Cognitive Radio for Efficient Spectrum Use

Jad Nasreddine
Institute for Networked Systems
RWTH Aachen University

COST Action IC0902 and Network of Excellence ACROPOLIS joint 2011 First Summer School on Cognitive Wireless Communications July 12-15, 2011, Florence, Italy

Starting Points ...

Why cognitive radio?

How to implement it?

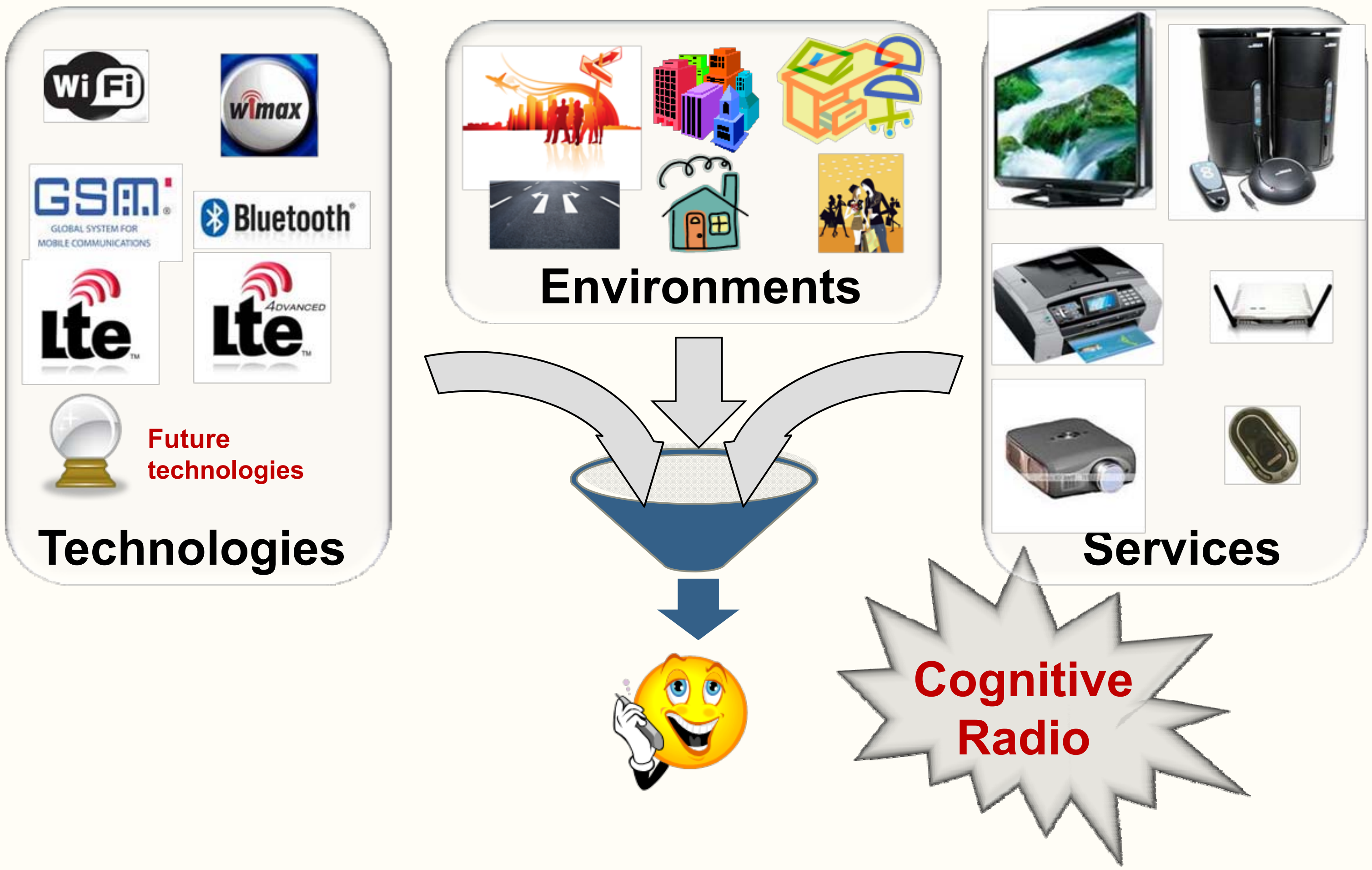
What is cognitive radio?

Where to use it?

What have we achieved?

What are the possible roadmaps?

Need for Intelligent Equipments and Networks



Outline

- General overview
- DSA to spatial spectrum holes
- DSA to spatio-temporal spectrum holes
- Uncertainty in propagation models
- Related standards
- Summary and open problems

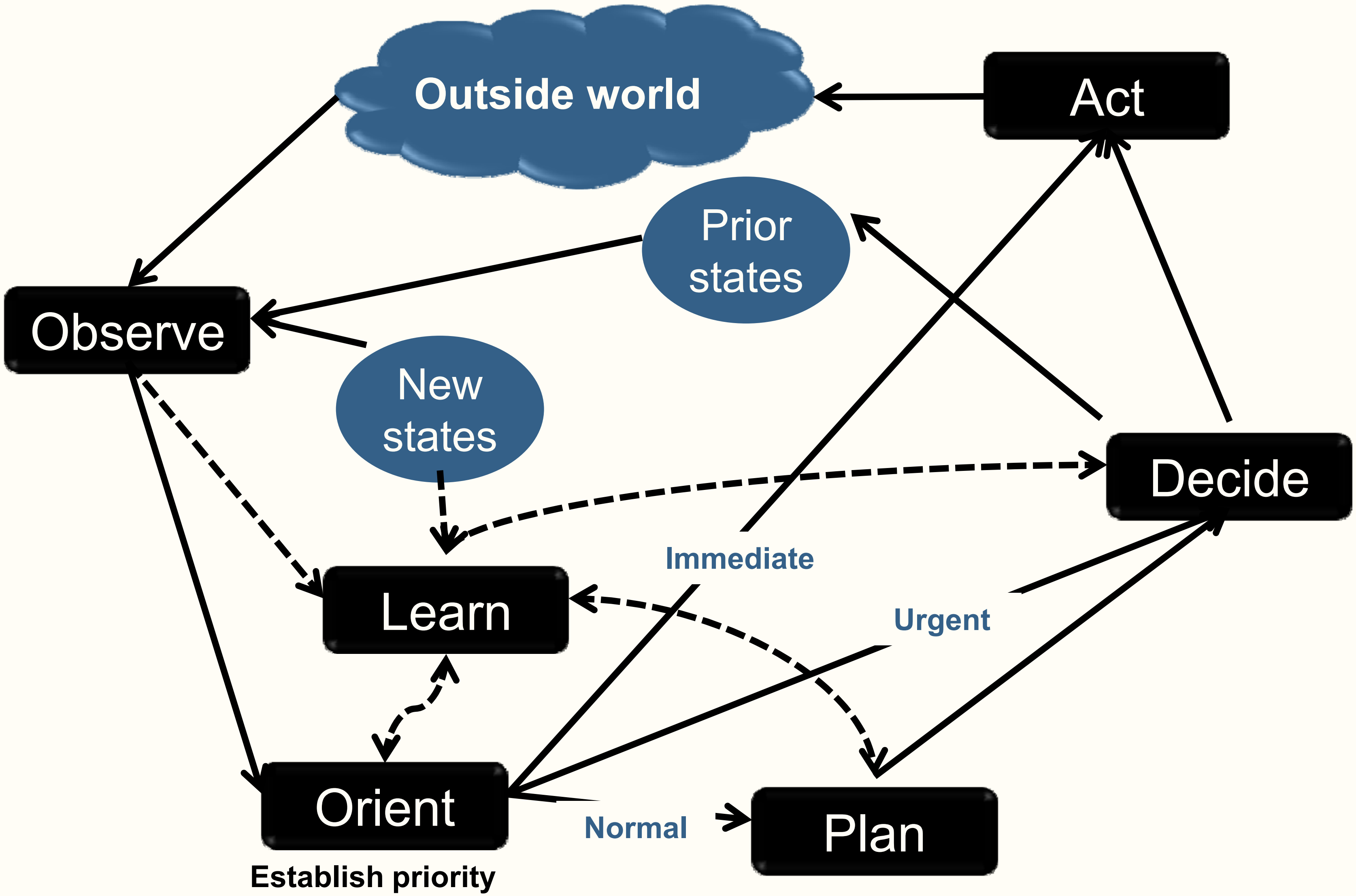
Mitola's Cognitive Radio

"The cognitive radio identifies the point at which wireless PDAs and the related networks are sufficiently computationally intelligent on the subject of radio resources and related computer-to-computer communications

- To detect **user communications needs as a function of use context**, and
- To **provide radio resources and wireless services most appropriate to those needs**"

J. Mitola, Cognitive radio: An integrated agent architecture for software defined radio, Doctor of Technology, Royal Inst. Technol. (KTH), Stockholm, Sweden, 2000.

Cognition Cycle



J. Mitola, "Cognitive Radio for Flexible Mobile Multimedia Communications," IEEE Mobile Multimedia Conference, 1999, doi: 10.1109/MOMUC.1999.819467

But then ...

"A radio that can change **its transmitter parameters** based on interaction with its environment in which it operates"

(FCC 2005)

"A radio or system that senses, and is aware of, its operational environment and can dynamically and autonomously **adjust its radio operating parameters** accordingly"

(ITU Radio Communication Study Group 2004)

"A cognitive radio is a radio frequency transmitter/ receiver that is designed to intelligently **detect whether a particular segment of the radio spectrum is currently in use**, and to jump into (and out of, as necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmissions of other authorized users"

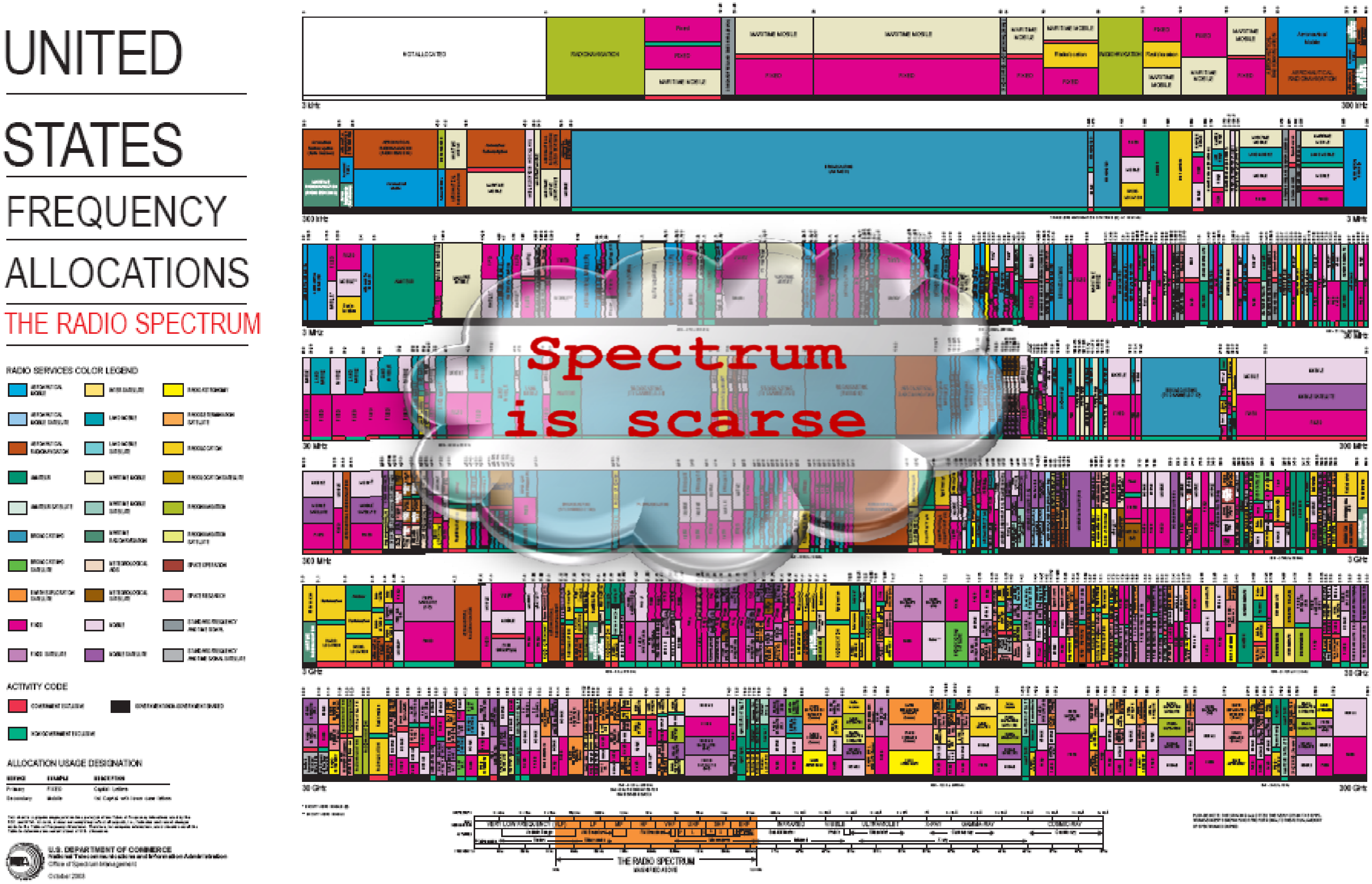
(IEEE-USA Board of Directors 2003)

CR Classification

- “CR-0: Not a cognitive radio; pre-programmed behavior, possibly SDR
- CR-I: Spectrum agile radio; exploits Dynamic Spectrum Allocation/Access **(DSA)**
- CR-II: Smart Cognitive Radio, Mitola Radio with Artificial Intelligence/Learning capabilities; requires
  1. Goal orientation; aware of environment
  2. Aware of the context; aware of user goals
  3. Models environment; self-awareness
  4. Analyses, optimizes, and plans its operations yet”

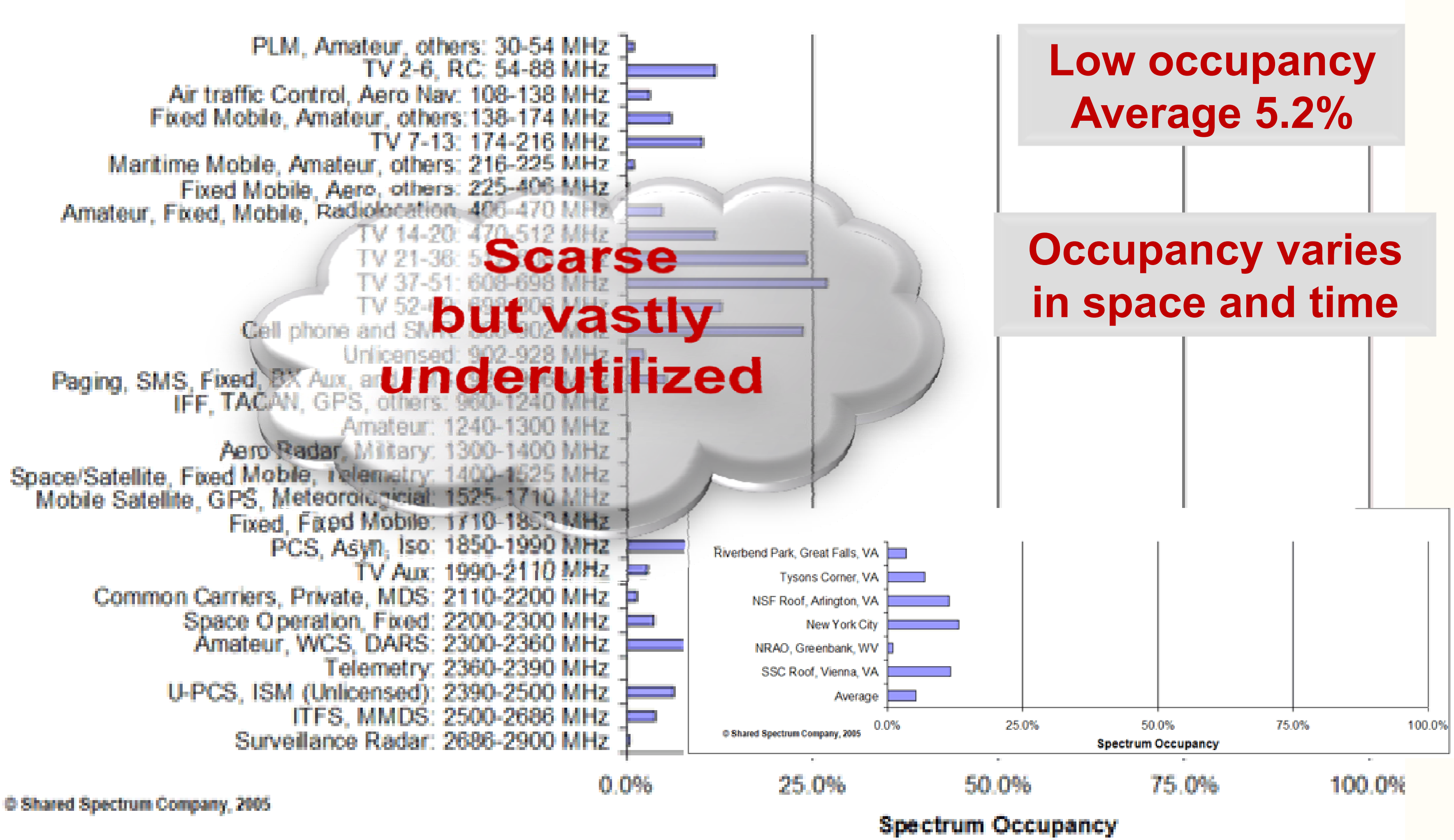
J. Mitola, Cognitive Radio Architecture, J. Wiley & Sons, New York, 2006

Current Spectrum Allocation



http://www.ntia.doc.gov/osmhome/allochrt.pdf

Example of Current Spectrum Use (USA)



http://www.sharedspectrum.com/measurements/#

In Summary ...

- "Spectrum access and not spectrum scarcity reduces spectrum efficiency (FCC)"

Future wireless networks
« Dynamic Spectrum Management»

Flexible spectrum allocation	Architecture and algorithms	New technologies and equipments
Regulators	**Operators**	**Manufacturers**

« High spectrum efficiency »
High profits for IT companies
New emergent services
Low radiations

FCC, Spectrum Policy Task Force, "Report of the Spectrum Efficiency Working Group," Nov. 15, 2002

Possible Evolution

Coordinated Dynamic Spectrum Access*

Centralized spectrum management
No priorities

The term DSA will refer to this approach in the following

Primary and Secondary Networks

Opportunistic access of secondary
Higher priority of primary

Fully shared spectrum

Opportunistic access
No priorities

* M. M. Buddhikot, K. Ryan, “Spectrum Management in Coordinated Dynamic Spectrum Access Based Cellular Networks,” *IEEE DySpan,* 2005 , doi: 10.1109/DYSPAN.2005.1542646

Primary Network Categories

- Broadcast Networks (First step):
  - Example: TV
  - Advantage: Low frequency and stable transmission
  - Constraint: Receiver detection is difficult
- Cellular Networks:
  - Example: GSM, UMTS, CDMA-2000, LTE, LTE-A
  - Advantage: Uplink and downlink bands are jointly allocated, existence of pilot channel
  - Constraint: Dynamic traffic and frequency use, multiple transmitters, pervasive coverage, power control, different services, mobile transmitters and receivers, etc.
- Detect-and-avoid based networks:
  - Example: WiFi
  - Advantage: Existence of pilot channels
  - Constraint: opportunistic access to spectrum
- Push-to-talk like networks:
  - Always listening to the channel even if there is no transmission

Bruce A. Fette, Ed., Cognitive Radio Technology. Elsevier,2006

Setting the Scene

Regulator

- Defining policies and rules
- Defining allowed information exchange

Primary network

- Release of spectrum holes for a period of time
- Determining interference constraints
- Monitoring interference constraints

Information exchange

Secondary network

- Characterization of spectrum holes
- Respect of primary constraints
- Guaranteeing acceptable QoS levels

Information Exchange

No information exchange

Standard and regulator information
- Allocated bands for different RATs and power limits
- Acceptable interference levels (should be fixe)

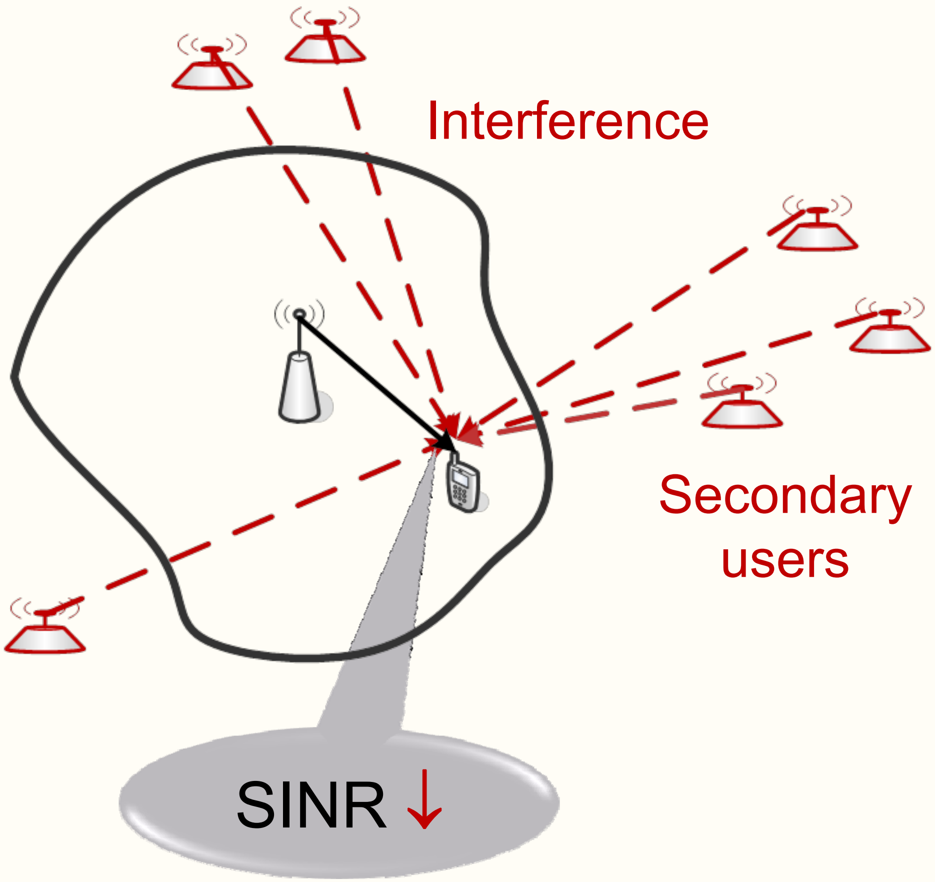
Limited information exchange

Can be through a broker or direct exchange
- Dynamic acceptable interference levels
- Traffic patterns

Full information exchange

Secondary is owned by primary network
- Receiver position distribution
- Possibility of decoding control channels

Spectrum Holes and Primary Protection



Primary network has to sacrifice

In time domain

Each primary receiver is satisfied in at least X% of time

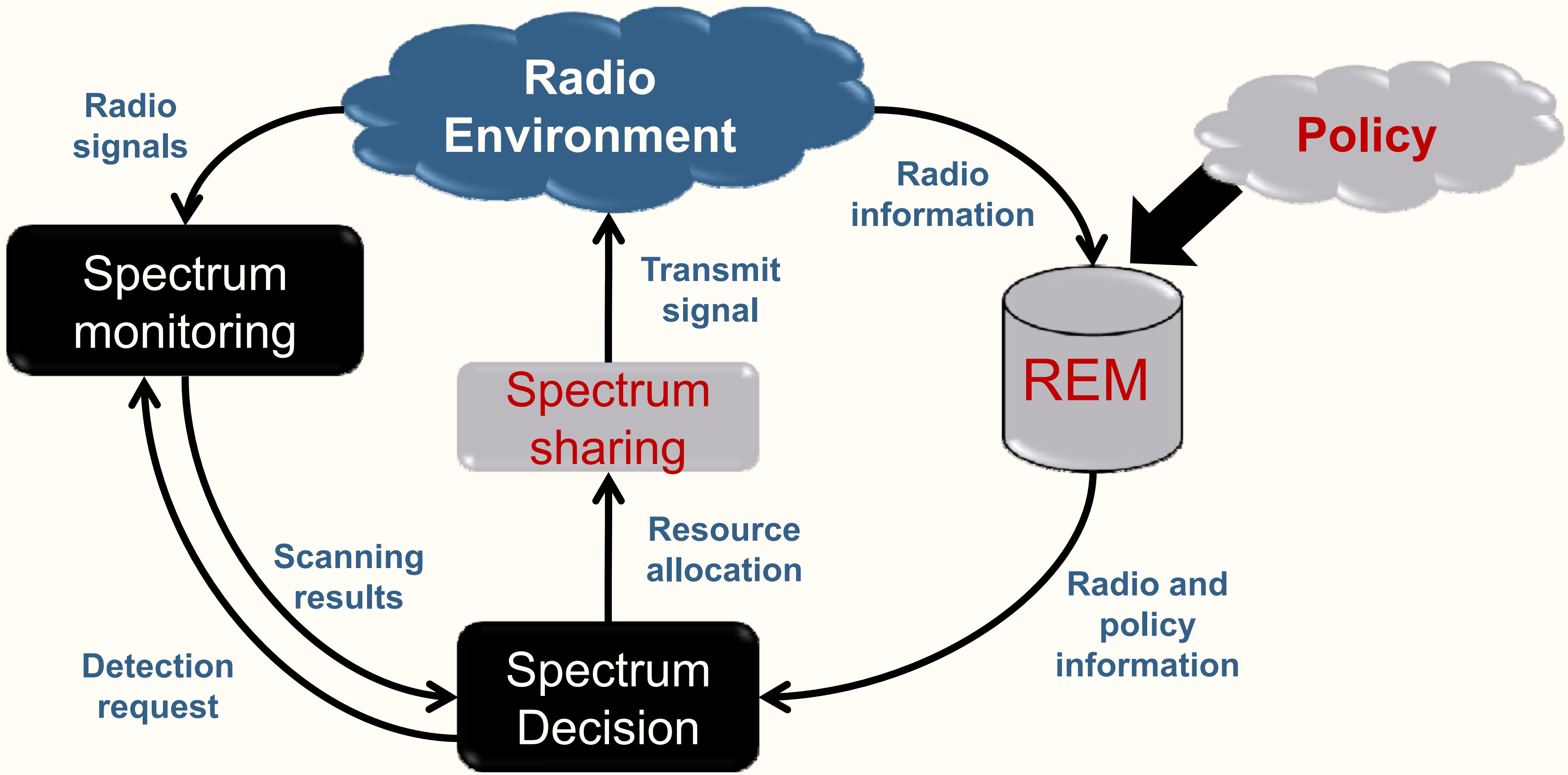
In space domain

At least X% of primary users are satisfied at a given period of time

In power

Increase transmission power

Cognitive Cycle Becomes DSA Cycle



Enabling Technologies

- Software Defined Radio (SDR)
  - Allows spectrum agility
- Cheap mobiles with high performance
  - Integrated positioning techniques and increasing storage capacity
- Flexible access technologies (OFDMA, TDD, UWB)
  - Allows more flexible spectrum allocation
- Antennas
  - Smart antennas, beamforming
- Self-organized networks
  - Minimization of Drive Tests (MDT), Femtocells

Outline

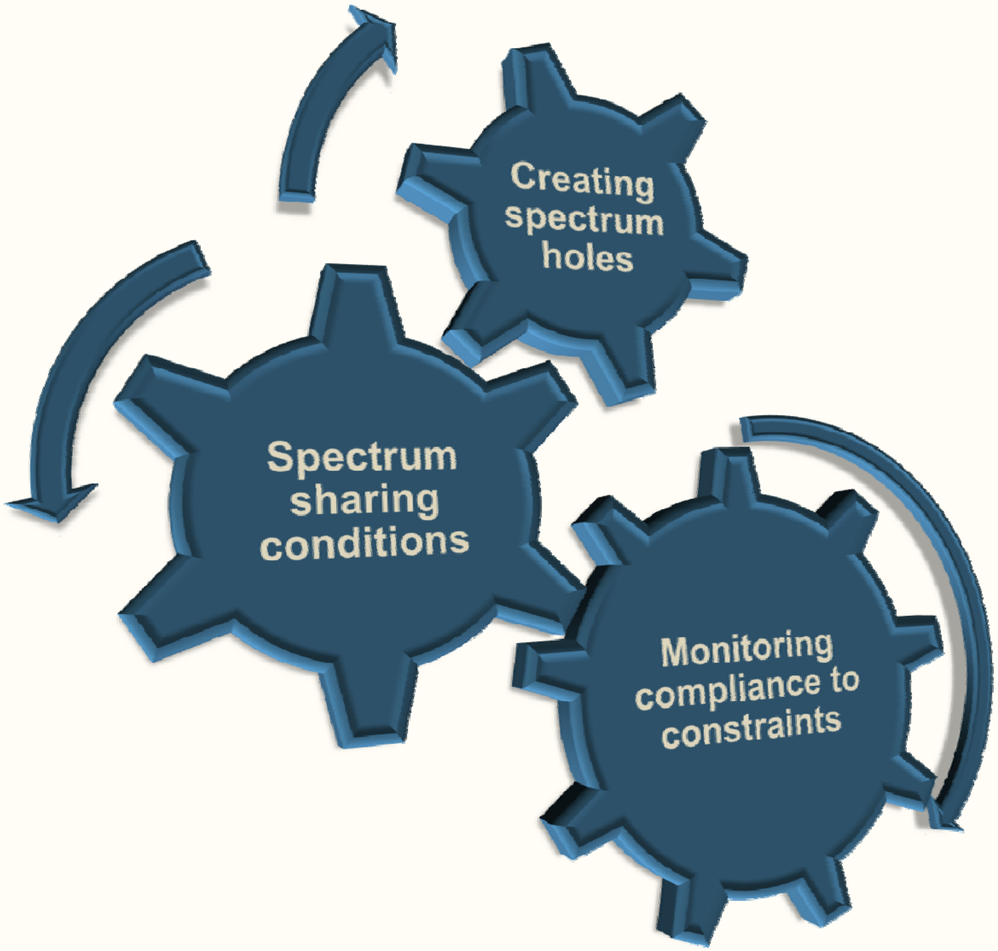
- General overview
- DSA to spatial spectrum holes
- DSA to spatio-temporal spectrum holes
- Uncertainty in propagation models
- Related standards
- Summary and open problems

Motivations

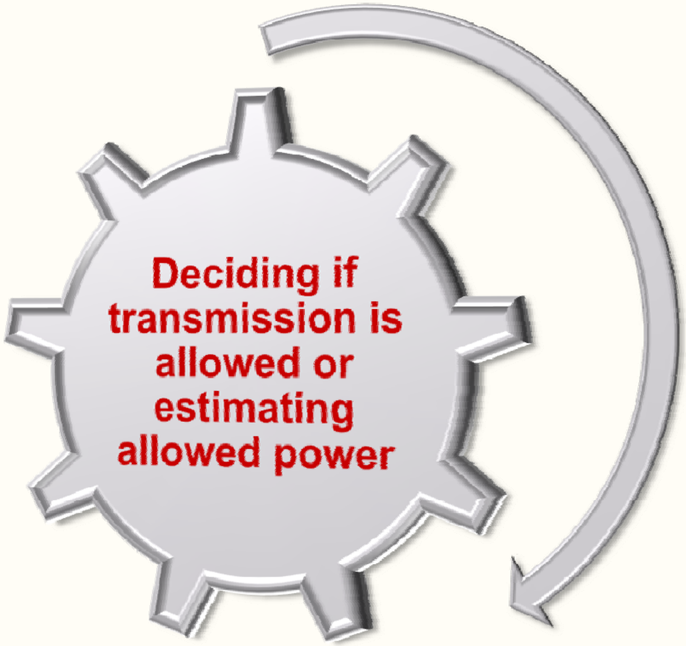
- VHF/UHF bands between 54 MHz and 862 MHz
  - Low frequencies → low propagation losses
- Frequency reuse
  - Creation of large zones where some channels are not used
- Known position of TV transmitters and constant transmission characteristics
- Good understanding of propagation patterns

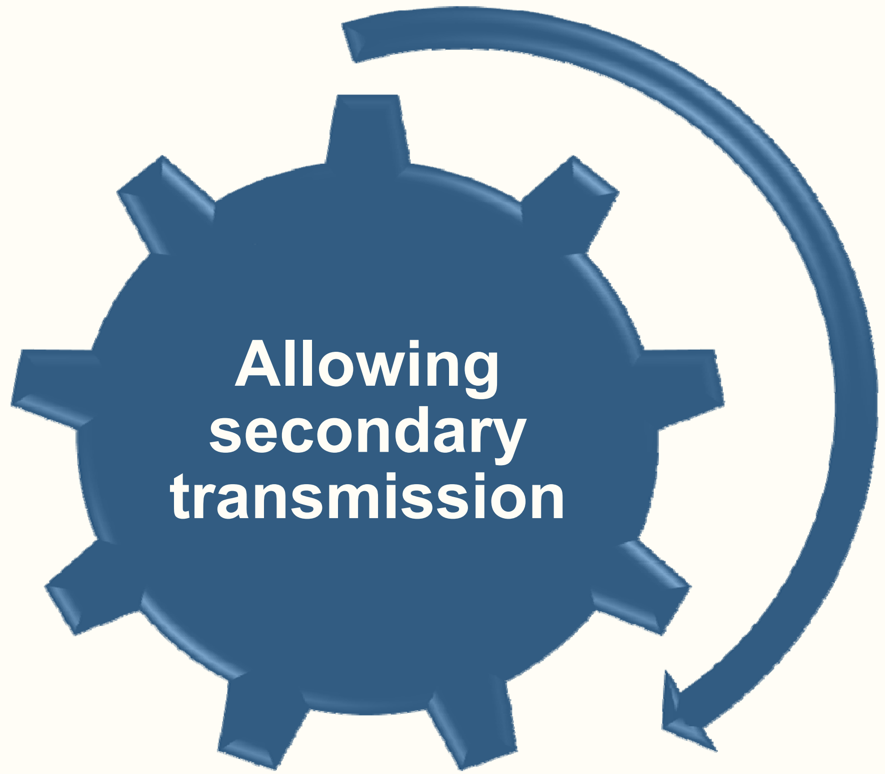
Creating and Using Spatial Holes

Allowing secondary transmission

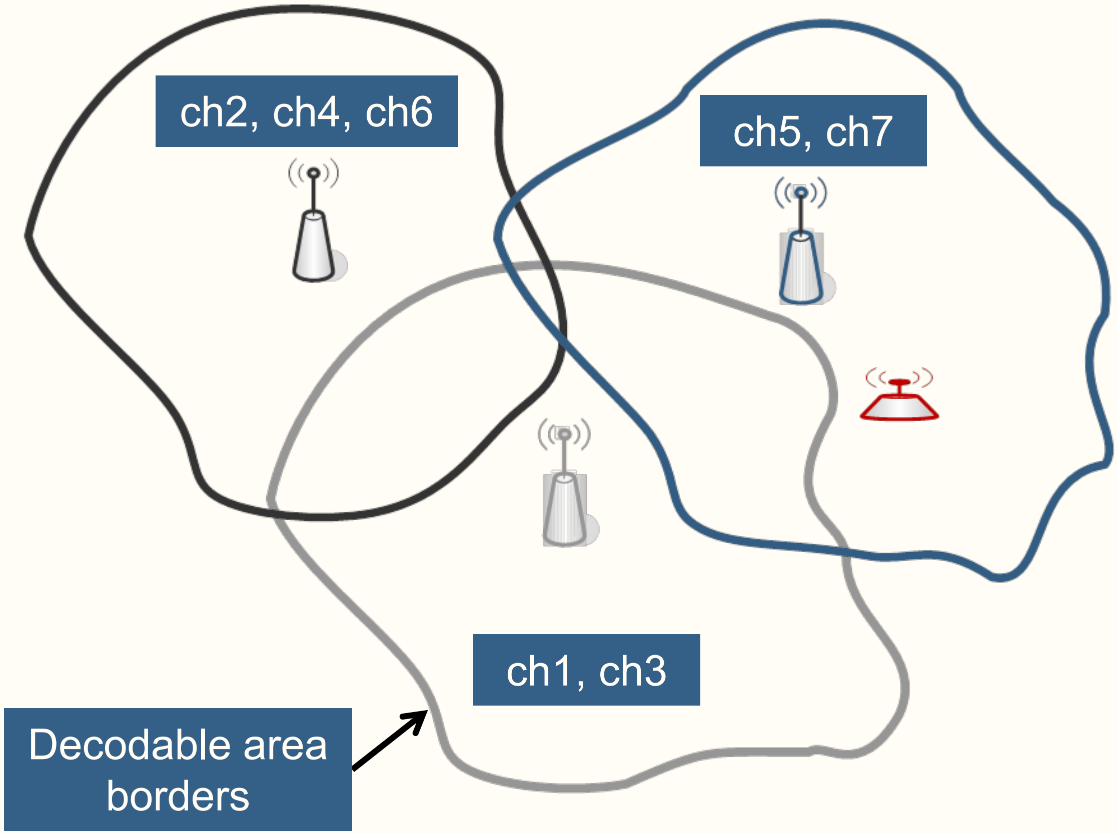


Using Spectrum holes



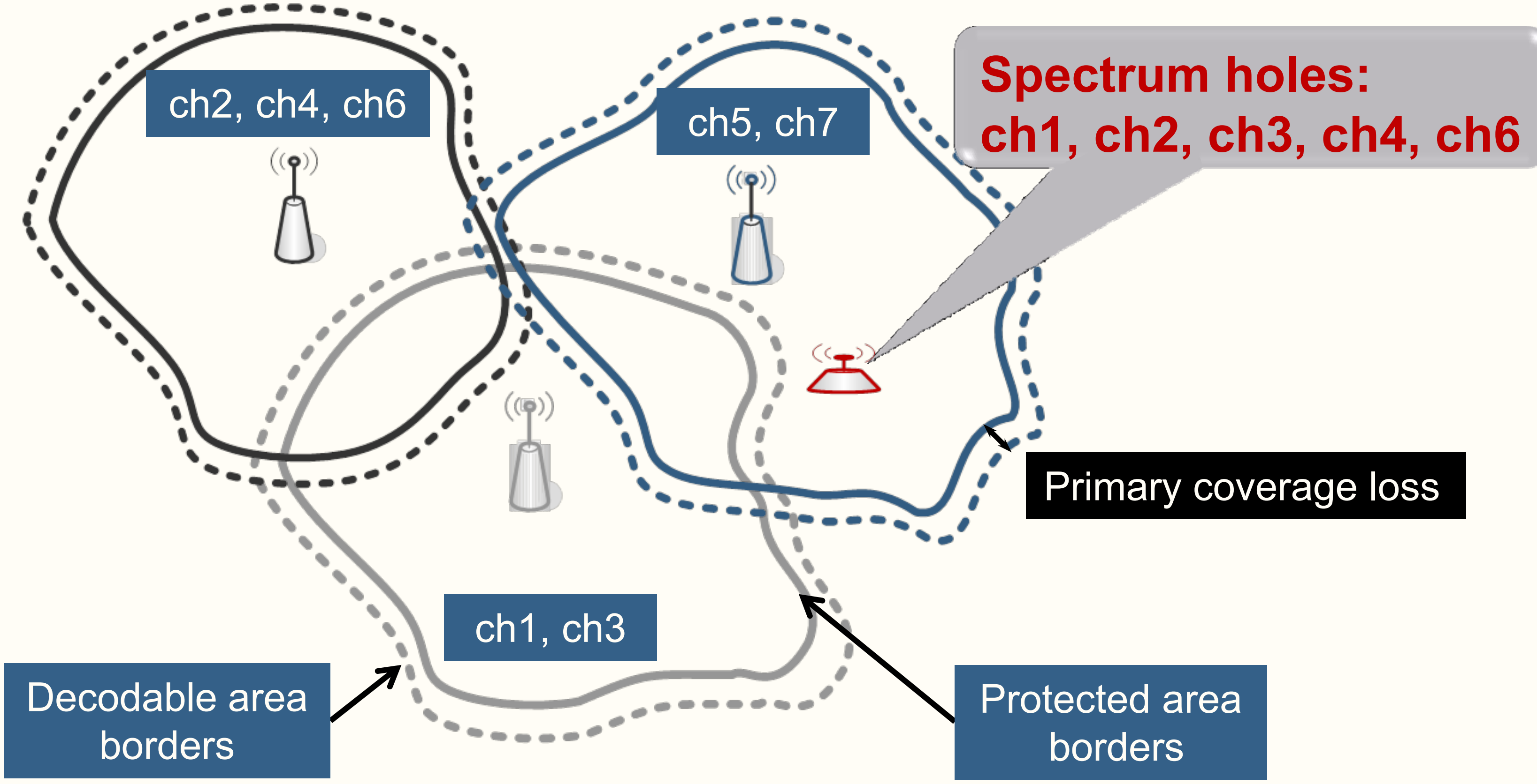

Allowing secondary transmission

Spectrum Hole Concept



Spectrum Hole Concept

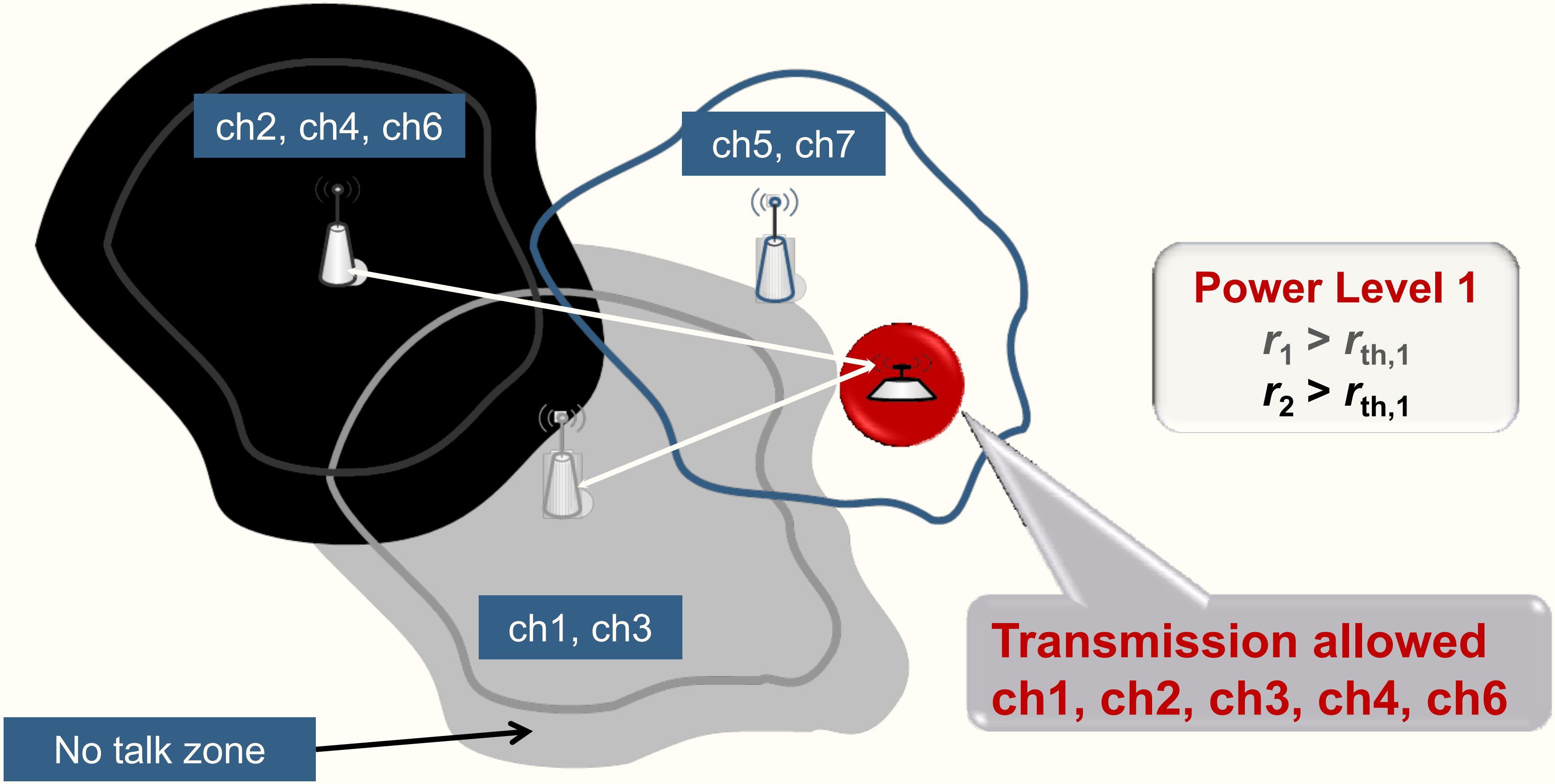
Allow secondary transmission → Erosion in the SINR (or coverage area)*



* Anant Sahai, Kristen Woyach, Kate Harrison, Hari Palaiyanur, and Rahul Tandra, "Towards ``A Theory of Spectrum Zoning'’," Allerton, October 2009.

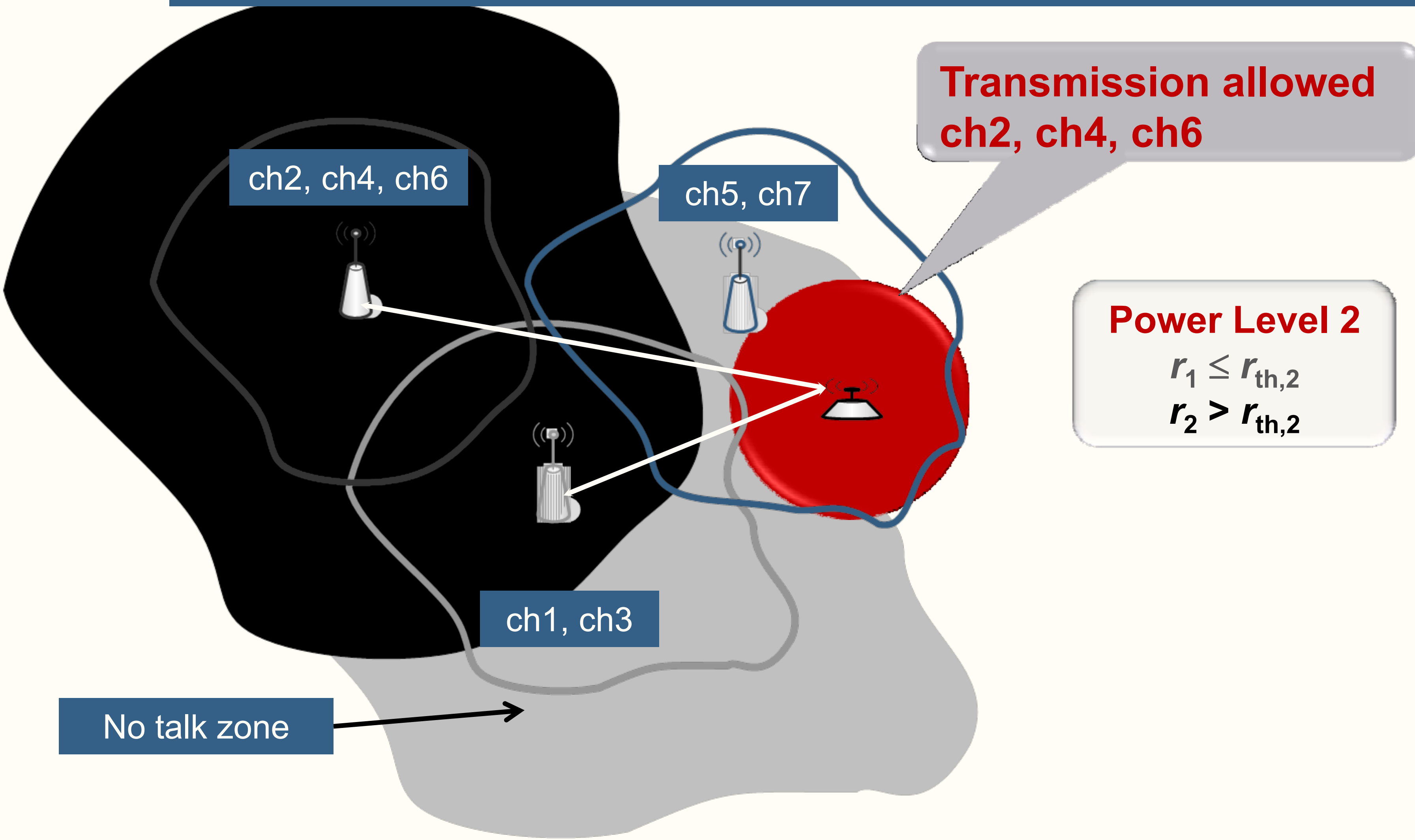
Allowed Transmit Power and No-talk Zone

Secondary power $P \rightarrow$ Allowed transmission at distance r higher than r_{th}

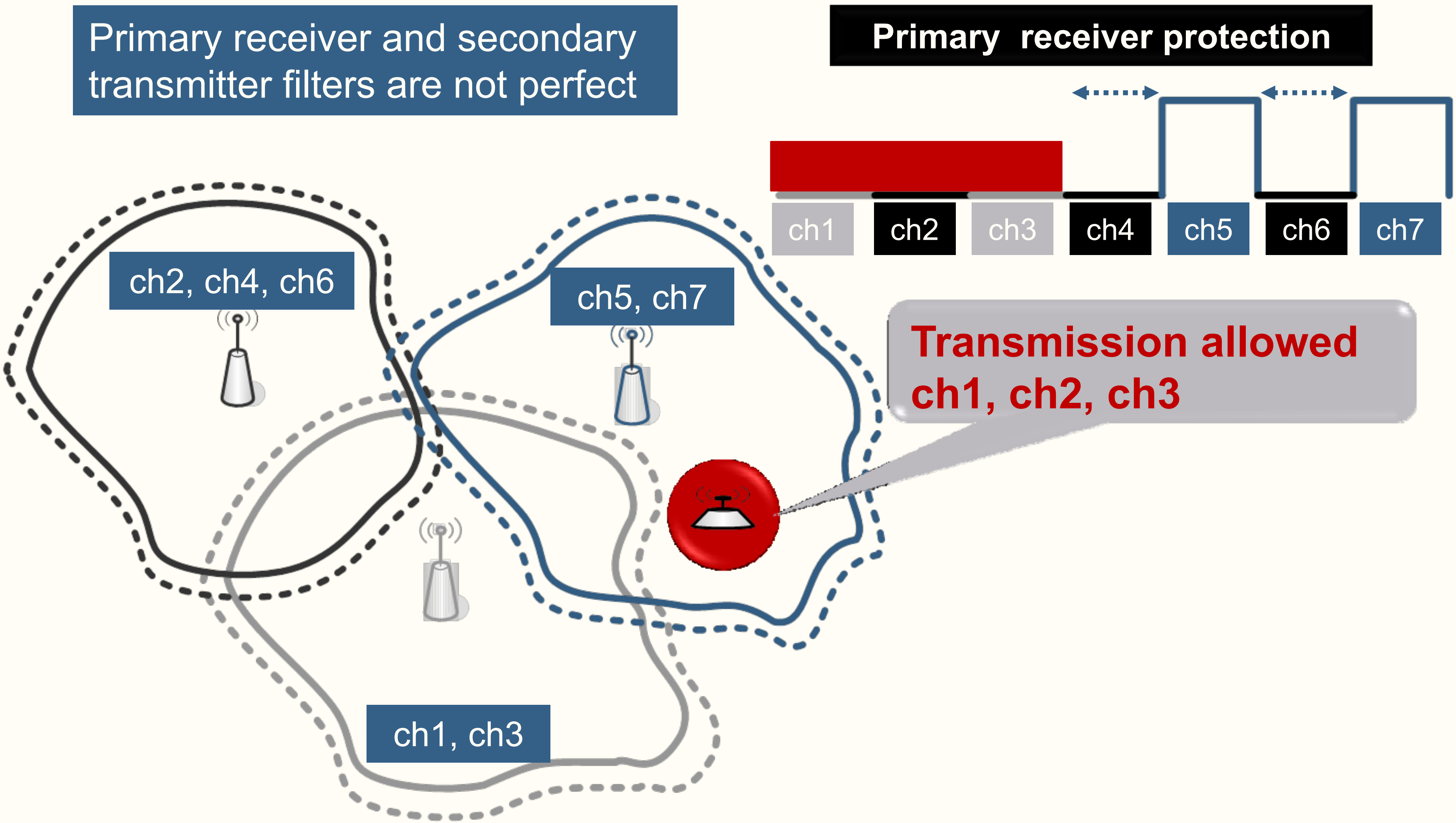


Allowed Transmit Power and No-talk Zone

Secondary power $P \rightarrow$ Allowed transmission at distance r higher than r_{th}

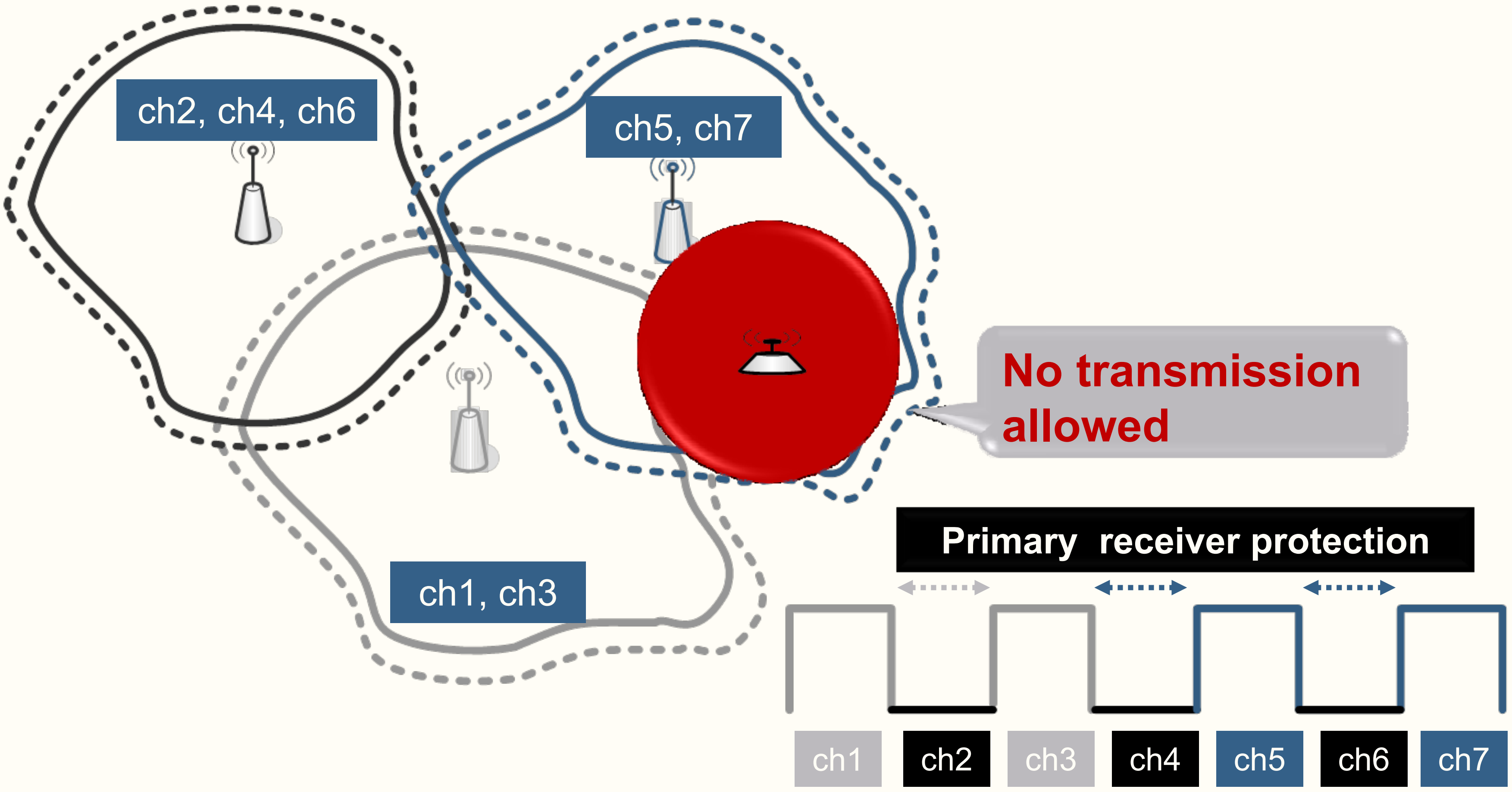


Spectrum Holes in Practice

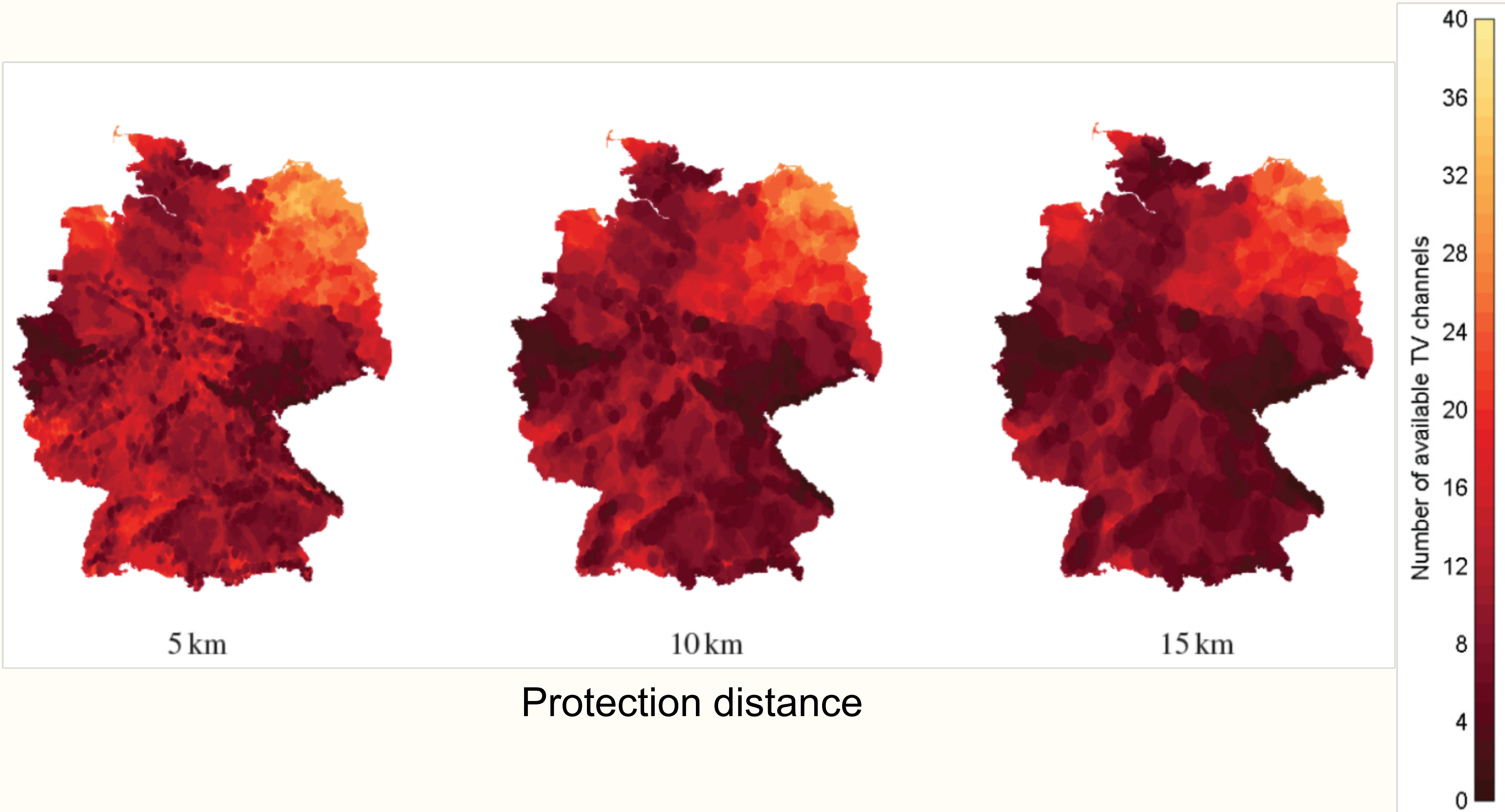


Spectrum Holes in Practice

Primary receiver and secondary transmitter filters are not perfect



Example of Channel Availability in Germany



Protection distance

J. van de Beek, J. Riihijärvi, A. Achtzehn, P. Mähönen "UHF white space in Europe — A quantitative study into the potential of the 470–790 MHz band," IEEE DySPAN, 2011, doi: 10.1109/DYSPAN.2011.5936207

Monitoring Compliance to Constraints

No feedback loop reporting TV receiver quality

Implement monitoring nodes

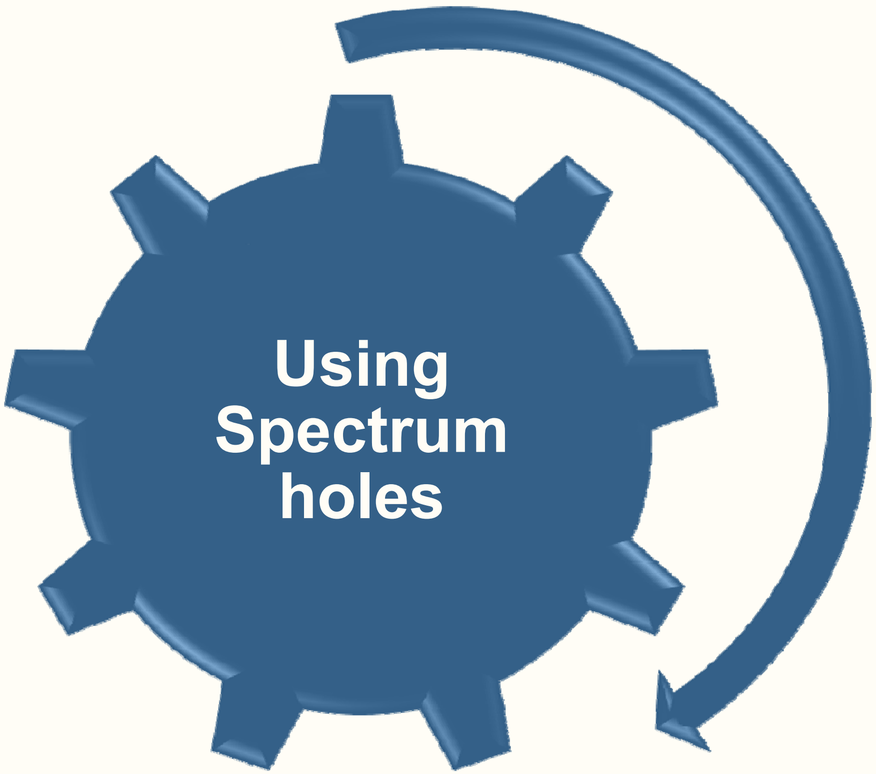
Secondary network | Third party | Primary network

Different propagation characteristics for monitoring nodes and TV receivers

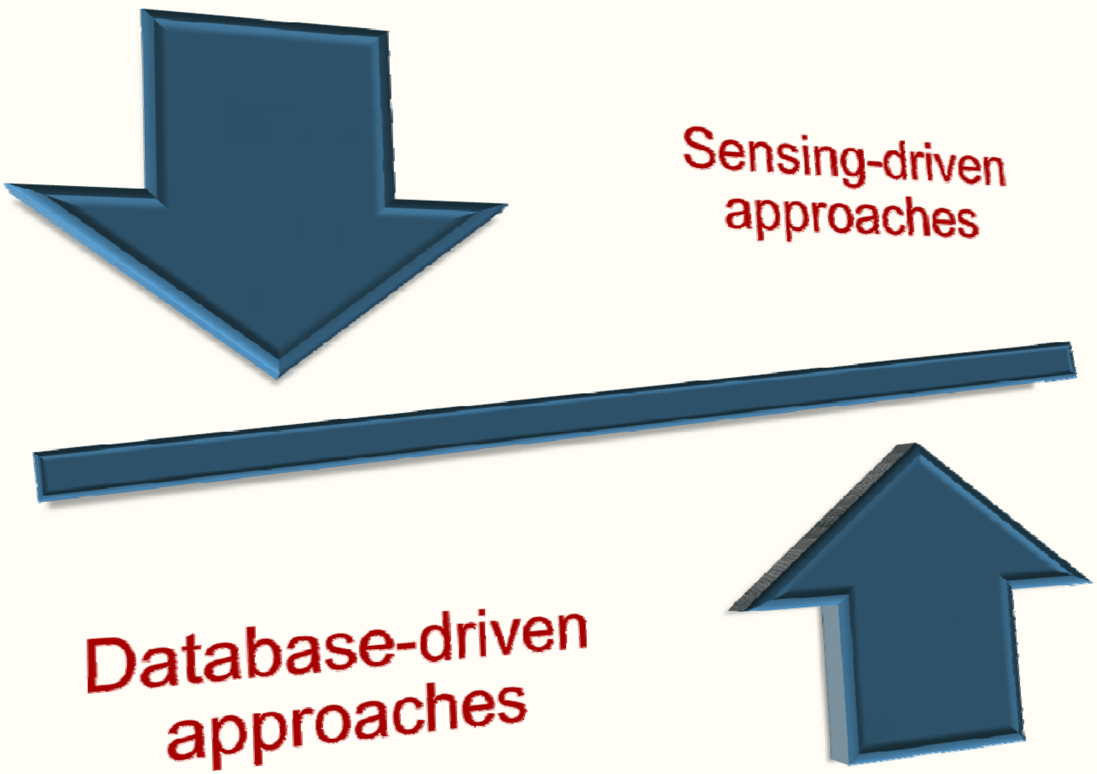
Different locations for monitoring nodes and TV receivers

Cooperative monitoring*

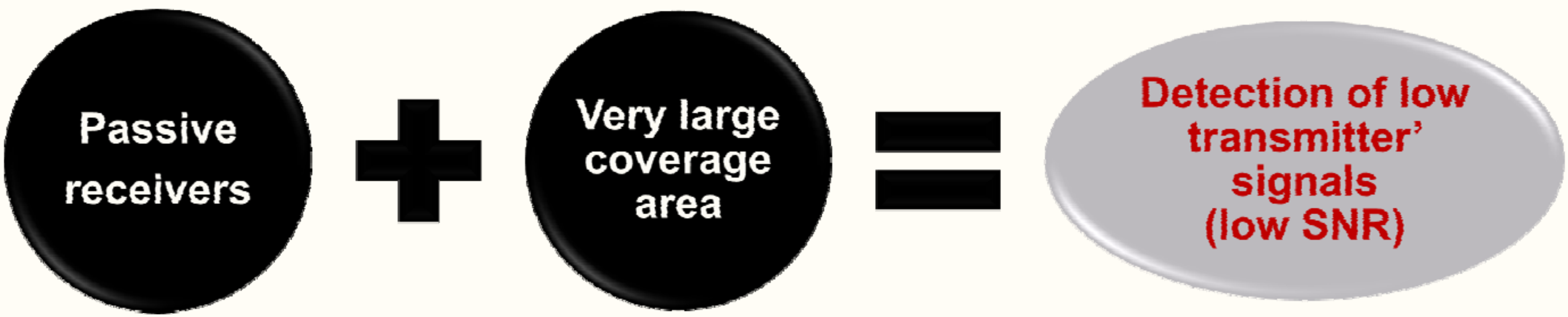
K. Muraoka, H. Sugahara, M. Ariyoshi, "Monitoring-based spectrum management for expanding opportunities of white space utilization," IEEE DySPAN 2011, doi: 10.1109/DYSPAN.2011.5936216


Using
Spectrum
holes

Approaches



Sensing Principles



Sensing-driven Techniques

Determine if the secondary is outside the non-talk zone based on the received signal

Energy detection

- Used if there is no information on primary user signal
- Very simple

Matched filter detection

- Optimal detector if all information of the primary user signal is known
- Produces poor performance if primary users information is not known

Feature detection

- Exploit in the characteristics of primary signals (periodic components)
- Computationally complex and requires long observation time

Cooperative Detection

Database-driven Approach

Some facts

Positions of TV towers are known
Transmit power is known
Continuous transmission

Database architecture

- Based on primary and secondary traffic distribution
- Distribution of equipments and software

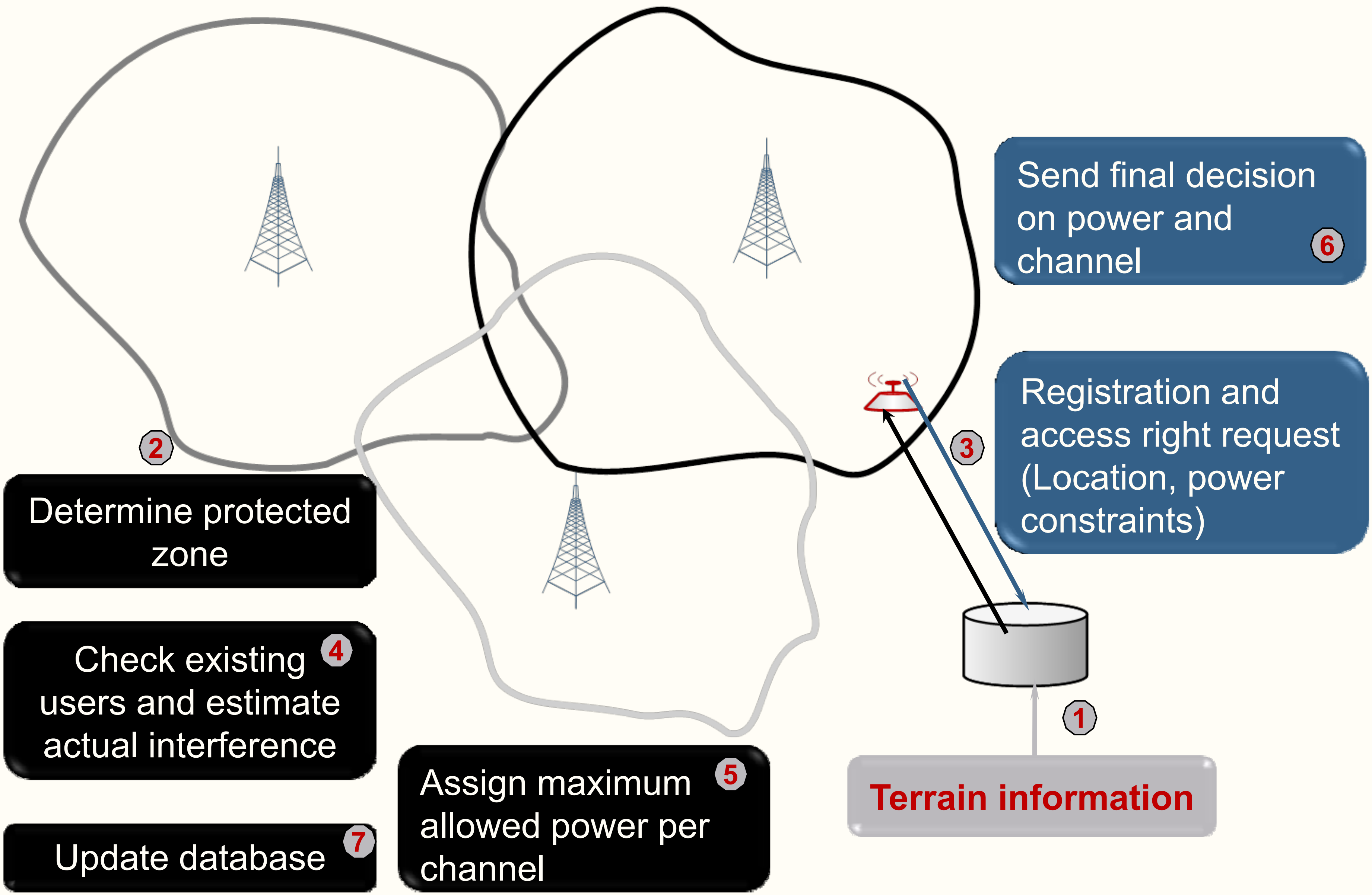
Spectrum availability determination

- Offline process
- Based on primary properties
- Requires good propagation models and terrain models
- Periodical or on demand updates

Information dissemination

- Can be bi- or uni-directional
- Requires node localization, propagation models and mobility estimation

Database-driven Example



Sensing or No Sensing?

- TV transmission is continuous
- Spectrum holes may seldomly appear or disapear

Last regulation decision is to use sensing as an optional technique*

Sensing can be used as a support for database-driven techniques

To enhance propagation models

"Second report and order and memorandum opinion and order," in ET Docket No. 04-186 and ET Docket No. 02-380, FCC 08-260, November 4 2008

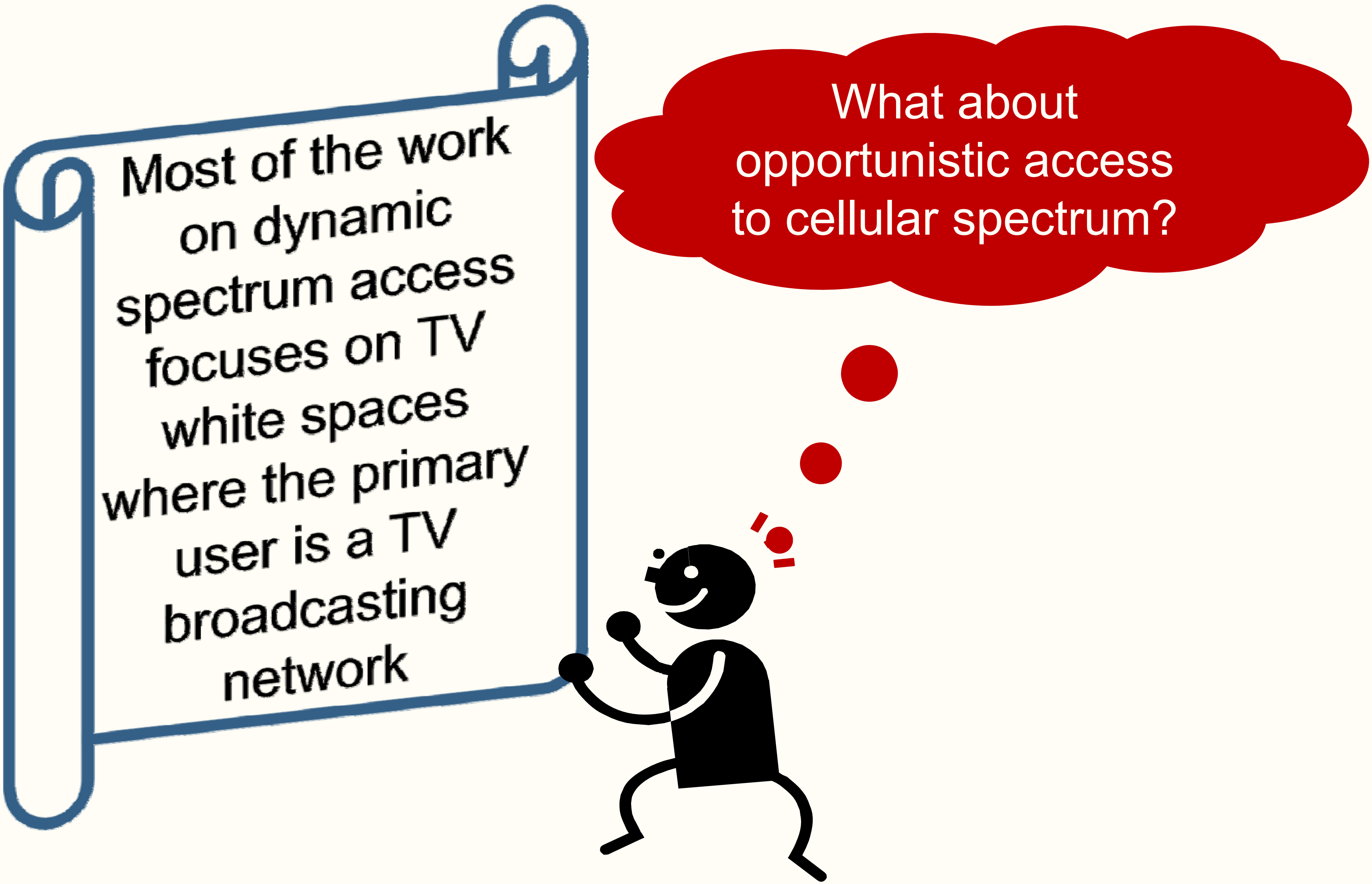
Main Remaining Challenges

- Propagation models
- Multiple secondary transmitter power
- Multiple secondary access providers
- Applications
  - Can we deploy LTE networks as secondary networks?
- Secondary mobility
- Channel allocation and planning
- Measuring and verifying compliance

Outline

- General overview
- DSA to spatial spectrum holes
- DSA to spatio-temporal spectrum holes
- Uncertainty in propagation models
- Related standards
- Summary and open problems

Motivations



Cellular Primary Spectrum

The spectrum assigned to cellular networks can be underutilized at some periods of time …

What type of applications can we have?

Inter-operator sharing
- Machine to Machine and medical applications
- Monitoring networks

Intra-operator sharing
- Macro-femtocell scenario
- WiFi hotspots

New spectrum opportunities to explore

Challenges

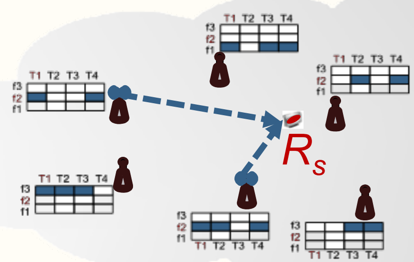
Dynamic primary traffic patterns

µs/ms ON/OFF, non-uniform receiver spatial and temporal distributions, …

Presence of primary services with different quality constraints and adaptive transmit powers

Fixed sharing constraints shall not be used

Multiple neighboring primary transmitters



Aggregate received power

Unknown and unstable propagation losses

No guarantee for primary constraint respect

Pervasive coverage

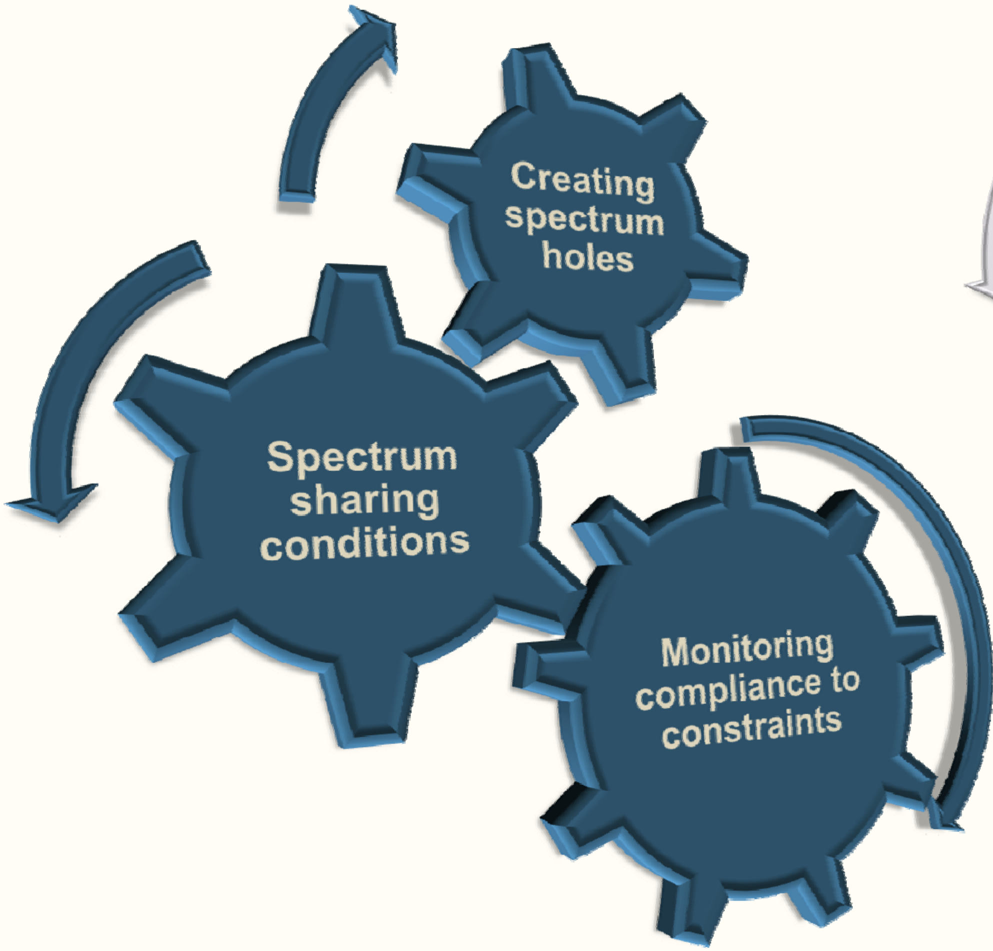
No dead zones are allowed

Main Questions

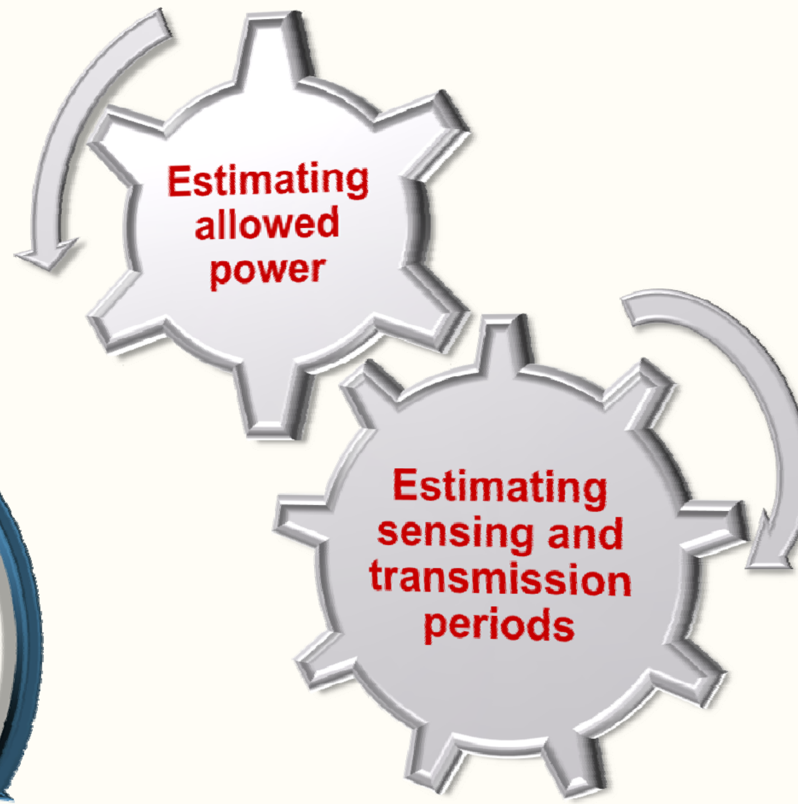
- How primary networks can release spectrum blocks and determine constraints on experienced interference?
  - Exploit the flexibility of access technologies to enable secondary activities (Creating artificial spectrum opportunities)
- How the secondary can find, in the fastest way, the best spectrum blocks and respect primary constraints?
  - Use of available information of primary transmitters

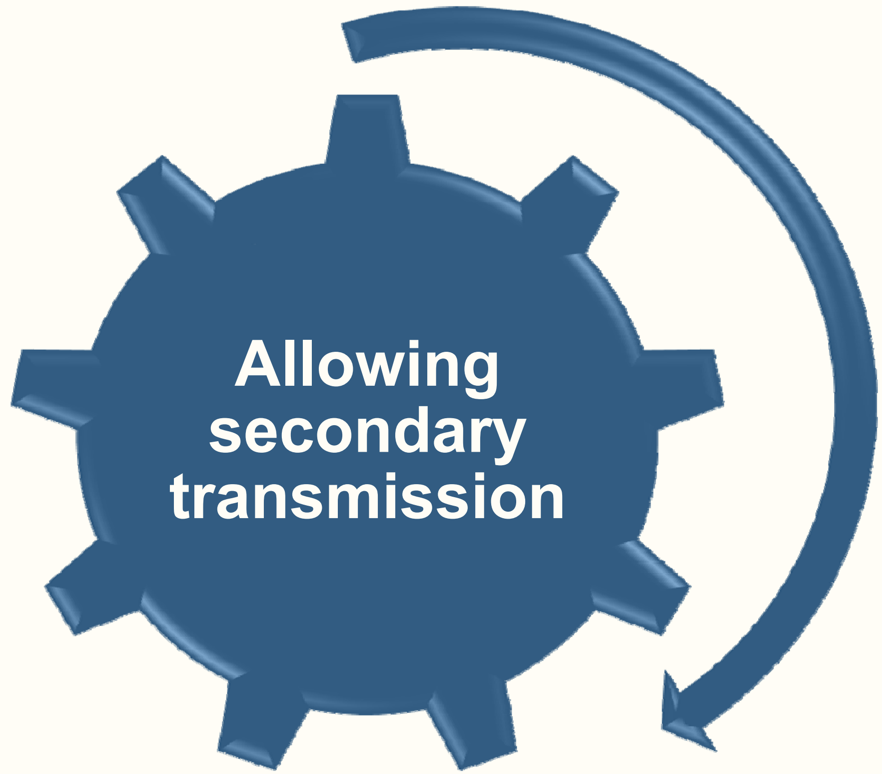
Creating and Using Spatio-Temporal Holes

Allowing secondary transmission



Using Spectrum holes

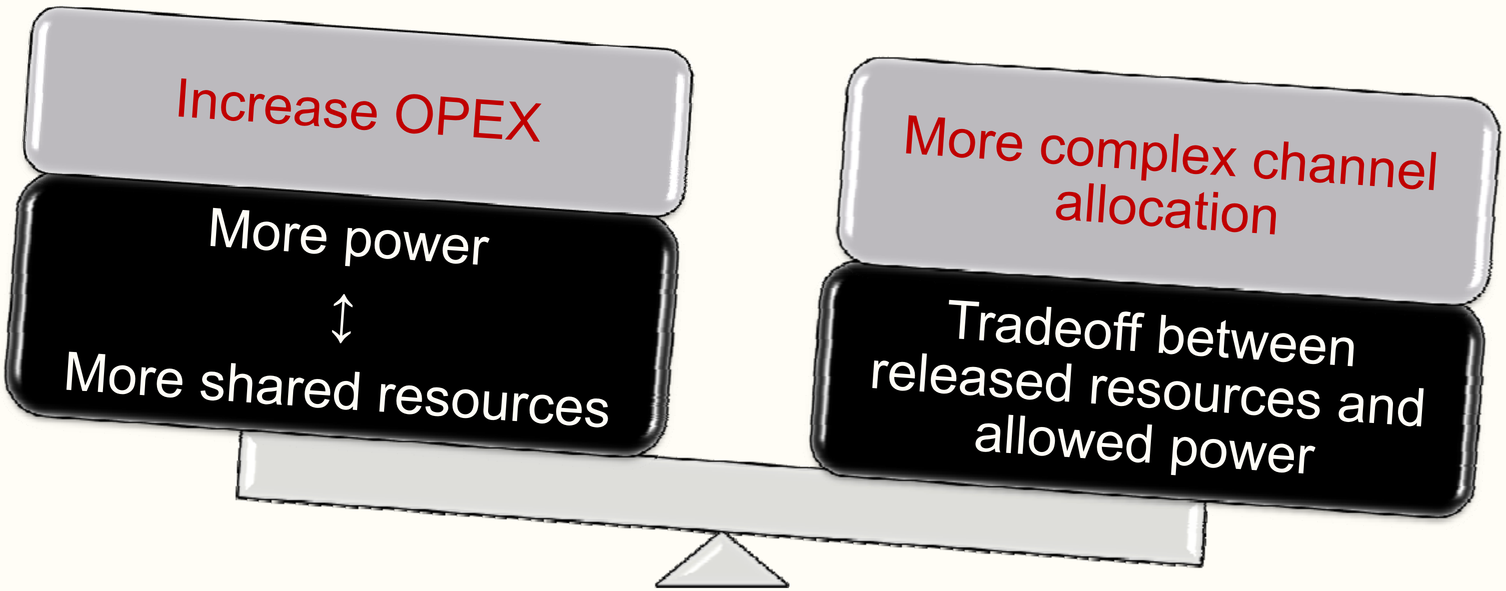



Allowing
secondary
transmission

Creating Spectrum Holes

- No loss of coverage → No dead zones
  - Reducing the coverage as in broadcast network *is not* a solution
  - Adding more base stations solution *is costly*

Power increase | **Dynamic planning**



Conservative Approach

- Any approximation in the model should be biased to a more conservative approach with respect to primary protection
  - Secondary node will consider the Worst Case primary terminal Position (WCP) for
    - Primary receiver
    - Secondary transmitter
  - The estimated primary and secondary coverage area by the secondary is the circle that contains the real coverage area

General Approach

Probability of non-satisfaction ε should be always lower than threshold ε_{th}

Probability of non-satisfaction ε

- ι_{max} is not harmful
- $I > \iota_{max}$

- ι_{max} is harmful

Secondary DSA algorithms

$\varepsilon_s = \mathrm{Pr}_{int}$ controlled by secondary

ε_p controlled by primary

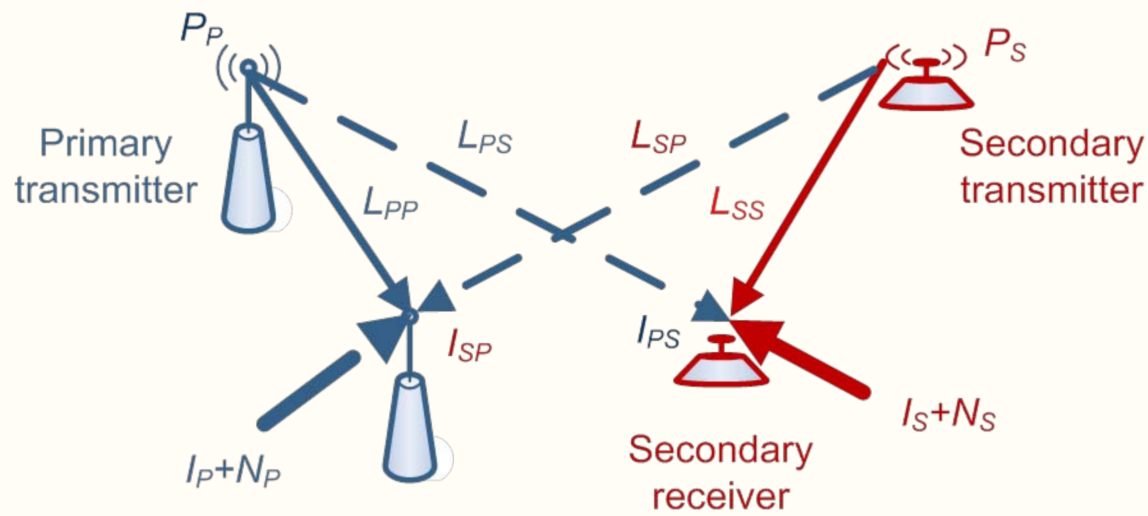
Creating artificial spectrum opportunities

$\varepsilon < \varepsilon_p + \varepsilon_s$

$\varepsilon_{th} = \varepsilon_{p,th} + \varepsilon_{s,th}$

- The primary determines ι_{max} to guarantee $\varepsilon_p < \varepsilon_{p,th}$
- Secondary transmission should guarantee $\varepsilon_s < \varepsilon_{s,th}$

System Model



$$SINR_P = \frac{P_P / L_{PP}}{N_{\mathrm{T},P} + I_P + I_{SP}}$$

$$SINR_S = \frac{P_S / L_{SS}}{N_{\mathrm{T},S} + I_S + I_{PS}}$$

$P_{S,\max} \geq P_{S,\min}$

$$I_{SP} = \frac{P_S}{L_{SP}}$$

Estimated using database or sensing driven techniques

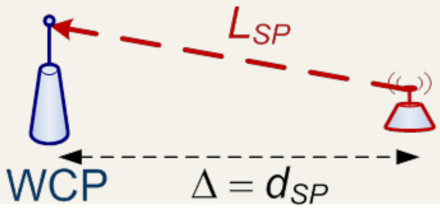
$P_S \leq P_{S,\max}$

$$I_{PS} = \frac{P_P}{L_{PS}}$$

$P_S \geq P_{S,\min}$

L_{SP} with Known Position of Secondary Transmitter

Case A: Known position of primary receiver



$$L_{SP}(\mathrm{P1}) \approx F_{SP}(\Delta)$$

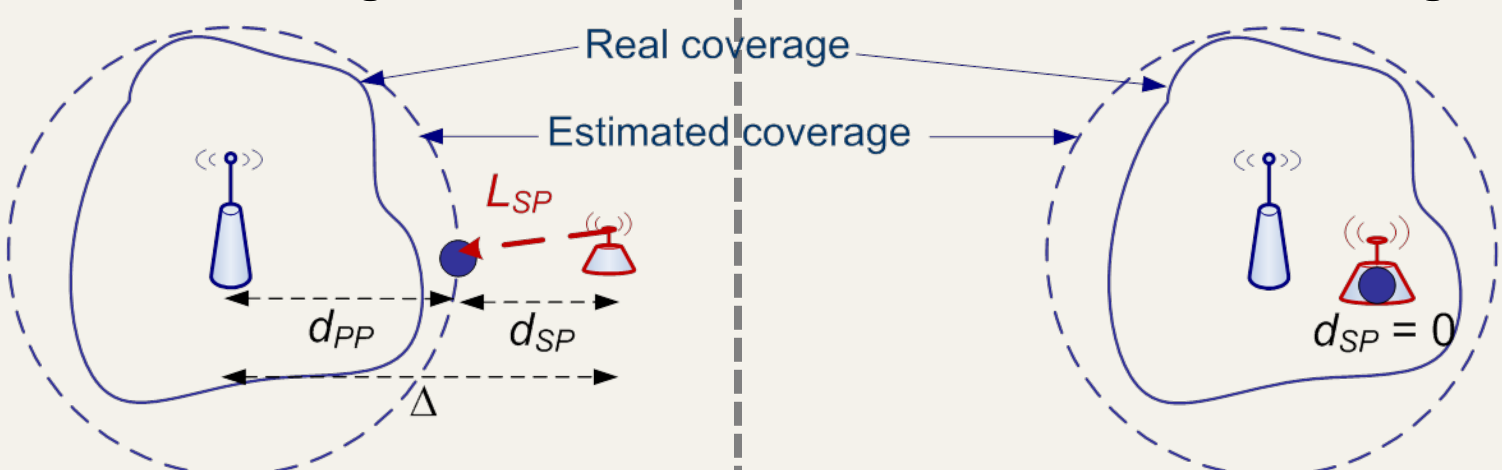
Propagation function

Case B: Unknown position of primary receiver

Case B.1: Secondary outside the estimated coverage area

Case B.2: Secondary inside the estimated coverage area

● WCP

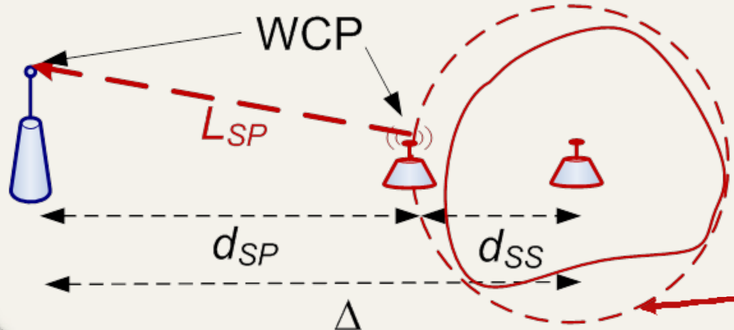


$$L_{SP}(\mathrm{P1}) \approx F_{SP}(\Delta - d_{PP})$$

No transmission

L_{SP} with UnKnown Position of Secondary Receiver

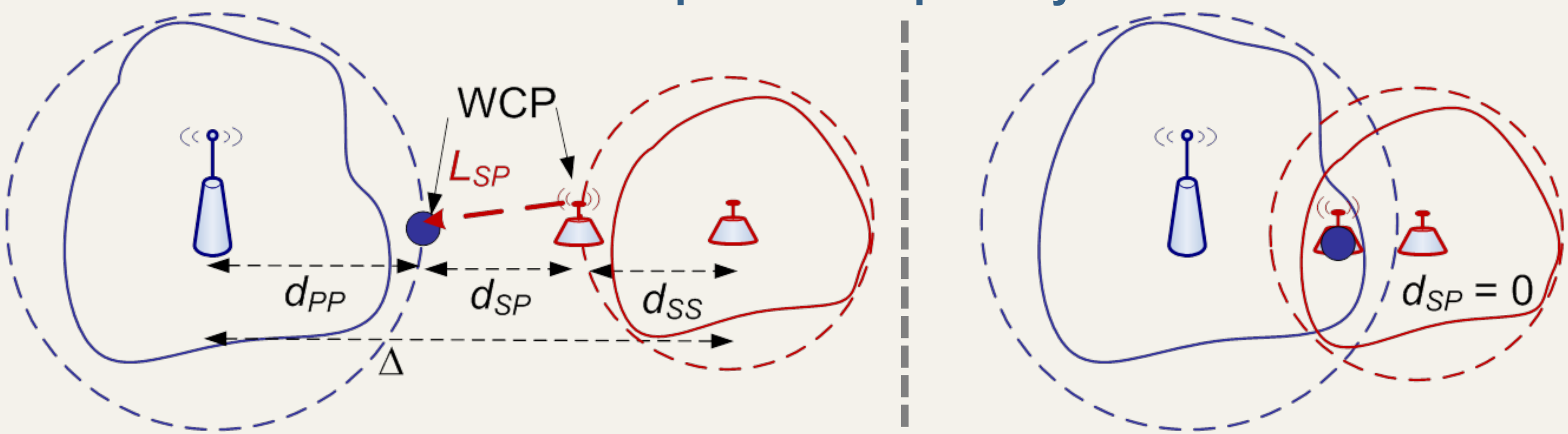
Case C: Known position of primary receiver



Secondary estimated coverage area

$$L_{SP}\left(\mathrm{P1}\right) \approx F_{SP}\left(\left|\Delta - d_{SS}\right|\right)$$

Case D: Unknown position of primary receiver



$$L_{SP}\left(\mathrm{P1}\right) \approx F_{SP}\left(\left|\Delta - d_{SS}\right| - d_{PP}\right)$$

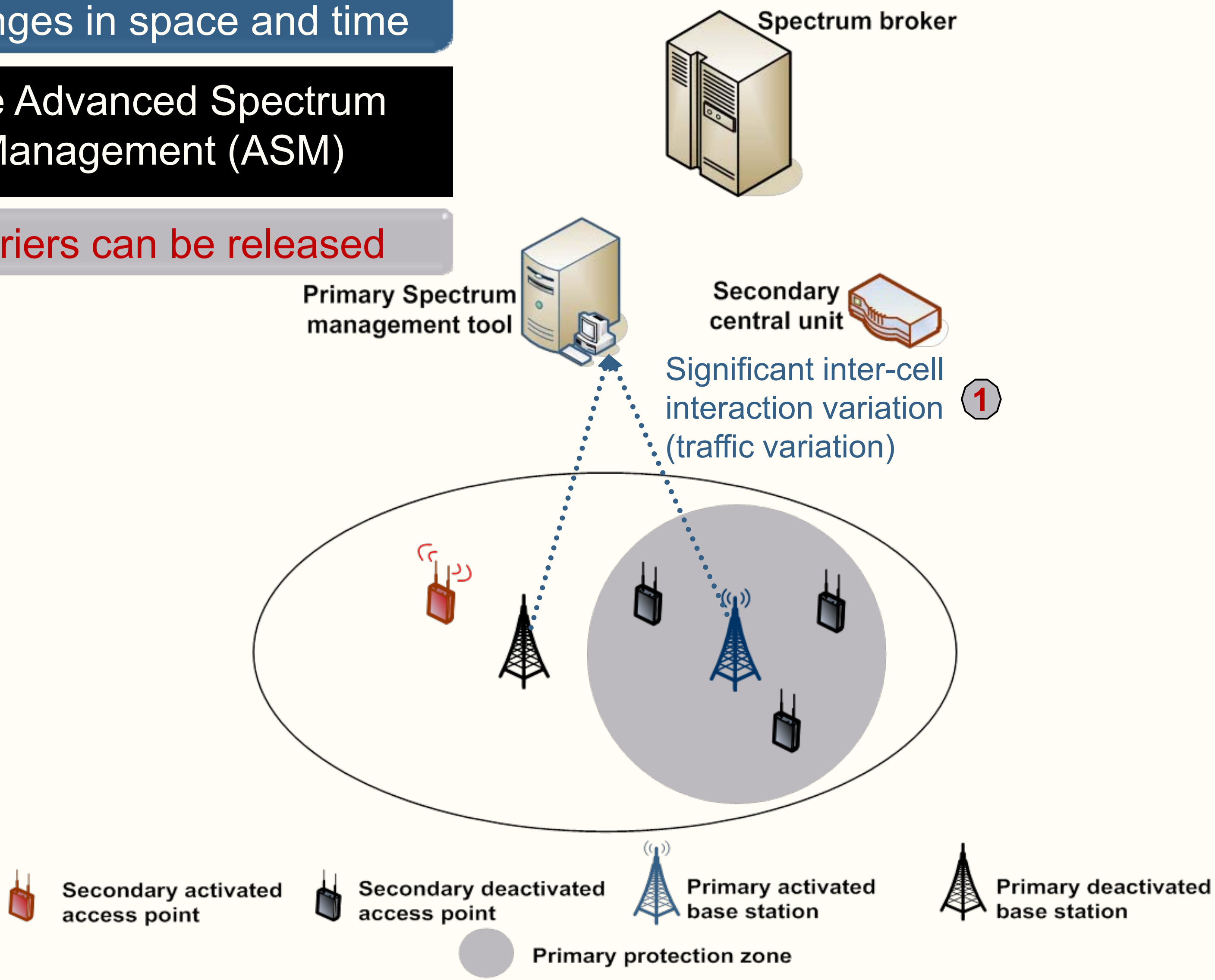
No transmission

Creating and Exploiting Spectrum Holes

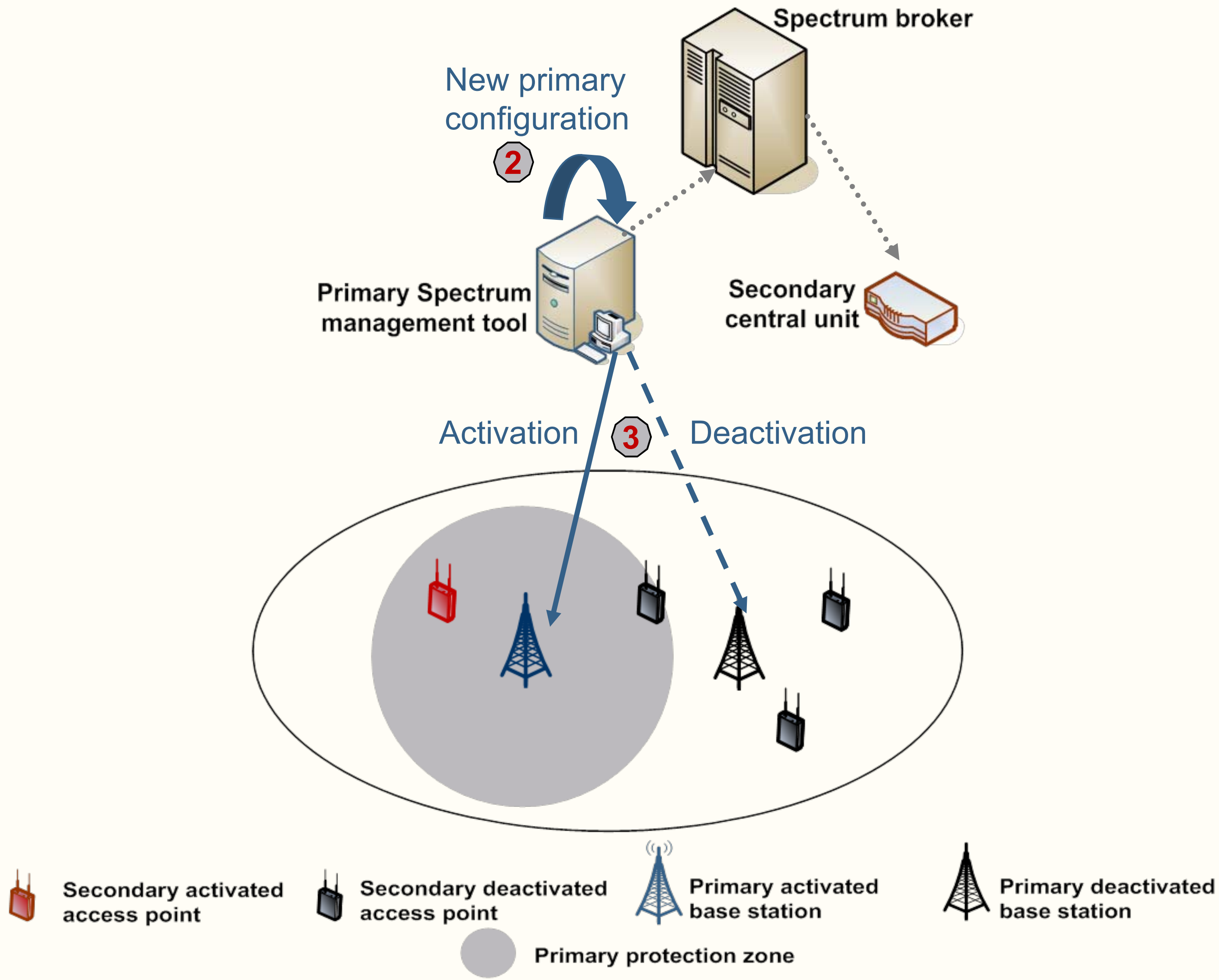
Cellular network traffic changes in space and time

Use Advanced Spectrum Management (ASM)

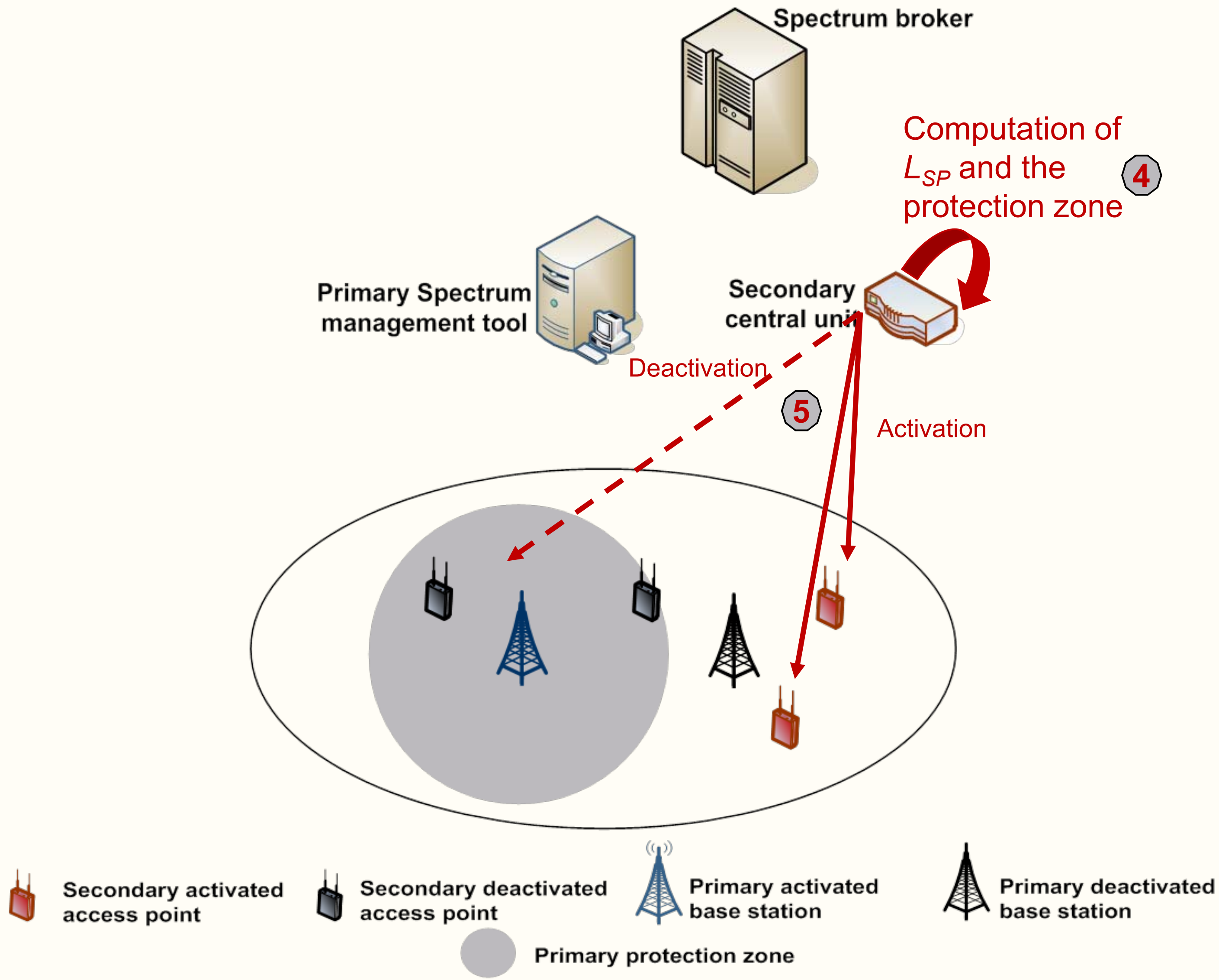
Carriers can be released



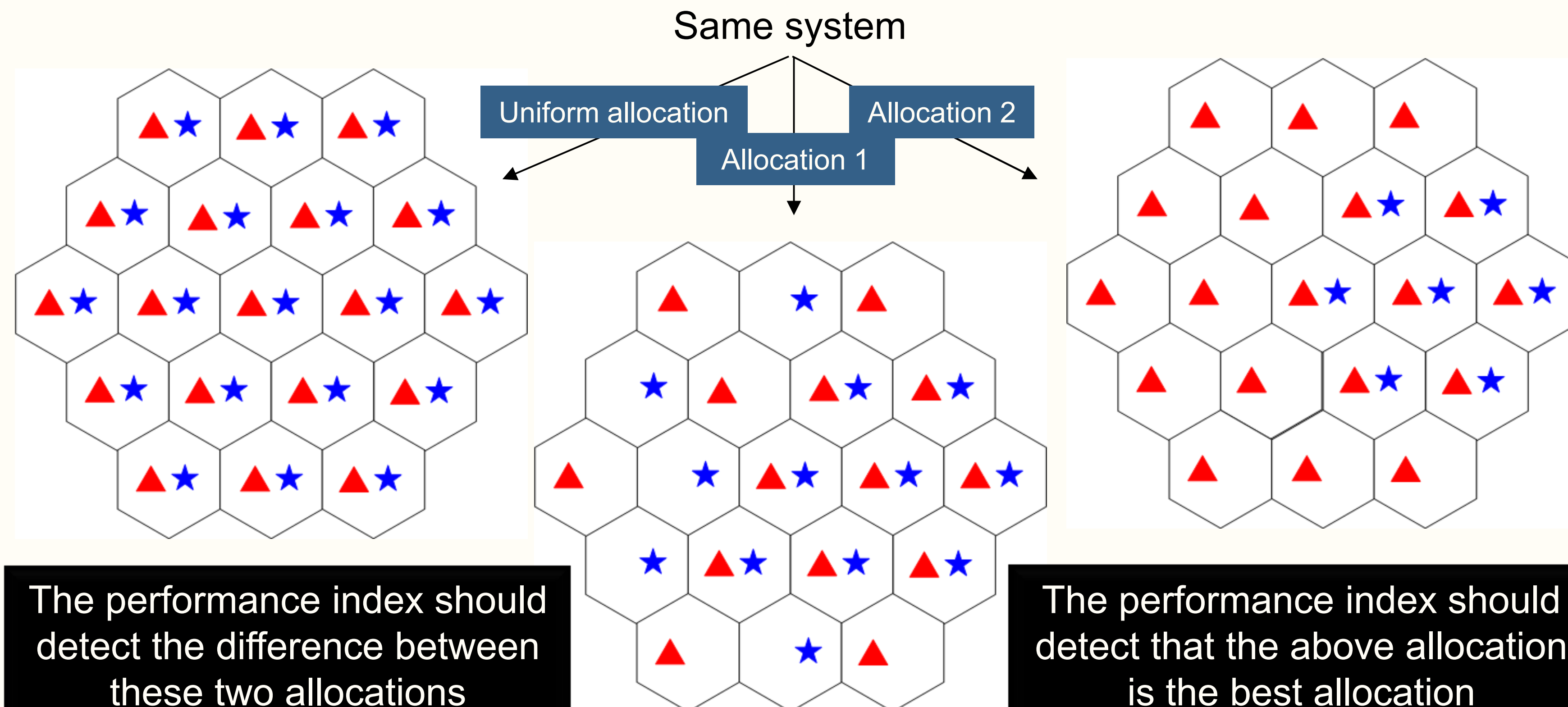
Creating and Exploiting Spectrum Holes



Creating and Exploiting Spectrum Holes



Performance Index



The performance index should detect the difference between these two allocations

The performance index should detect that the above allocation is the best allocation

Traditional spectrum efficiency (bps/Hz/cell)

New index that depends on the surface of the released zone

Useful Released Surface (URS)

- For a given frequency allocation:

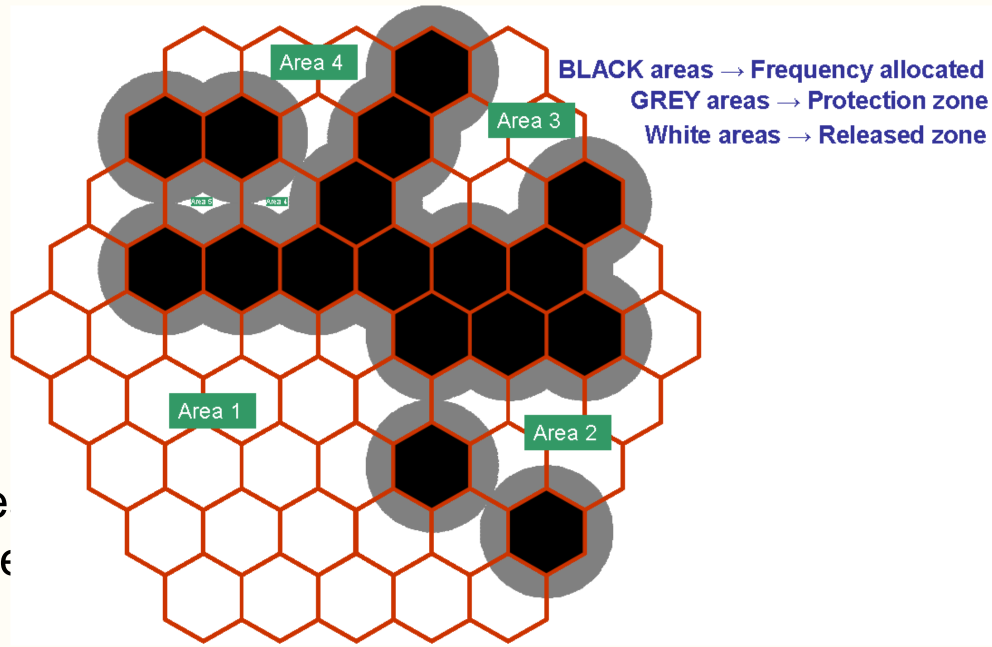
$$URS = \sum_{f=1}^{F} W^{(f)} \sum_{c=1}^{C^{(f)}} S_c^{(f)} \omega_c^{(f)}$$

W(*f*): the bandwidth of carrier *f*

C(*f*): the set of non-contiguous areas where *f* could be used by another network

$S_c^{(f)}$: the surface of contiguous are c where *f* could be used by anothe network

$\omega_c^{(f)}$: the weight given to this area depending on the expected number of other network' users in this area



J. Nasreddine, J. Pérez-Romero, O. Sallent, R. Agustí, "A Primary Spectrum Management Solution Facilitating Secondary Usage Exploitation," ICT-Mobile Summit, Stokholm-Sweden, 2008

Example: Releasing Channels in OFDMA-based Systems

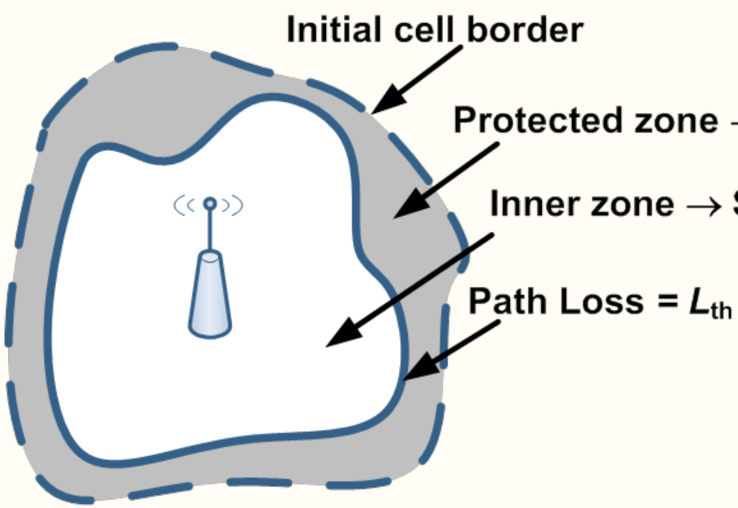
T orthogonal frequency channels
No dead zones should be allowed in the primary system
Same propagation characteristics
Same probability of activity for all base stations α

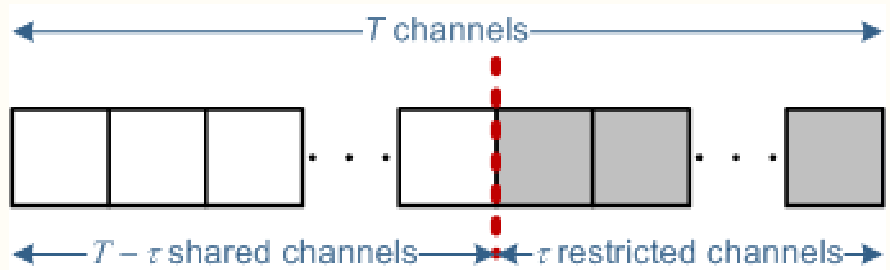
Find the number of shared channels and the value of the tolerable interference threshold $\iota_{\max}$ and released resources corresponding to the non-satisfaction probability $\varepsilon_{p,\mathrm{th}}$

J. Nasreddine, A. Achtzehn, J. Riihijärvi, P. Mähönen, "Enabling Secondary Access through Robust Primary User Channel Assignment," IEEE GLOCECOM 2010, doi: 10.1109/GLOCOM.2010.5683150

Example: Main Idea

- Divide the cells into two zones





- L_{th} is defined by
  - Zone where users sharing a channel with secondary will have the same SINR as the one at the initial borders without secondary

$$P - L_{\text{th}} - 10\log\left(\boxed{10^{I_{S,\text{th}}/10}} + 10^{P_N/10} + 10^{\iota_{\max}/10}\right) = P - \boxed{L_{\max}} - 10\log\left(\boxed{10^{I_{S,\max}/10}} + 10^{P_N/10}\right)$$

  - Takes into account cell load $I_{S,th} = I_{S,max} + 10\log(\alpha)$

Example: Computing Sharing Parameters

- Probability ε_p is defined as
  - The probability of having at least one user from the protected zone associated to a shared channel
  - N_p users in the protected zone → constraint on ε_p becomes

$$\mathbb{P}\{N_p \leq \tau - 1\} \leq 1 - \varepsilon_s \leq \mathbb{P}\{N_p \leq \tau\}$$ → the value of τ

where

$$\mathbb{P}\{N_p \leq \tau\} = \sum_{i=0}^{\tau} \binom{N}{i} P_{\text{th}}^{i} (1 - P_{\text{th}})^{N-i}$$

$$= (\boxed{N} - \tau) \binom{N}{\tau} \int_0^{1-P_{\text{th}}} t^{N-\tau-1} (1-t)^{\tau} \, dt$$

$$P_{\text{th}} \equiv \mathbb{P}\{L > L_{\text{th}}\} = 1 - \int_{-\infty}^{\boxed{L_{\text{th}}}} p_L(t) \, dt$$

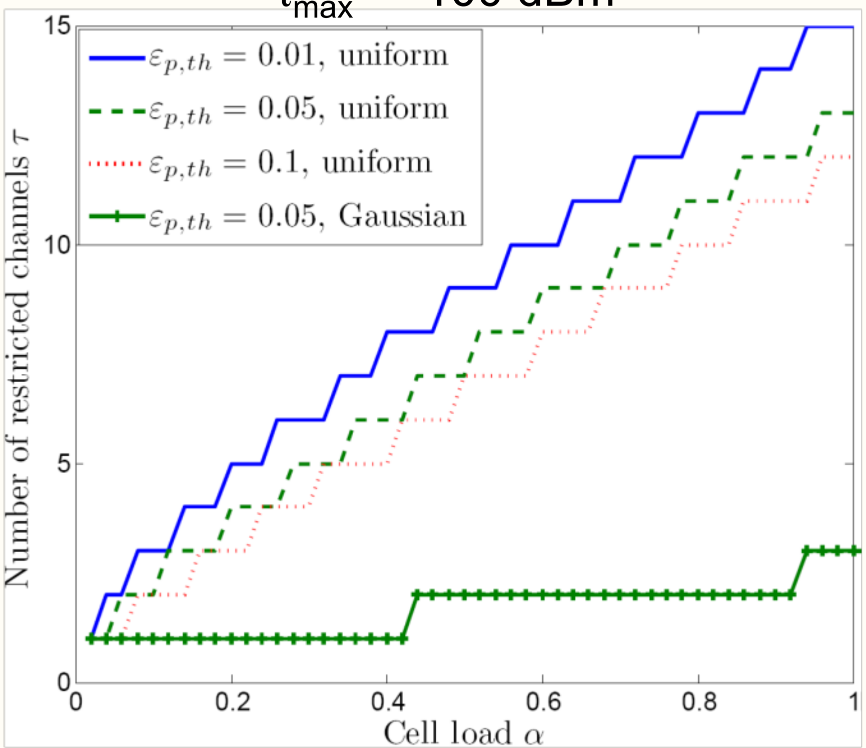
$$p_L(t) = \int_{-\infty}^{\infty} \boxed{p_{L_r}(s)} \boxed{p_{\chi}(s-t)} \, ds$$ (pdf of the total path loss)

Example: Results

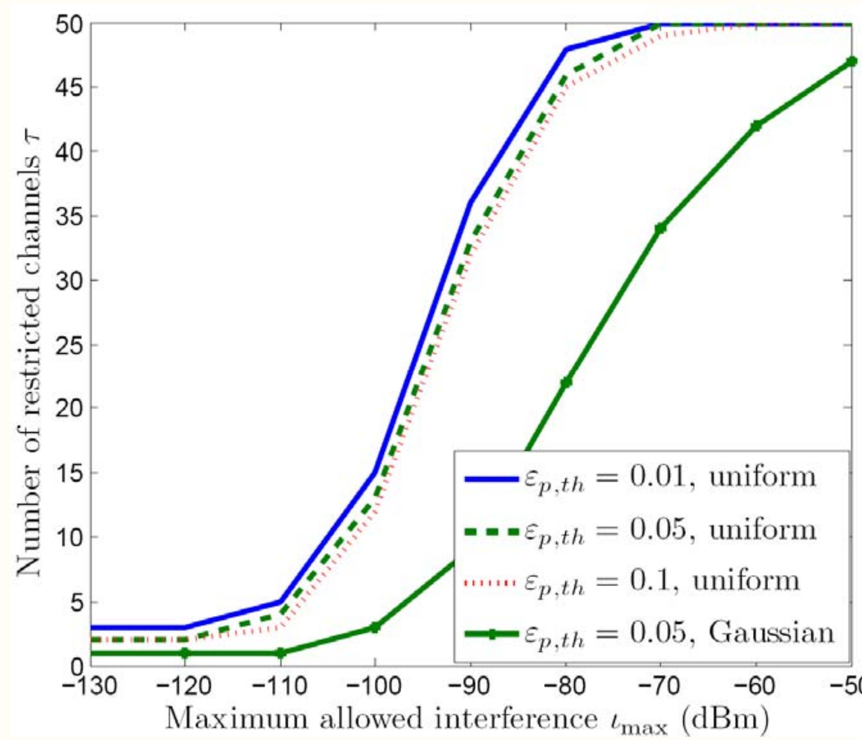
System parameter	value
Bandwidth W	10 MHz
Number of channels T	50
Cell radius r	500 m
Path loss threshold $L_{\max}$	128.65 dB
Noise power P_N	-121 dBm
Transmitted power per channel P	29 dBm
Internal interference $I_{S,\max}$	-110 dBm

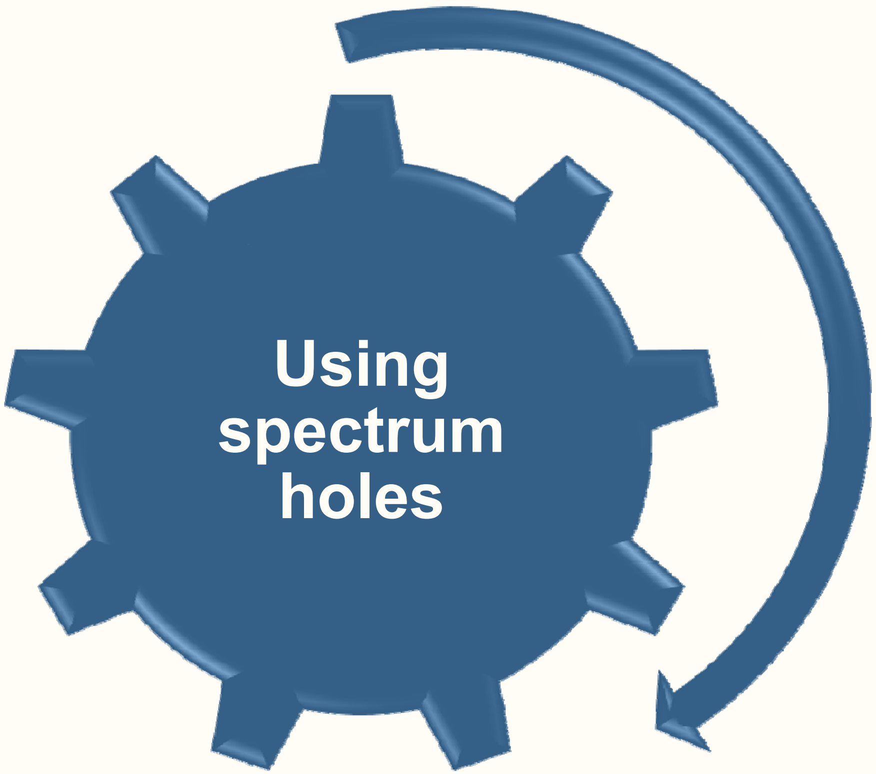
	$\iota_{\max}$				
α	-130 dBm	-110 dBm	-90 dBm	-70 dBm	-50 dBm
0.2	(1, 1)	(1, 1)	(4, 1)	(10, 6)	(10, 10)
0.4	(1, 1)	(1, 1)	(6, 1)	(19, 10)	(20, 18)
0.6	(1, 1)	(1, 1)	(9, 2)	(28, 14)	(30, 26)
0.8	(2, 1)	(2, 1)	(11, 2)	(37, 18)	(40, 34)
1	(2, 1)	(2, 1)	(13, 3)	(46, 22)	(50, 42)

ι_{max} = -100 dBm



α = 1




Using
spectrum
holes

Challenges

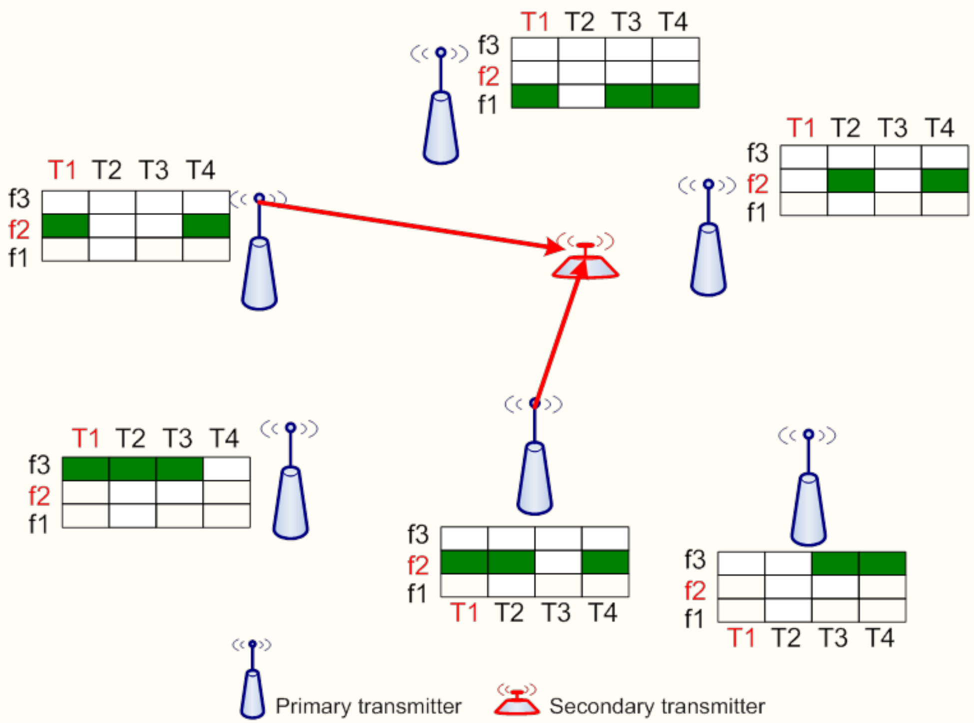
- Estimation of allowed transmit power
  - Multiple primary transmitters with dynamic activity
  - Information uncertainty (location, activity patterns, etc.)
- Finding the best channel to transmit taking into account
  - Allowed transmit power in each channel
  - Interference from primary and secondary users in each channel
  - Opportunity duration
    - Renewal theory can be used here
- Rendez-vous problem
  - Opportunity dynamism is very high
- Secondary spectrum sharing problem
  - Multiple secondary transmitter impact on primary network
  - Secondary internal interference problem

Does Sensing Make Sense?

- Unknown primary transmit power, multiple primary transmitters, short temporal spectrum opportunities …
  - Traditional energy detection cannot be used
    - Multiple transmitter, unknown transmit power, fast traffic patterns, …
  - Cooperative sensing, cyclostationary detection and database-driven are also very difficult
    - Time to transfer data can be longer than the temporal spectrum opportunity

Estimation of Allowed Power: Problem Formulation

- Locations of primary base stations are known
- Primary instantaneous activity patterns are unknown to the secondary nodes
- Frequency allocation to primary cells can be optionally sent to secondary network
  - In this case the algorithm is called ESDA-AT otherwise SDA-AT
- Spectrum hole: frequency band where the secondary allowed transmit power is higher than P_{min}



Secondary receives signals from multiple primary transmitters

Find the maximum allowed transmit power satisfying primary constraints

J. Nasreddine, J. Riihijärvi, P. Mähönen, "Location-based Adaptive Detection Threshold for Dynamic Spectrum Access," IEEE DySPAN 2010), doi: 10.1109/DYSPAN.2010.5457863

Main Idea

- Transmit with a power leading to $\Pr_{int} = \varepsilon_{s,th}$
- Iterative algorithm
  - For each primary cell, we estimate whether it is active at present time or not
  - Given event *M* that we miss-detect the activity of the given cell, we have for the total interference probability that

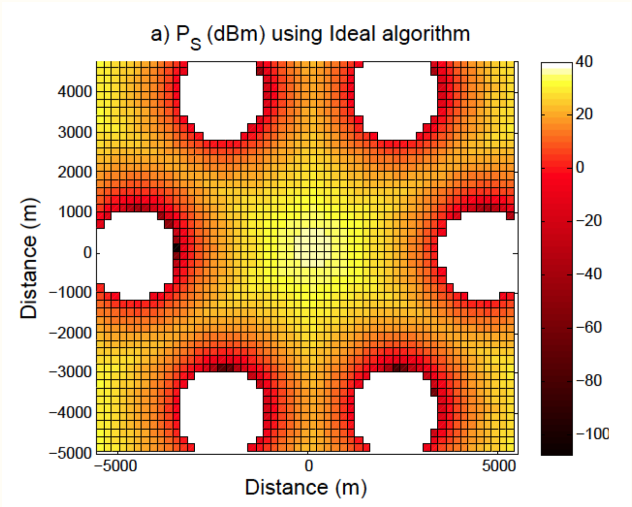
$$\Pr\{I \geq \iota_{\max} \mid M\}\Pr_m + \Pr\{I \geq \iota_{\max} \mid \bar{M}\}(1-\Pr_m) = \varepsilon_{s,\text{th}}$$

$P_{S,1} > P_{S,2}$

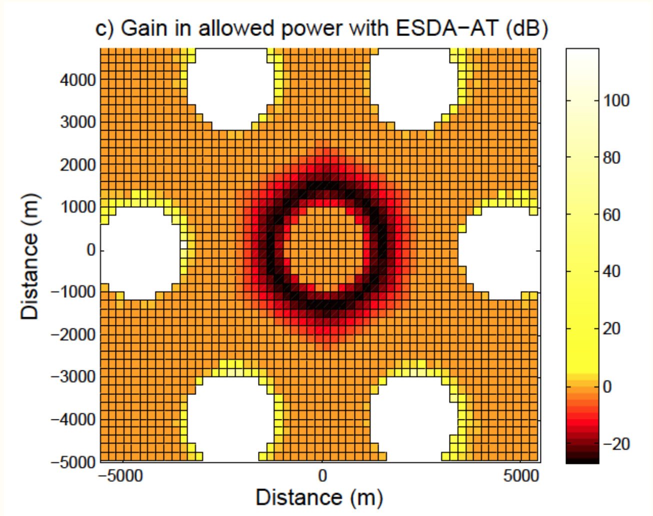
The method can be also extended to take into account primary activity distribution

Simple Scenario Results

- Seven hexagonal cells with frequency reuse factor 7
- All cells, except central cell, are transmitting
- In the Ideal algorithm the secondary node knows which are the active primary base stations



$\varepsilon_{s,th} = 0.05$



In more than 70% of the cases where the secondary node is allowed to transmit
The power loss by the ESDA-AT is always lower than 0.5 dB

In the central cell the gain decreases when we move further away from the base station

Sensing and Transmit Periods

- With what periodicty the secondary should sense?
  - Frequent sensing requires complex hardware
  - Seldom sensing may lead to high temporel miss-detection
- When a spectrum hole is detected, for how long the secondary can transmit?
  - Long periods lead to high temporel miss-detection
  - Short periods reduce secondary performance

Assume On-OFF model and use alternating theory*†

* H. Kim and K. G. Shin, "Efficient discovery of spectrum opportunities with MAC-layer sensing in cognitive radio networks," IEEE Transactions on Mobile Computing, vol. 7, no. 5, pp. 533 –545, May 2008, doi: 10.1109/TMC.2007.70751

† M. Sharma, A. Sahoo, and K. D. Nayak, "Model-based opportunistic channel access in dynamic spectrum access networks," IEEE GLOBECOM 2009, doi: 10.1109/GLOCOM.2009.5425907

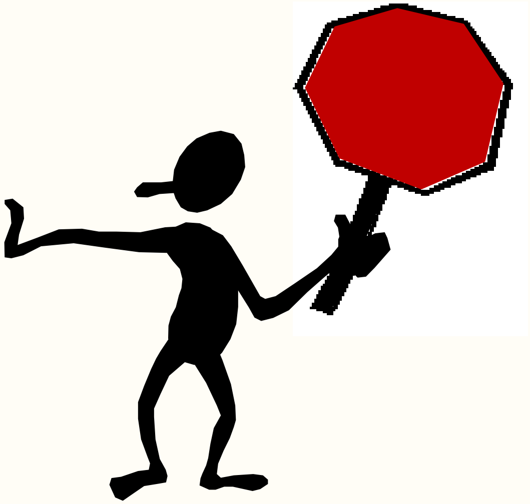
Outline

- General overview
- DSA to spatial spectrum holes
- DSA to spatio-temporal spectrum holes
- Uncertainty in propagation Models
- Related standards
- Summary and open problems

Uncertainty

Uncertainty in the required information

Main problem in DSA and future wireless networks



Uncertainty Sources in DSA

Noise level and distribution

- Main problem for TV white space detection based on sensing
- Determines detector sensitivity through SNR wall or the SNR below which robust detection is impossible for the given detector*
- Mitigated by sensing techniques and sensitivity enhancement

Primary transmitters' characteristics

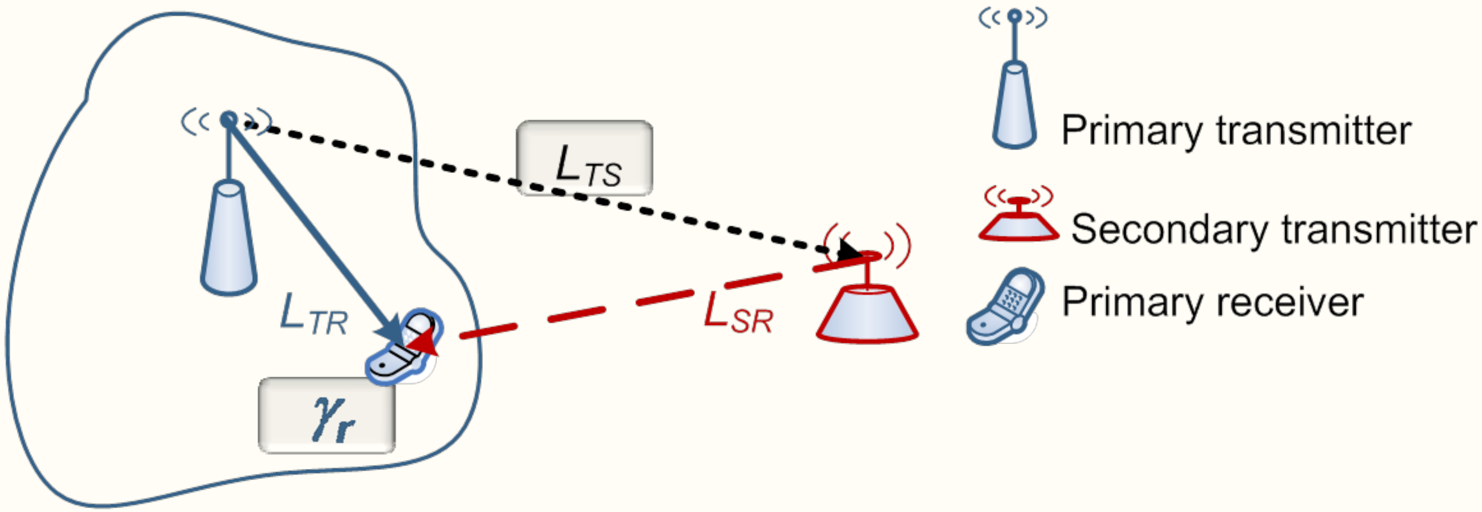
- Main problem for DSA techniques in cellular networks and database-driven techniques for TV white space
- Includes uncertainty in location†, traffic patterns, transmit power, etc.

Propagation models

- Main problem of all DSA techniques
- Affects the estimation of protection zone in TV white space and the estimation of allowed transmit power
- Uncertainty in distance-dependent loss†‡, shadow and fast fading, shadow correlation⌂, etc.

* R. Tandra, A. Sahai, "Noise calibration, delay coherence and SNR walls for signal detection," IEEE DySpAN 2008
† R. Murty & al. "SenseLess: A Database-Driven White Spaces Network," IEEE DySPAN 2011
‡ C. Phillips, D. Sicker, D. Grunwald, "Bounding the Error of Path Loss Models," IEEE DySPAN 2011
⌂ J. Nasreddine & al., "Transmit Power Control for Secondary Use in Environments with Correlated Shadowing," ICC 2011

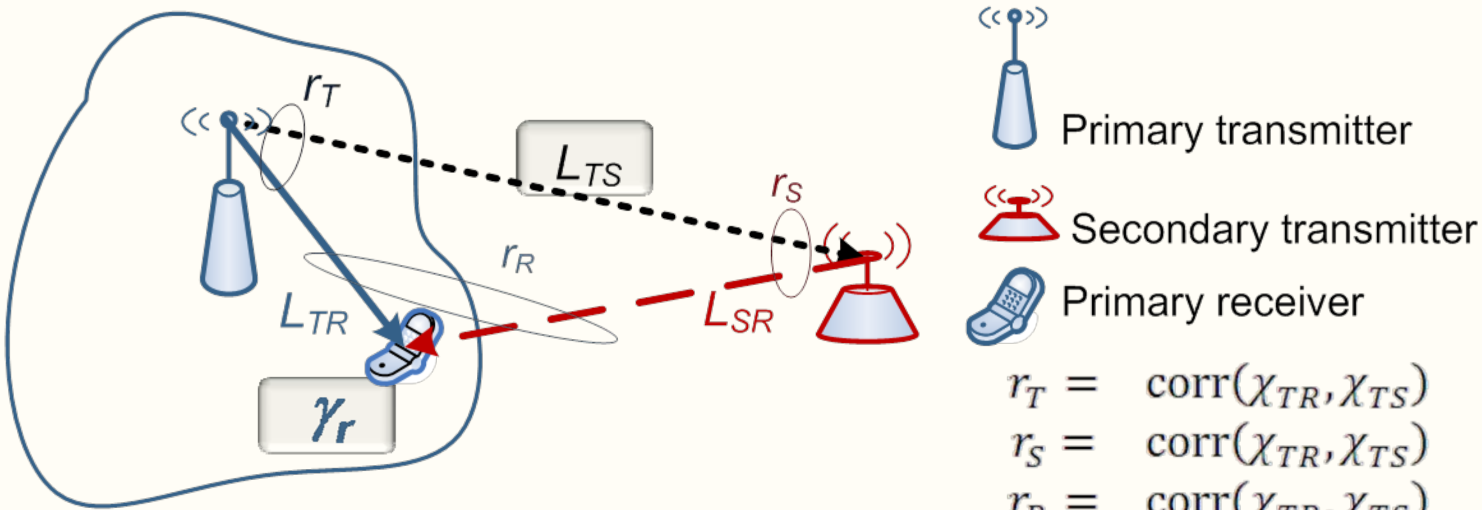
System Model



We have:
Primary SINR threshold γ_r
Estimated path loss L_{TS}

We want to estimate the maximum secondary allowed transmit power P_S

System Model



$$r_T = \text{corr}(\chi_{TR}, \chi_{TS})$$
$$r_S = \text{corr}(\chi_{TR}, \chi_{TS})$$
$$r_R = \text{corr}(\chi_{TR}, \chi_{TS})$$

$L_{XY} = F_{XY}(d_{XY}) + \chi_{XY}$ (function F_{XY} and distribution of χ_{XY} are known)

$$\text{corr}(\chi_X, \chi_Y) = \frac{E\left[\left(X - E(X)\right)\left(Y - E(Y)\right)\right]}{\sigma_X \sigma_Y}$$

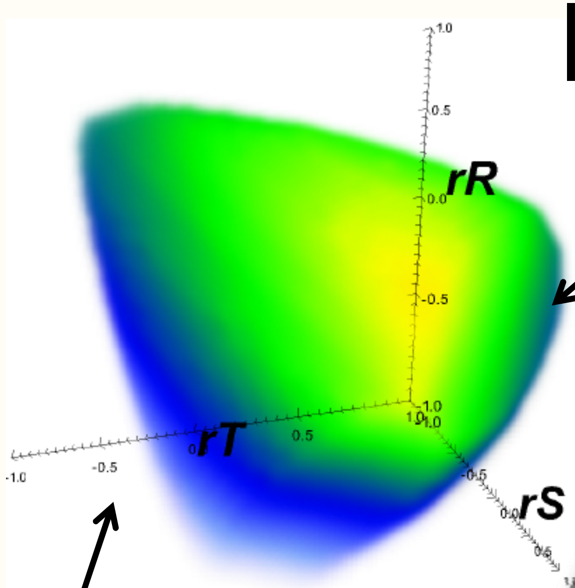
r_T, r_S and $r_R \in [-1,1]$

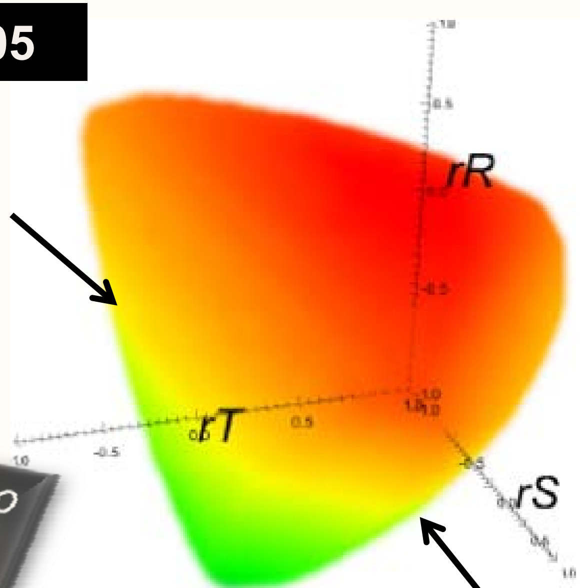
The correlation matrix is positive semi-definite

Case with Known Correlation Matrix

d_{TR} = 500 m, ε = 0.05

γ_r = -2.6 dB (QPSK, 1/8)

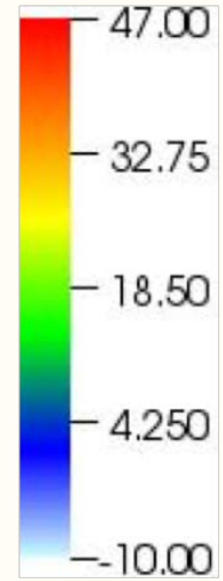


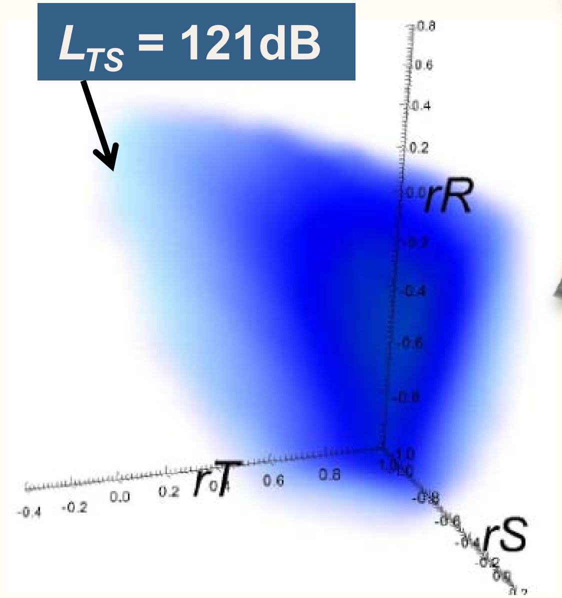


Range of P_S is up to 50 dB due to changes in the correlation matrix

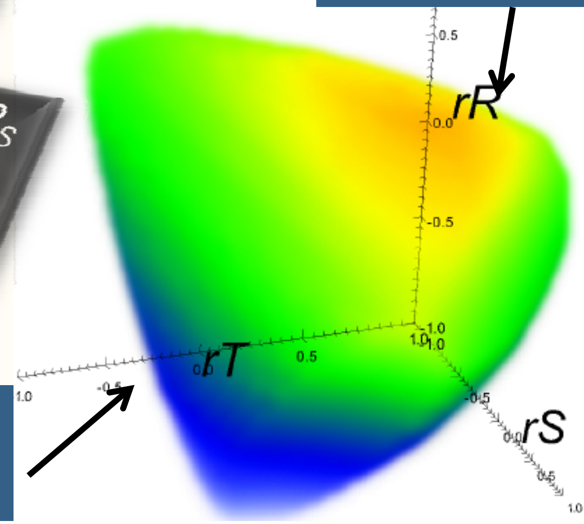
L_{TS} = 121dB

L_{TS} = 133 dB





The minimum of P_S corresponds always to the tuple ($r_T = -1, r_R = -1, r_S = 1$)

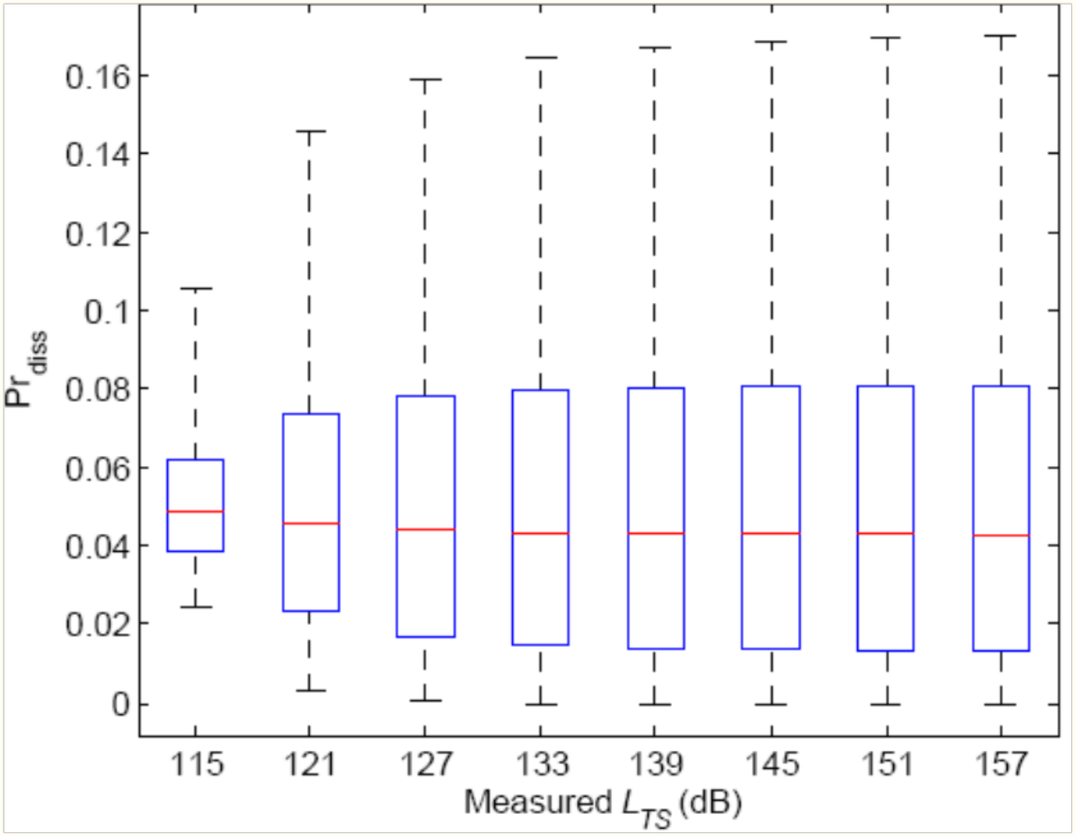


γ_r = 10.9 dB (16QAM, 1/2)

Case with Unknown Correlation Matrix

Assume no correlation when computing P_S

$\varepsilon = 0.05$
$\gamma_r = -2.6$ dB



The median of Pr_{diss} is always lower than ε

The median of Pr_{diss} is decreasing function of L_{TS}, but its range is an increasing function

The value of Pr_{diss} can reach 0.17

Outline

- General overview
- DSA to spatial spectrum holes
- DSA to spatio-temporal spectrum holes
- Uncertainty in propagation models
- Related standards
- Summary and open problems

IEEE P1900 (IEEE DySPAN-SC)

- A standard for Dynamic spectrum access networks
  - Address new technologies and techniques being developed for DSA
- Working Groups
  - IEEE1900.1: Definitions and Concepts for Dynamic Spectrum Access
  - IEEE1900.2: Recommended Practice for the Analysis of Inband and Adjacent Band Interference and Coexistence Between Radio Systems
  - IEEE1900.3: Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules(disbanded)
  - IEEE1900.4: Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks
  - IEEE1900.5: Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications
  - IEEE1900.6: Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems
- New working group1900.7 for white space radio interface

http://grouper.ieee.org/groups/scc41/

IEEE 802.22

- Specifications
  - TV white Space: VHF/UHF bands (54 MHz – 862 MHz)
  - MAC and PHY for large and sparsely populated areas
  - Network with infrastructure for fixed and portable terminals
  - Based on sensing and geolocation database
  - Beacon system for low-power license–exempt devices
- Geo-location
  - Mandatory by the FCC for white Space (2008)
  - GPS-based and triangulation is supported: GPS antenna at each terminal
  - Possibility of off-line geo-location processing
- Beacon
  - Signal of 250 mW transmitted by wireless microphone BS
  - Repeated as pseudo-noise sequences and occupying 78kHz

http://www.ieee802.org/22

More IEEE 802.xx

- IEEE 802.19
  - "Reviews coexistence assurance (CA) documents produced by working groups developing new wireless standards for unlicensed devices"
- IEEE 802.11af
  - "Modifications to both the 802.11 PHY and MAC layers, to meet the legal requirements for channel access and coexistence in the TV White Space"
- IEEE 802.11y: Co-primary access
  - Small non-exclusive fees for Licensees (3650-3700 MHz)
  - Spectrum sharing among licensees
  - Might be applied to IMT Advanced

http://grouper.ieee.org/groups/802/19/
https://mentor.ieee.org/802.19/documents
http://en.wikipedia.org/wiki/IEEE_802.11y-2008

Other Standards

- IETF PAWS: Protocol to Access White Space Devices
  - “Specifying messaging interface between the devices and database”
  - Very early stage of development
    - Based on simple https “get” command
- ETSI RRS: Reconfigurable Radio Systems
  - System solutions and architectures related to software defined radio and Cognitive Radio
  - Cognitive radio in white space for public safety
  - Cognitive Pilot Channel (CPC)

http://www.etsi.org/WebSite/technologies/RRS.aspx
https://www.ietf.org/mailman/listinfo/paws

Outline

- General overview
- DSA to spatial spectrum holes
- DSA to spatio-temporal spectrum holes
- Uncertainty in propagation models
- Related standards
- Summary and open problems

And Now ...

What are the possible roadmaps?

Insight to the Future

- Back to the source: Mitola's cognitive radio
  - A cognitive engine that spans over all layers
  - Machine learning techniques where it is possible
  - Cognitive base stations, femtocells and terminals that can learn their environments
- Application for TV white space
  - Distributed solutions for multiple secondary transmitters
- Dynamic propagation models
- Impact of uncertainty → TRUST
- Spatio-temporal spectrum holes!

ACROPOLIS

European NoE on Cognitive Communications

Thank You!