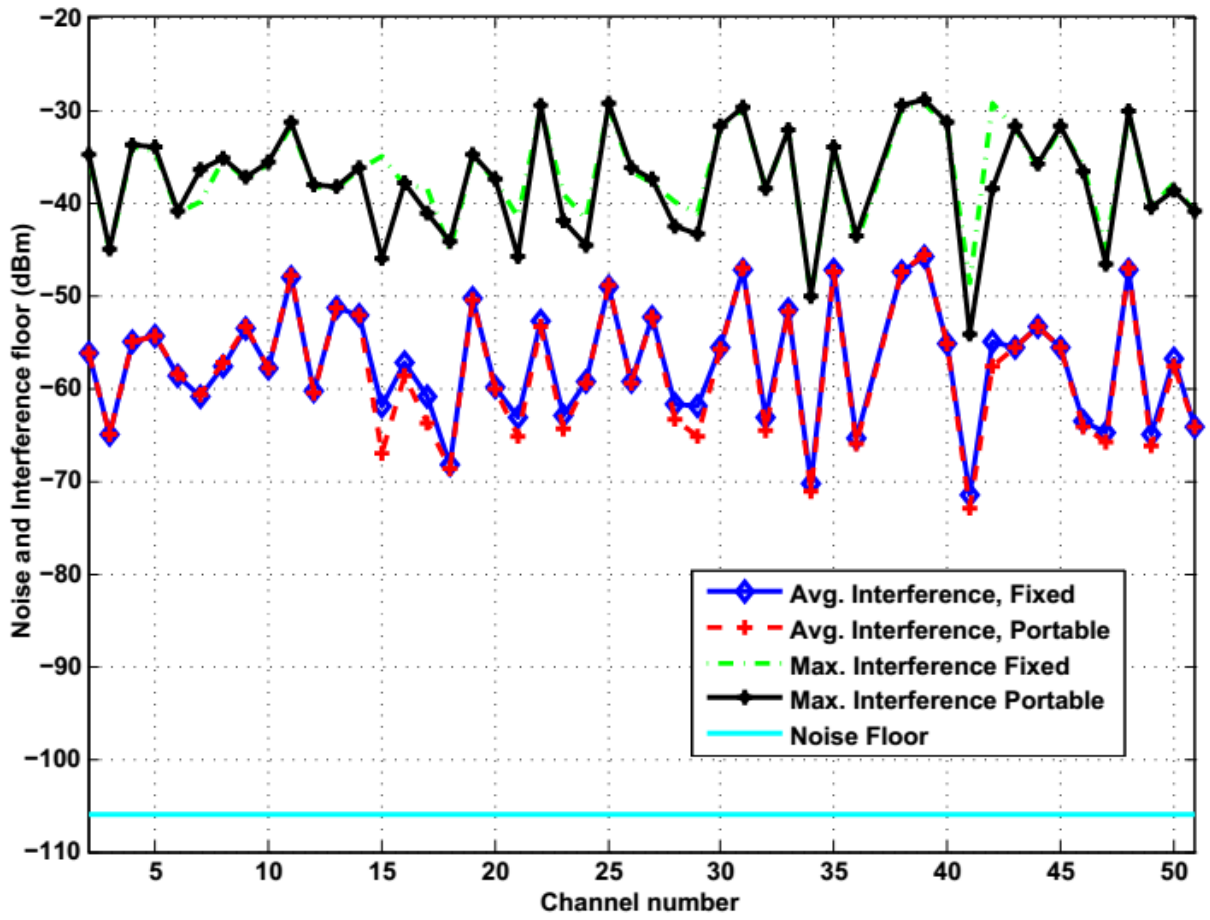


Channel Availability Statistics



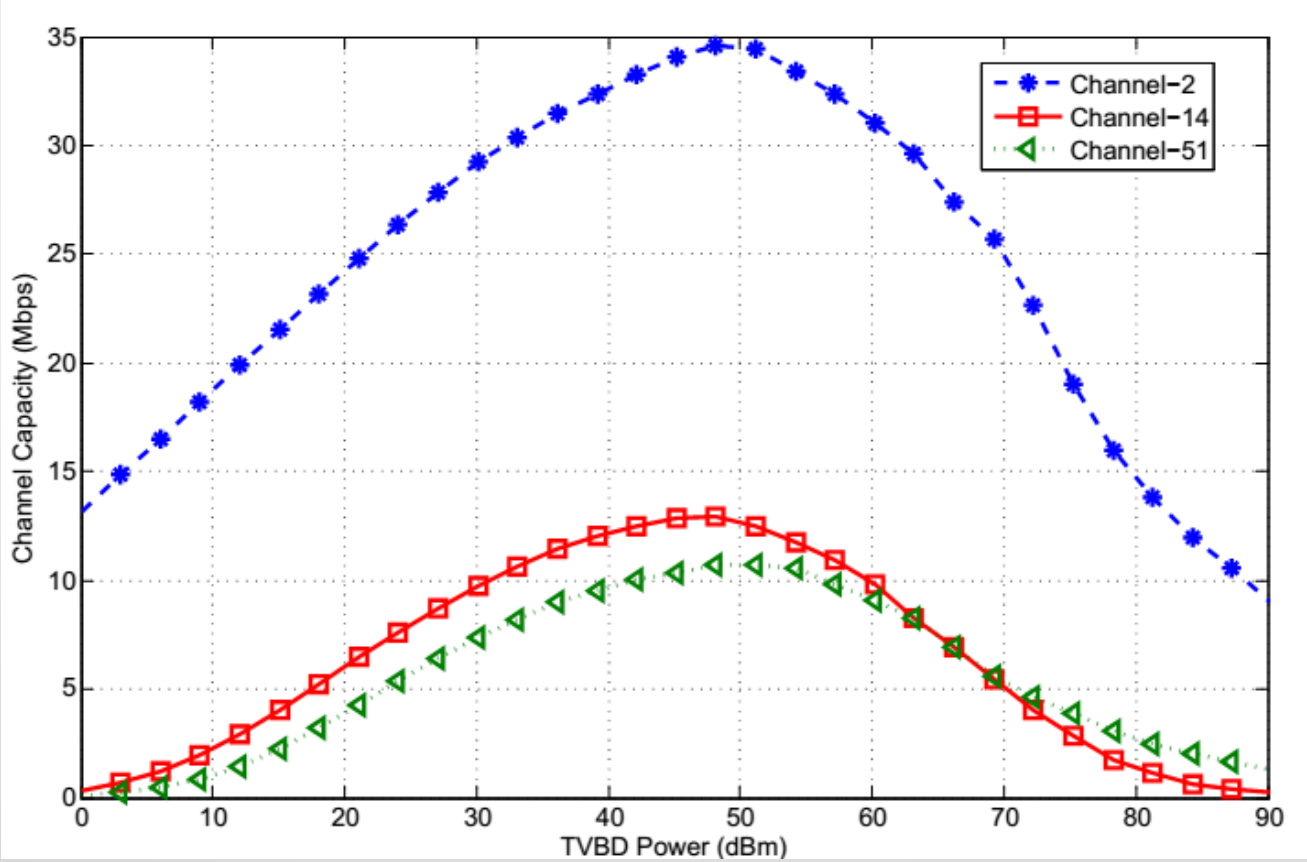
Device Type	LVHF (2:6)	HVHF (7:13)	UHF (14:51\37)	Total
Total Available	2.36	2.59	21.77	26.73
Fixed Devices	2.36	2.59	15.2	20.17
Portable/Personal	0	0	18.79	18.79
Reserved (Microphone)	2	0	2	4
Busy Channels by TV	0.45	2.22	10.43	13.11
Unused Channels	2.18	2.19	4.67	9.05
Channel Utilization Factor	56%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

Num. Results – Noise Floor



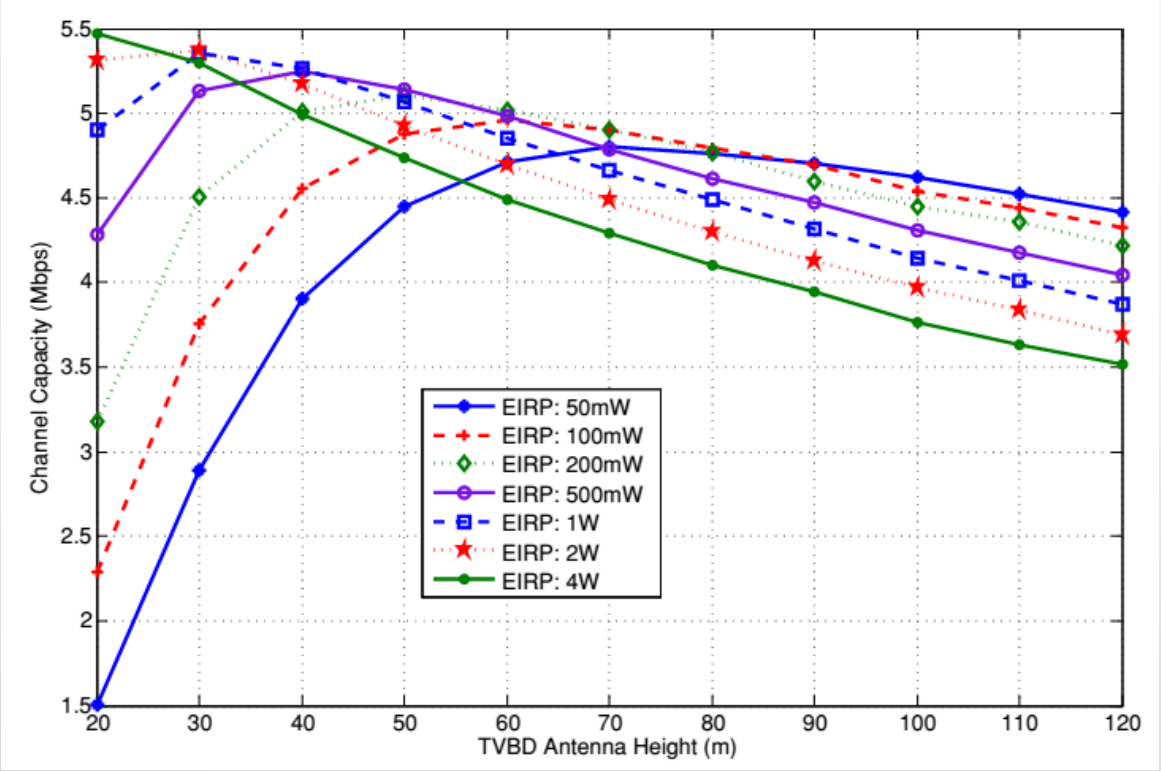
Practical Trade-offs

- Link Capacity vs. TVBD Power



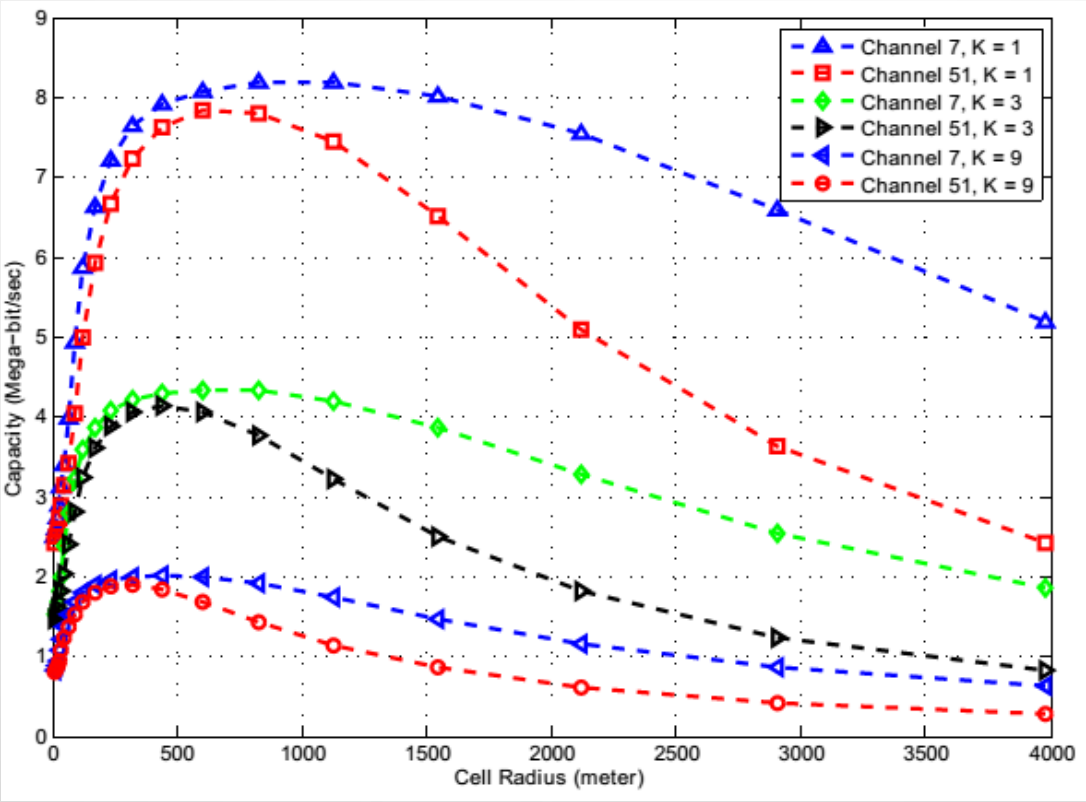
Practical Trade-offs ctd.

- Link Capacity vs. TVBD Antenna Height

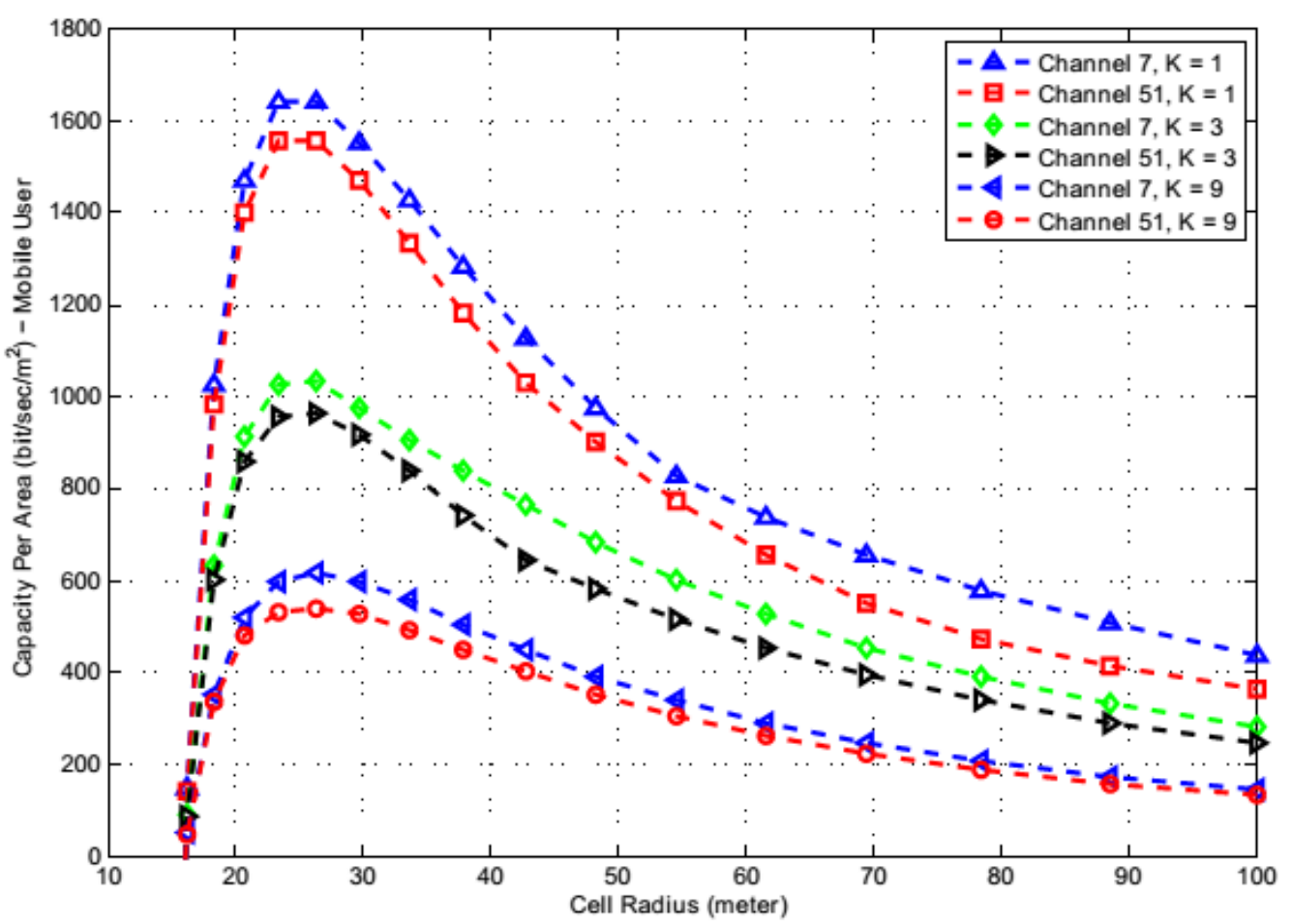


Practical Trade-offs ctd.

- Link Capacity vs. Cell Size



Practical Trade-offs ctd.



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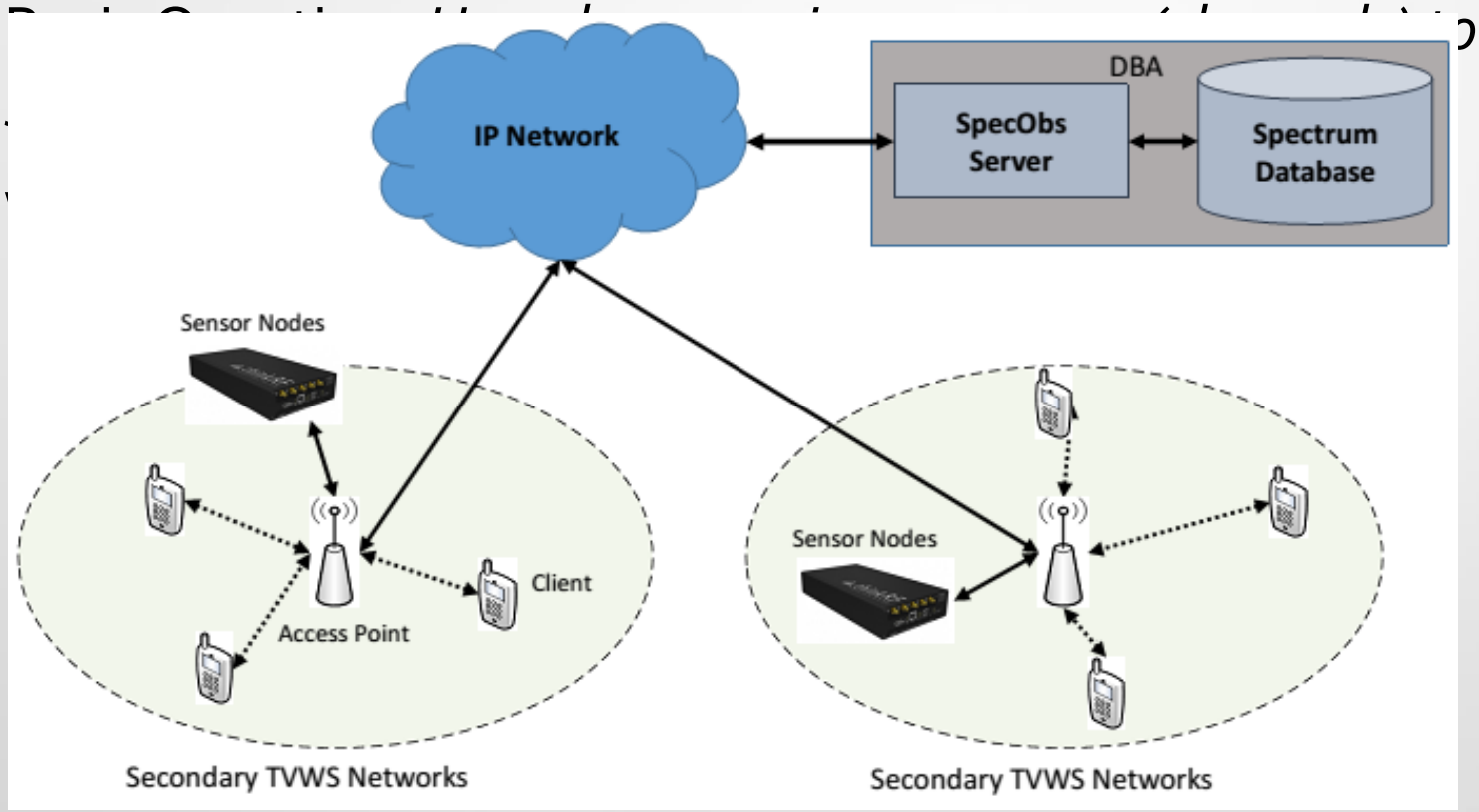
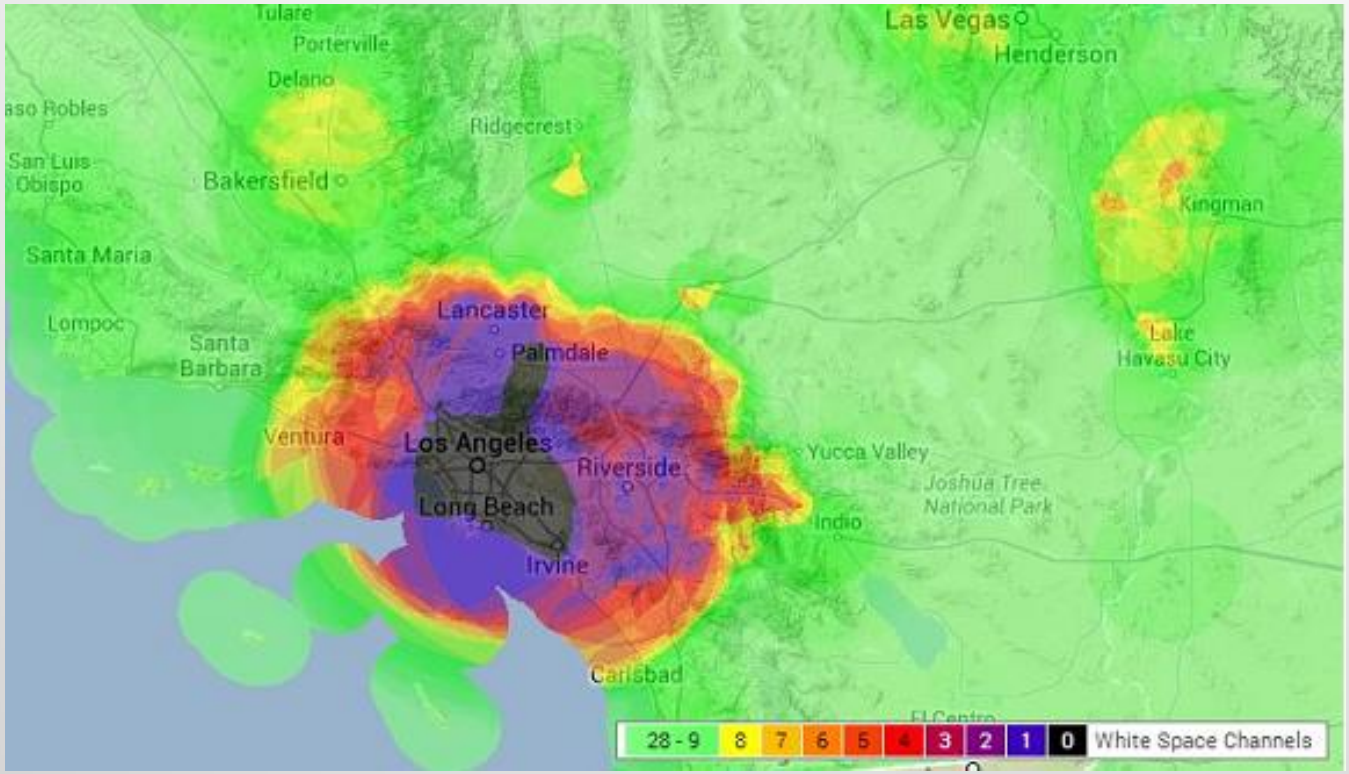
Problem Definition

- Basic Question: How do we [illegible] to
- [illegible]
- [illegible]

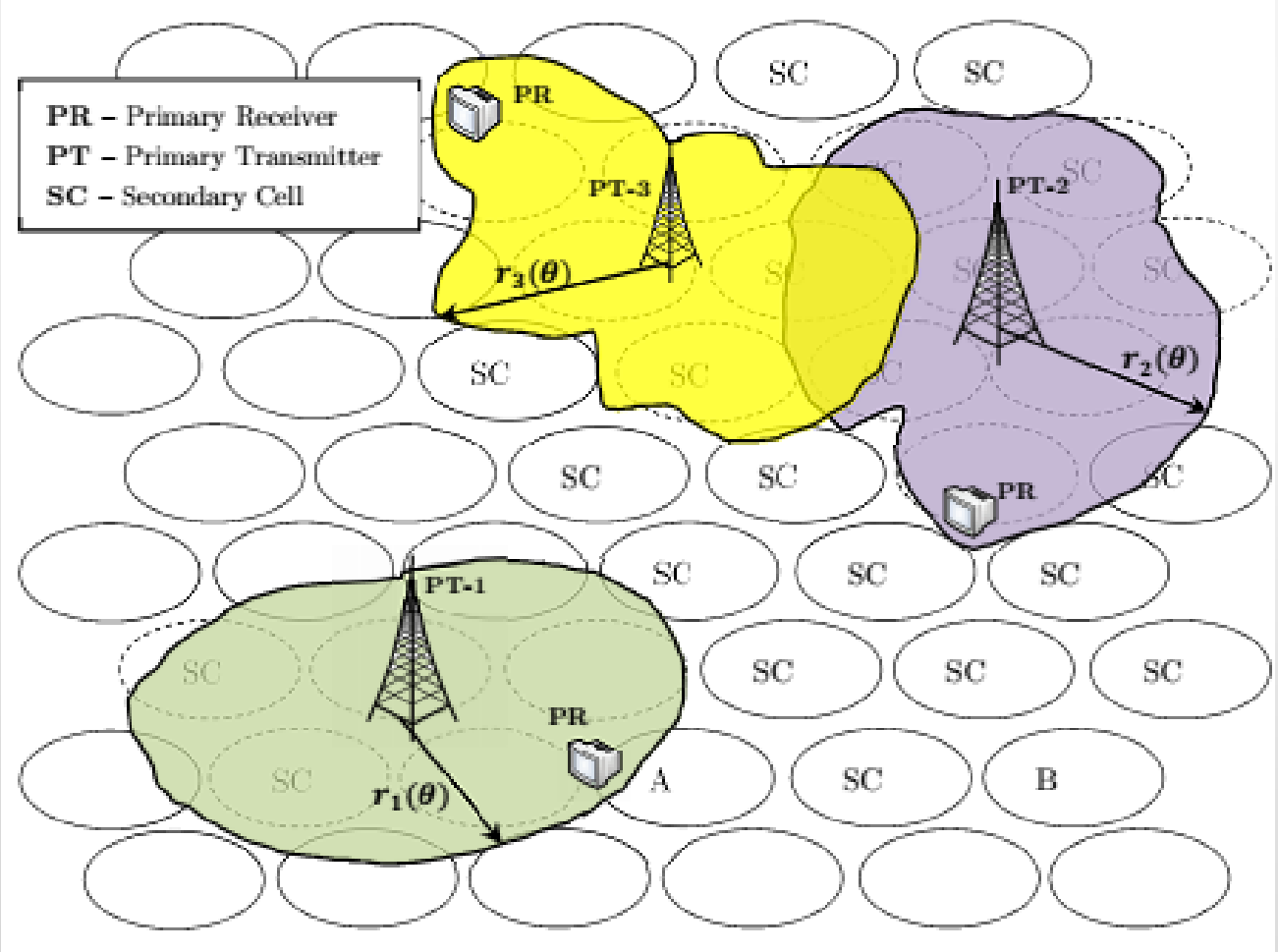


Problem Definition ctd.

- Available number of channels in Los Angeles area:

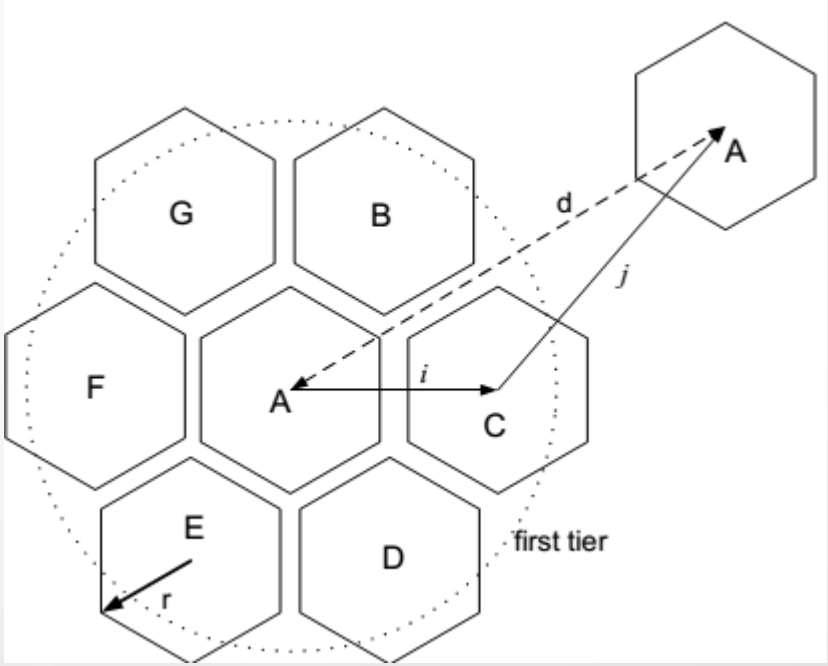


Secondary Cellular Network



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: $C = \{2,3, \dots, 36,38, \dots, 51\}$
- Available channels at cell A_i: $\Upsilon(A_i) \subseteq C$
- For $c \in \Upsilon(A_i)$ 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 $\{A_0, \dots, A_{N-1}\}$, with channel set $\{\Upsilon(A_0), \dots, \Upsilon(A_{N-1})\}$ 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:

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

$$C_i \neq \emptyset$$

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

Formulate Channel Allocation

- Pros and Cons for problem formulation-1
  - Threshold γ_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 $\{A_0, \dots, A_{N-1}\}$, with channel set $\{\Upsilon(A_0), \dots, \Upsilon(A_{N-1})\}$ a channel selection function f is desired $f: \Upsilon(A_i) \rightarrow C_i \in \Upsilon(A_i)$ so that:

$$f_{opt} = \arg\max_{f} \sum_{i=0}^{N-1} \sum_{c \in C_i} \log_2 (1 + SINR(c))$$

$$SINR(c) = \frac{P}{\sum_{j=0}^{N-1} \gamma_{i,j}(c) + \gamma_{i,P}(c) + \sigma_n^2}$$

- Subject to:

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

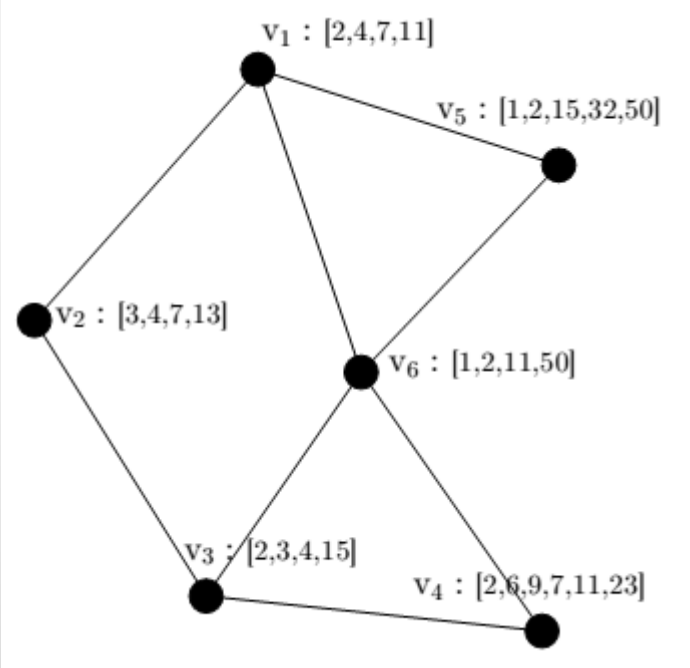
$$C_i \neq \emptyset$$

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

Solutions

- Suboptimal Greedy Algorithm for Problem 1



Greedy – Problem 1

Algorithm 1: Greedy algorithm for problem 1

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

Function `GreedyAssign()`
  while $\bigcup_{v_i \in V} \Upsilon(v_i) \neq \emptyset$ **do** ▷ some channels left unassigned
    $v_{cur} \leftarrow$ select $v \in V$ with min $|C(v)|$ and min $|\Upsilon(v)| \neq 0$ ▷ current cell
    $c_{\min} \leftarrow$ select $c \in \Upsilon(v_{cur})$ with min `InterferingNodes`(v_{cur}, c)
    $C(v_{cur}) \leftarrow C(v_{cur}) \cup c_{\min}$ ▷ assign selected channel to current cell
    $\Upsilon(v_{cur}) \leftarrow \Upsilon(v_{cur}) \backslash \{c_{\min}\}$ ▷ remove selected channel from set of available channels
    `UpdateChannels`$(c_{\min}, v_{cur})$
  end while
  return

Function `InterferingNodes`(v_{cur}, c)
  $V_n \leftarrow$ set of neighbors of v_{cur}
  $V_{shrd}(c) \leftarrow \{v \in V_n : c \in \Upsilon(v)\}$
  $V_{own}(c) \leftarrow \{v \in V_n : c \in C(v)\} \cup \{v_{cur}\}$
  count $\leftarrow$ number of $v \in V_{shrd}(c)$ for which `TotalInterference`$(c, v) > \gamma_t$
  return count

Greedy – Problem 1 ctd.

```
Function UpdateChannels(c, v_cur)
    V_n ← set of neighbors of v_cur; V_shrd(c) ← {v ∈ V_n : c ∈ ϒ(v)};
    V_own(c) ← {v ∈ V_n : c ∈ C(v)}
    forall the v ∈ V_shrd(c) do                    ▷ Check every nodes that has c available
        V_own(c) ← V_own(c) ∪ {v}                  ▷ Temporarily assign channel c to node v
        if TotalInterference(c, V_own(c)) > γ_t then    ▷ If any channel crosses
        threshold
            ϒ(v) ← ϒ(v)\{c}
        end if
        V_own(c) ← V_own(c)\{v}                    ▷ Remove temporarily channel assignment
    end forall
    return
```

Optimal – Problem 1 ctd.

- Channel availability vector $A_i^{|C|\times 1} \in \{0,1\}^{|C|\times 1}$
- Channel assignment vector $\mathcal{L}_i^{|C|\times 1} \in \{0,1\}^{|C|\times 1}$

$$\mathcal{A} = \begin{bmatrix} \mathcal{A}_0 \\ \mathcal{A}_1 \\ \dots \\ \mathcal{A}_{N-1} \end{bmatrix}, \mathcal{L} = \begin{bmatrix} \mathcal{L}_0 \\ \mathcal{L}_1 \\ \dots \\ \mathcal{L}_{N-1} \end{bmatrix}$$

Optimal – Problem 1 ctd.

- Integer Linear Programming:

$$\max_{\mathcal{L}} \mathbf{1}^T.\mathcal{L}$$

Subject to:

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

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

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

$$\gamma_t + [1 - \mathcal{L}(i|\mathcal{C}|+k)]\Lambda$$

NLIP Solution – Problem 2

- Non-linear IP:

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

Subject to:

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

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

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

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

$$i, k = 0, ..., N-1$$

Greedy – Problem 2

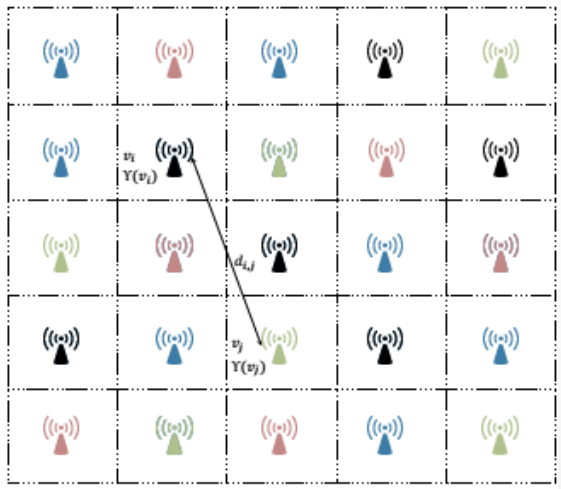
Algorithm 2: Greedy algorithm for problem 2

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

Function `TotalThroughput`$(c,\ V)$
  Input: V: Set of nodes, c: specific channel
  $f \leftarrow 0$
  forall the $v_i \in V$ **do** ▷ Assume c is assigned to all nodes in V
    $I \leftarrow \gamma_{i,P}(c) + \sum_{v_j \in V \setminus \{v_i\}} \gamma_{i,j}(c)$
    $f \leftarrow f + \log_2\left(1 + \frac{P}{I+\sigma_n^2}\right)$
  end forall
  return f
Function `RemoveNeighbors`(c)
  $D_1 \leftarrow \{v | c_i \in C(v)\}$; $D_2 \leftarrow \{v | c_i \in \Upsilon(v)\}$
  forall the $v_j \in D_2$ **do**
    if `TotalThroughput`$(c,\ D_1 \cup v_j) <$ `TotalThroughput`$(c,\ D_1)$ **then**
      $\Upsilon(v_j) \leftarrow \Upsilon(v_j) \setminus c_{\max}$
    end if
  end forall

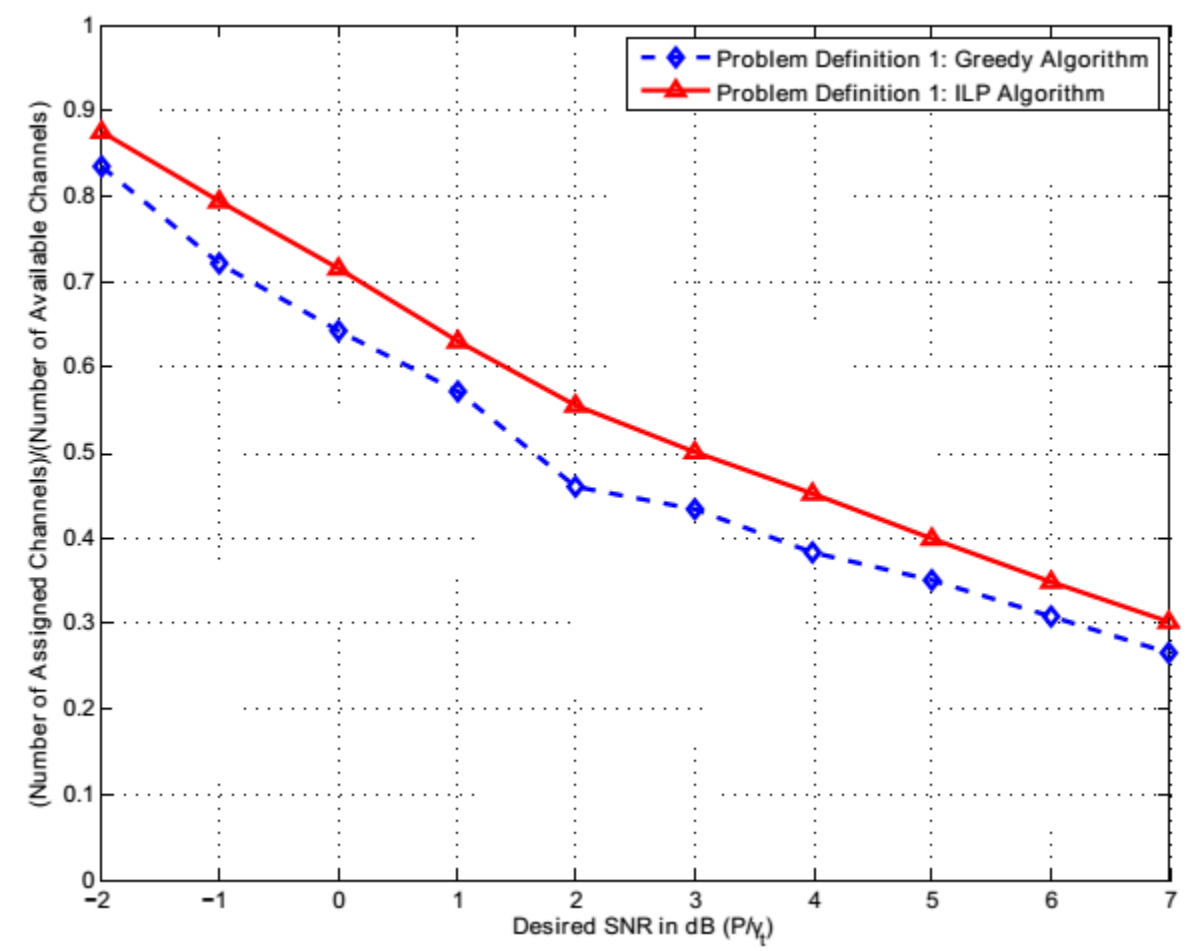
    end forall
    if `TotalThroughput`$(c_i,\ D_1) > f_{\max}$ **then**
      $f_{\max} \leftarrow$ `TotalThroughput`$(c_i,\ D_1)$; $c_{\max} \leftarrow c_i$
    end if
  end forall
  return $c_{\max}$

Numerical Results



Parameter	Value
Number of nodes $\lvert V \rvert$	25
Number of channels $\lvert \mathcal{C} \rvert$	10
Available channels $\Upsilon(v)$	$\sim U[3,5]$
Primary Interference $\gamma_{i,P}(.)$	$\sim U[0.0, 0.1]$
Secondary User's Power	1.0
Mutual Interference $\gamma_{i,j}$	$\propto \frac{P}{d_{i,j}^2}$
Noise Power σ_n^2	0.01

Numerical Results



Numerical Results ctd.

- Problem 1 vs. Problem 2

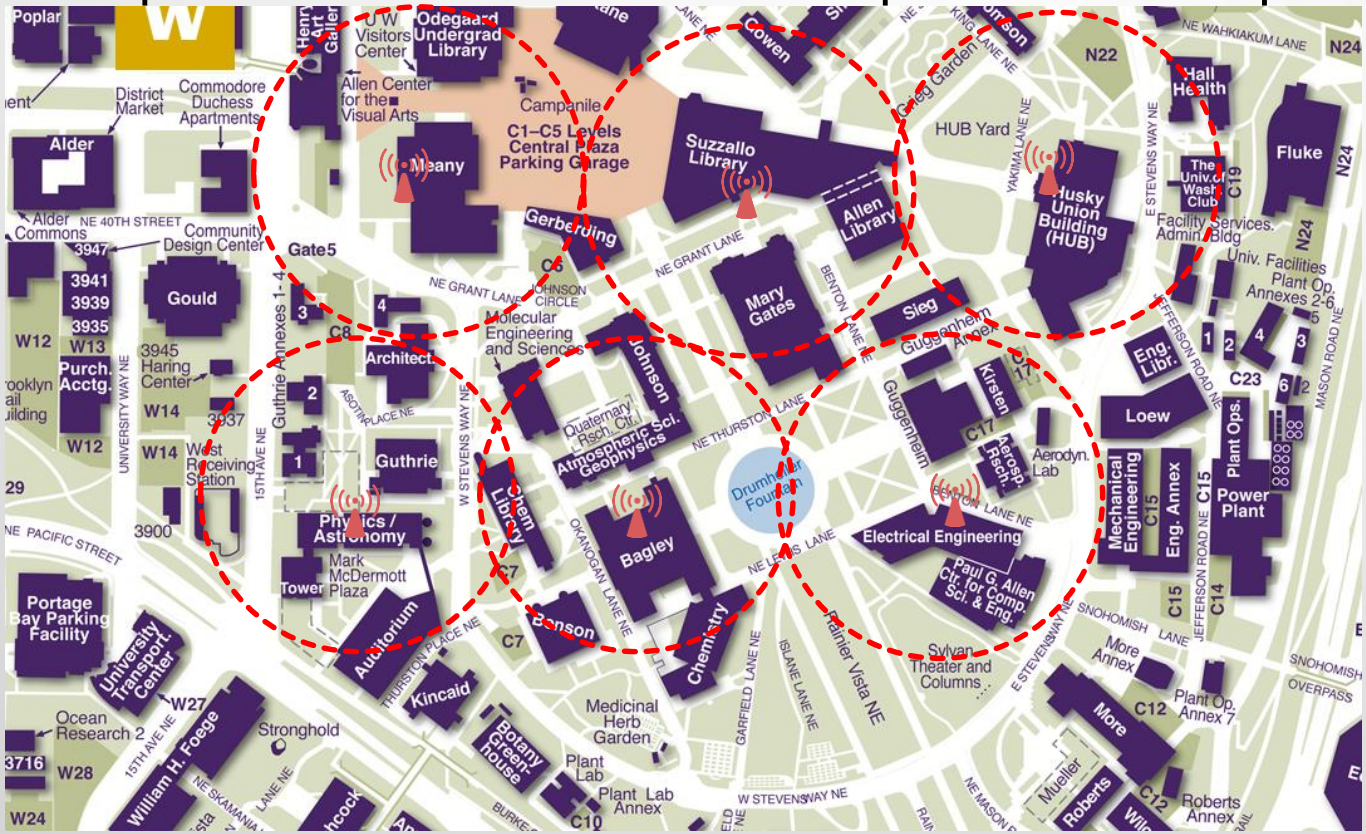
Method	Norm. No. Assigned Channels	Norm. Throughput
Greedy Prob. 2 with IQP	0.534	0.976
Greedy Prob. 2 with Heuristic	0.546	0.973
ILP Prob. 1	0.5	1.005
Greedy Prob. 1	0.57	0.88

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**

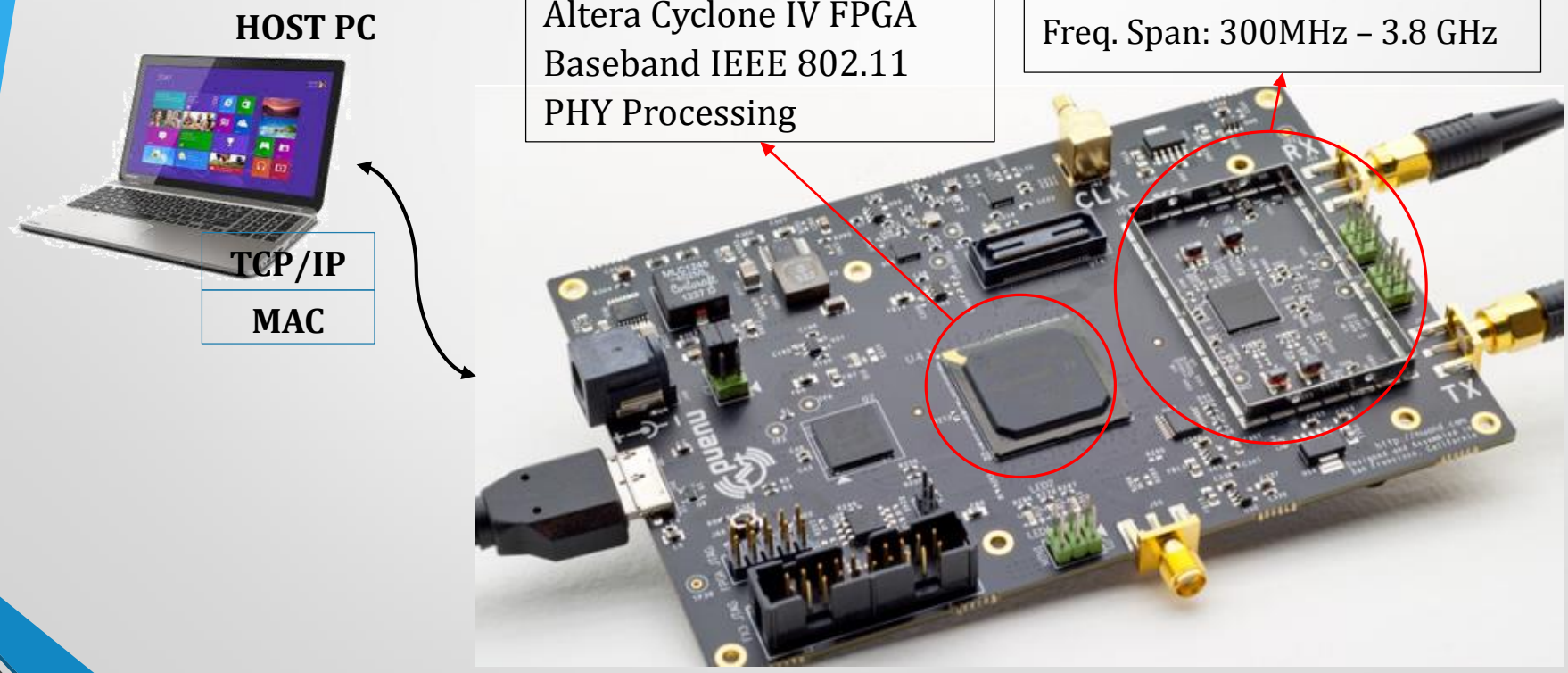
T VWS Network Design

- Campus Wide TVWS Network as proof of concept



TVWS Network Design

- Hardware

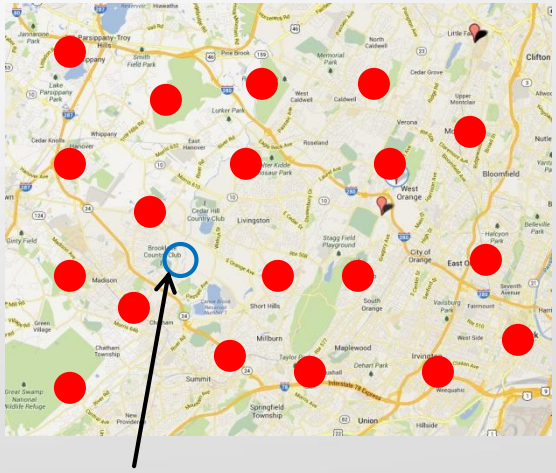


TVWS Network Design

- 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

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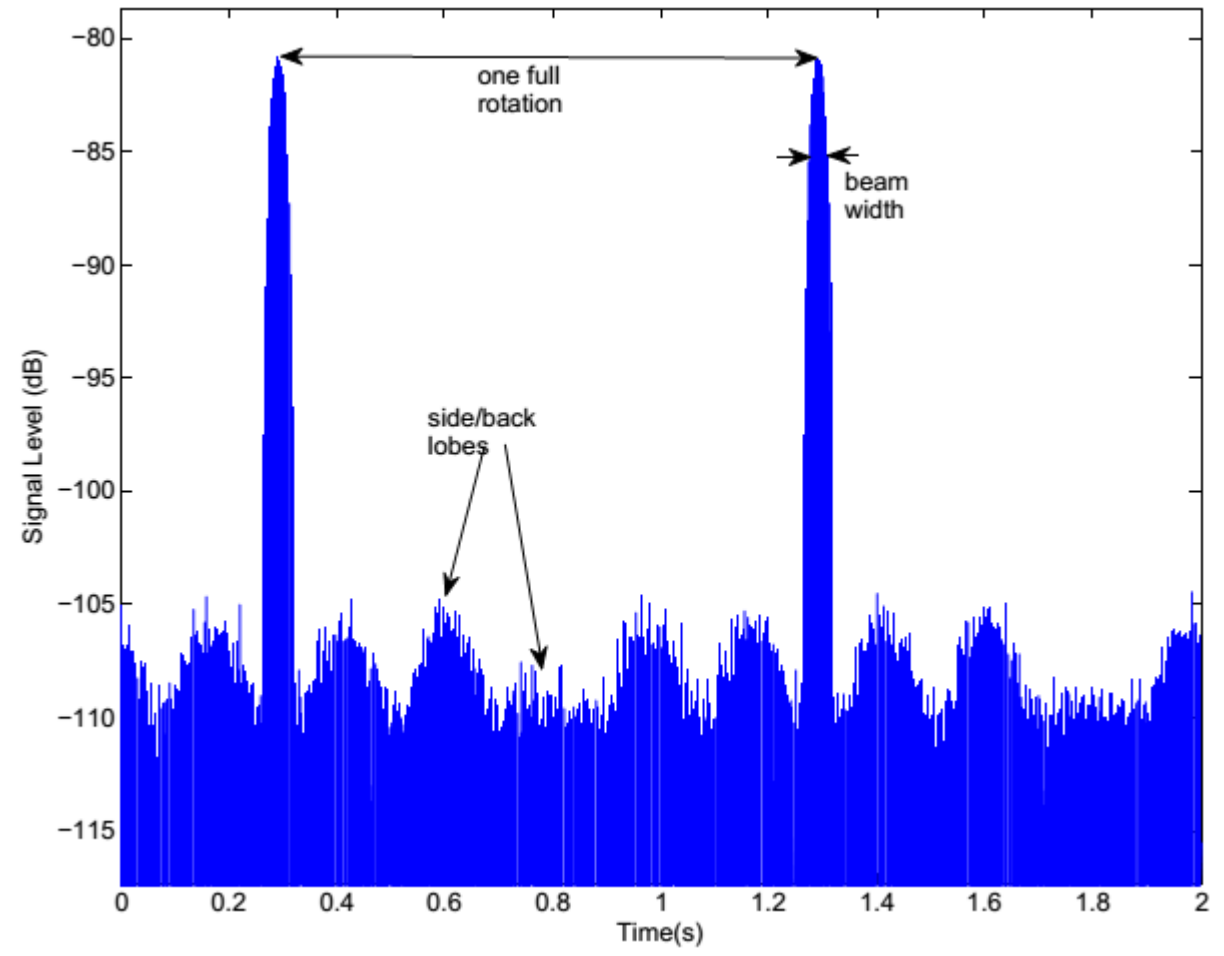

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Publications and Patents

- F. Hessar, S. Roy, "Capacity Considerations for Secondary Networks in TV White Space", minor revision for publication in IEEE Transaction on Mobile Computing.
- F. Hessar, S. Roy, "Resource Allocation Techniques for Cellular Networks in TV White Space Spectrum", in Proc. IEEE Symposium on New Frontiers in Dynamic Spectrum DYSPAN'14, 2014.
- F. Hessar, C. W. Kim and S. Roy, "Receiver Oriented Network Management", Provisional Patent, C4C 2014.
- F. Hessar, S. Roy, "Energy Based Performance Evaluation of Passive EPC Gen 2 Class 1 RFID Systems", in IEEE Transaction On Communication, 2013.
- F. Hessar, S. Roy, "Minimum Energy Source Coding for Asymmetric Modulation with Application to RFID", in Proc. 2013 IEEE International Conference on RFID (RFID 2013). Nominated for Best Paper Award.

Thank You

Question?