Networking Cognitive Radios for Dynamic Spectrum Access

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ICC 2010 Tutorial

Tutorial Outline

- Introduction
- Physical layer issues
- MAC layer issues
- Network layer issues
- Conclusion

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- Introduction
- Physical layer issues
- MAC layer issues
- Network layer issues
- Conclusion

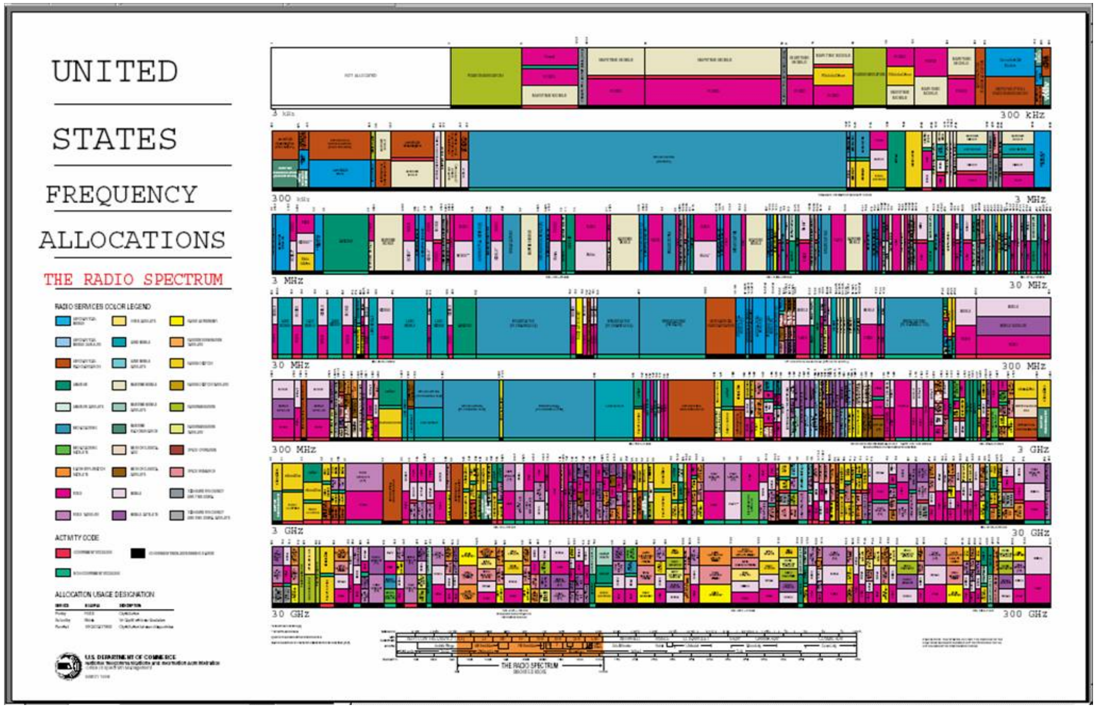
Introduction

- Motivation
- Taxonomy
- Technical challenges
- Applications

• Q. Zhao, A. Swami, “A Survey of Dynamic Spectrum Access: Signal Processing and Networking Perspectives,” ICASSP 2007.

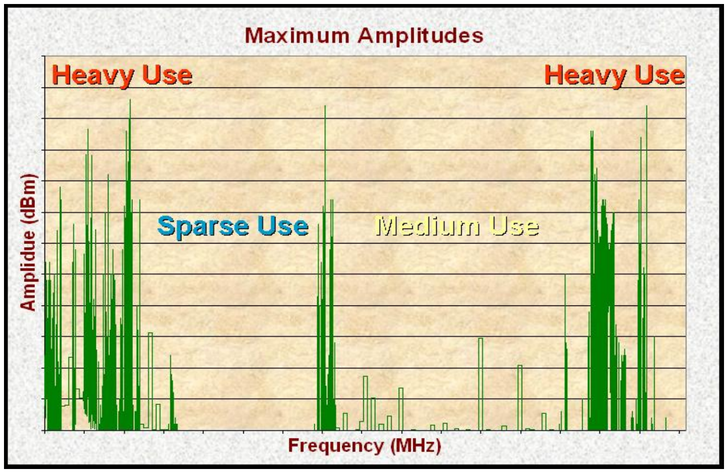
• Q. Zhao, B.M. Sadler, “A Survey of Dynamic Spectrum Access,” IEEE Signal Processing Magazine, May, 2007.

Current Policy & Spectrum Scarcity

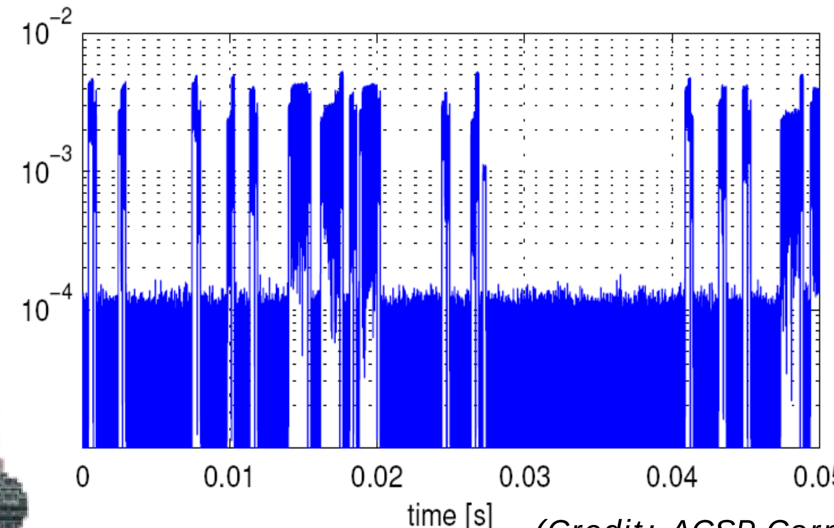


- Fixed allocation
- Little Sharing
- Rigid requirements on how to use

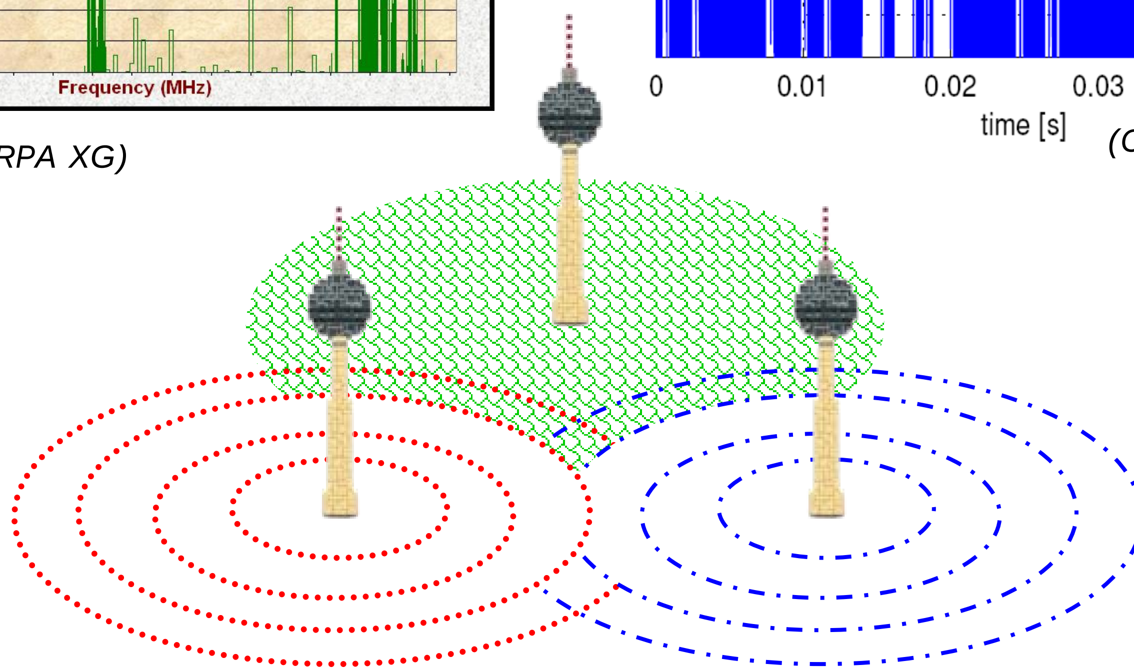
Spectrum Opportunities in Space, Time, & Frequency



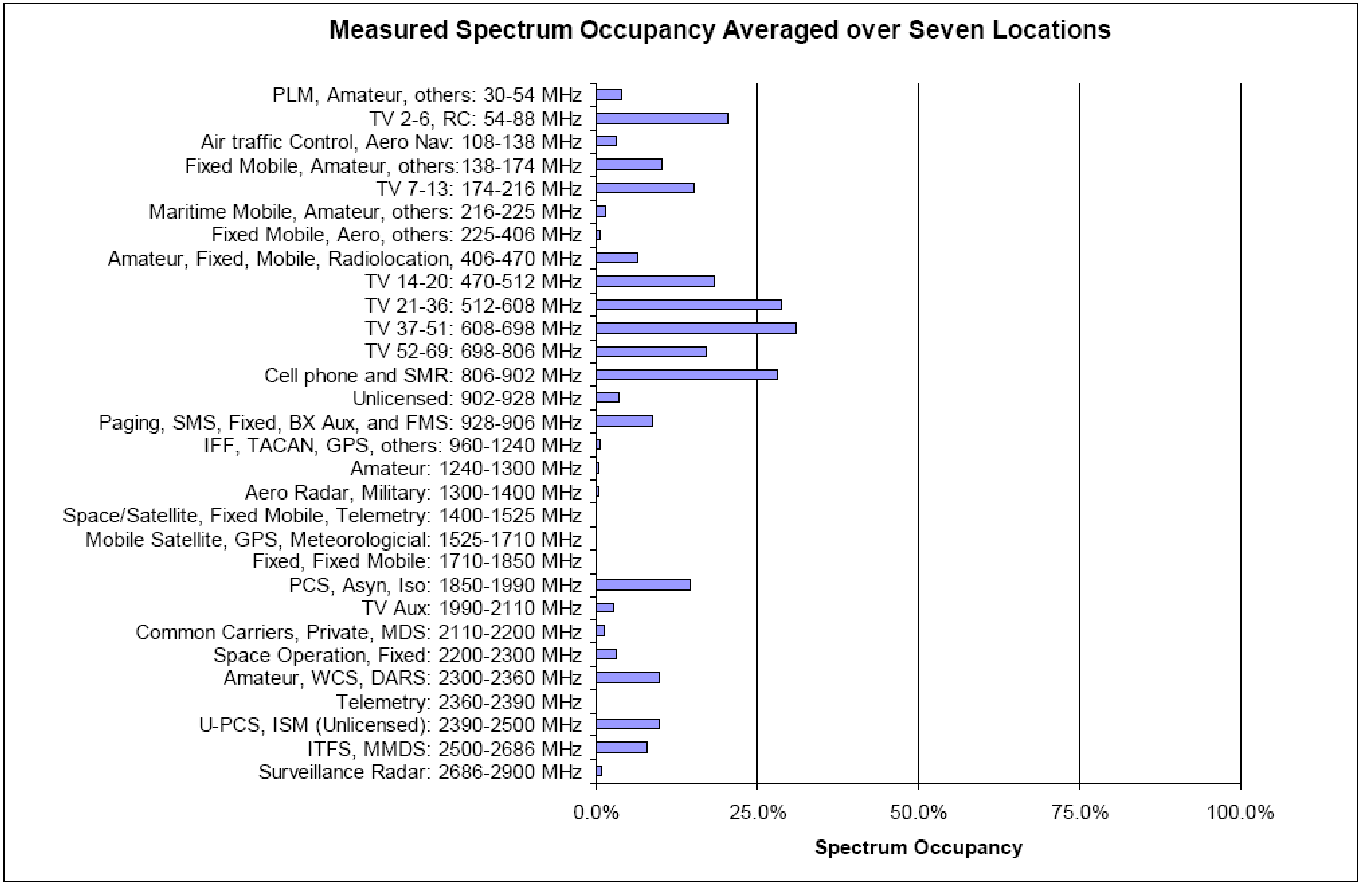
(Credit: DARPA XG)



(Credit: ACSP Cornell)

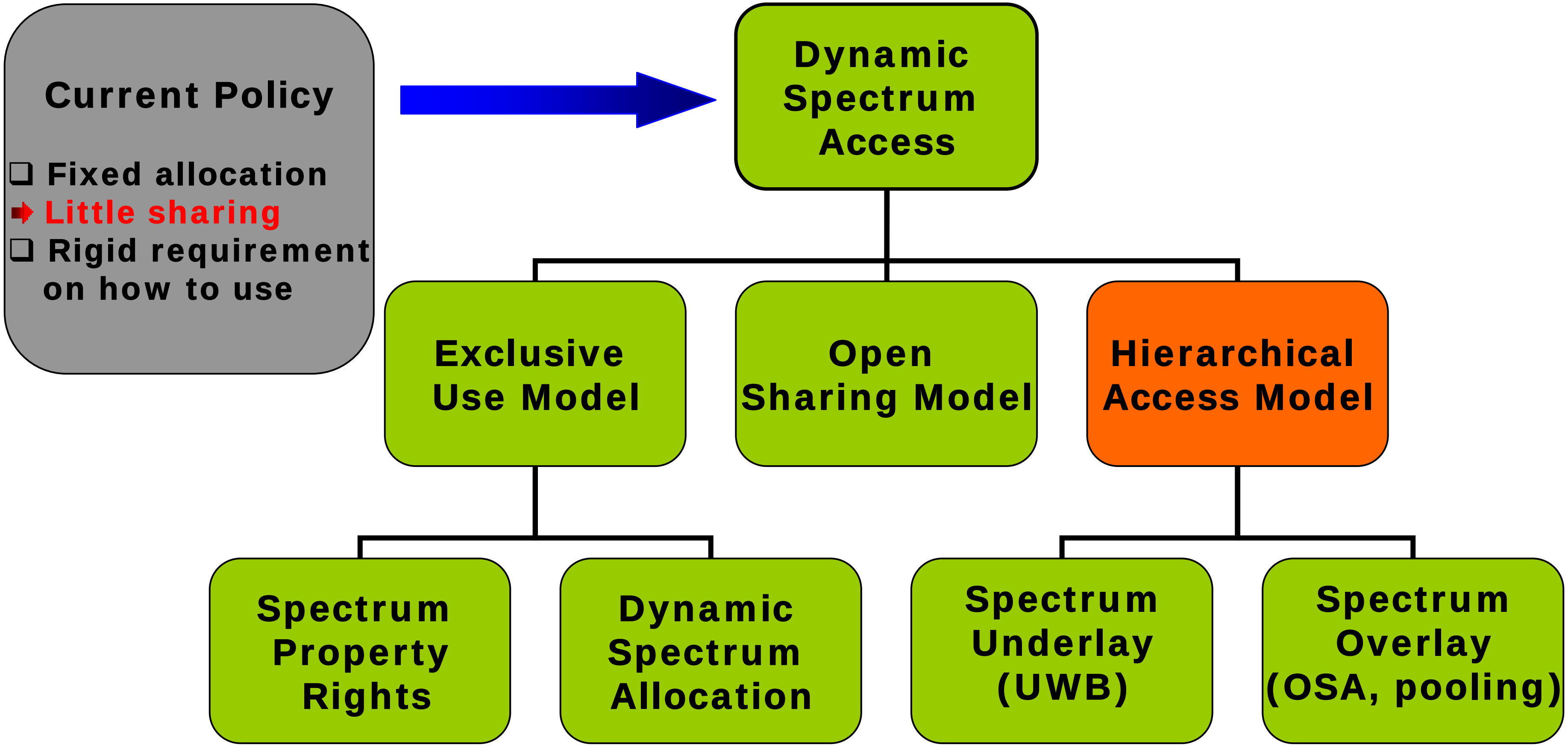


Measured Spectrum Occupancy



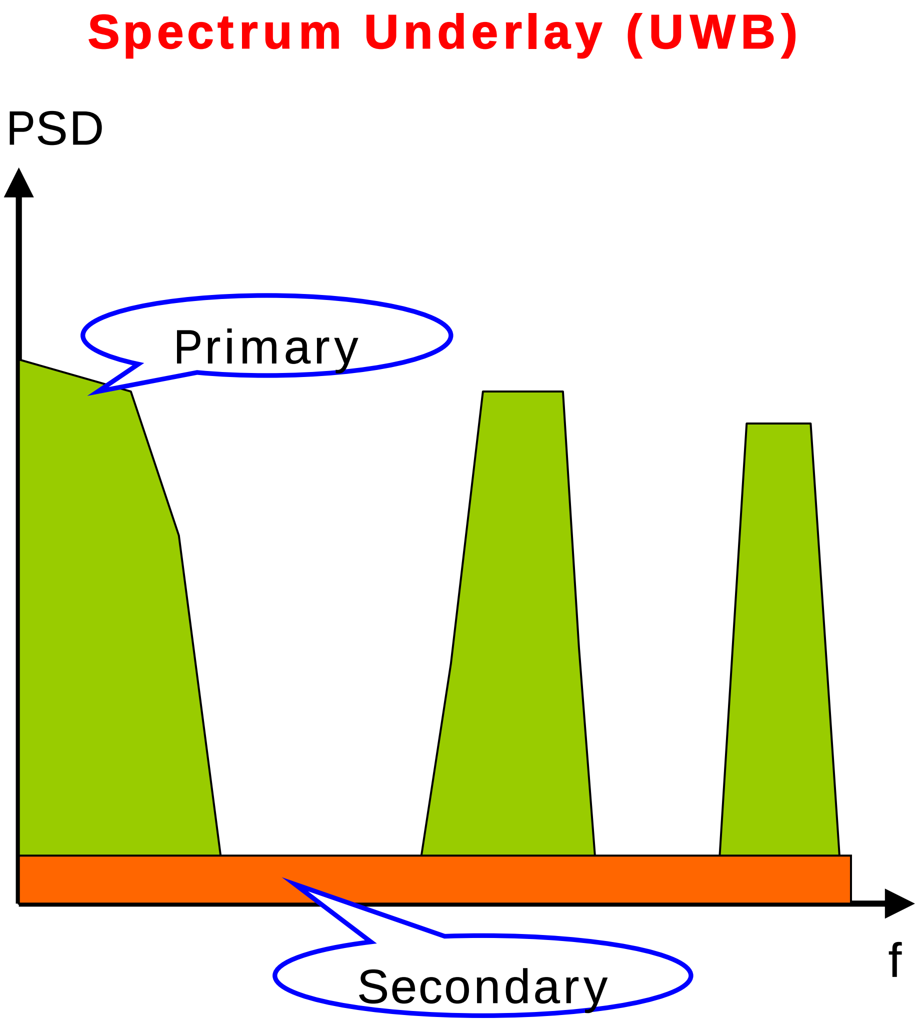
(Credit: SSC)

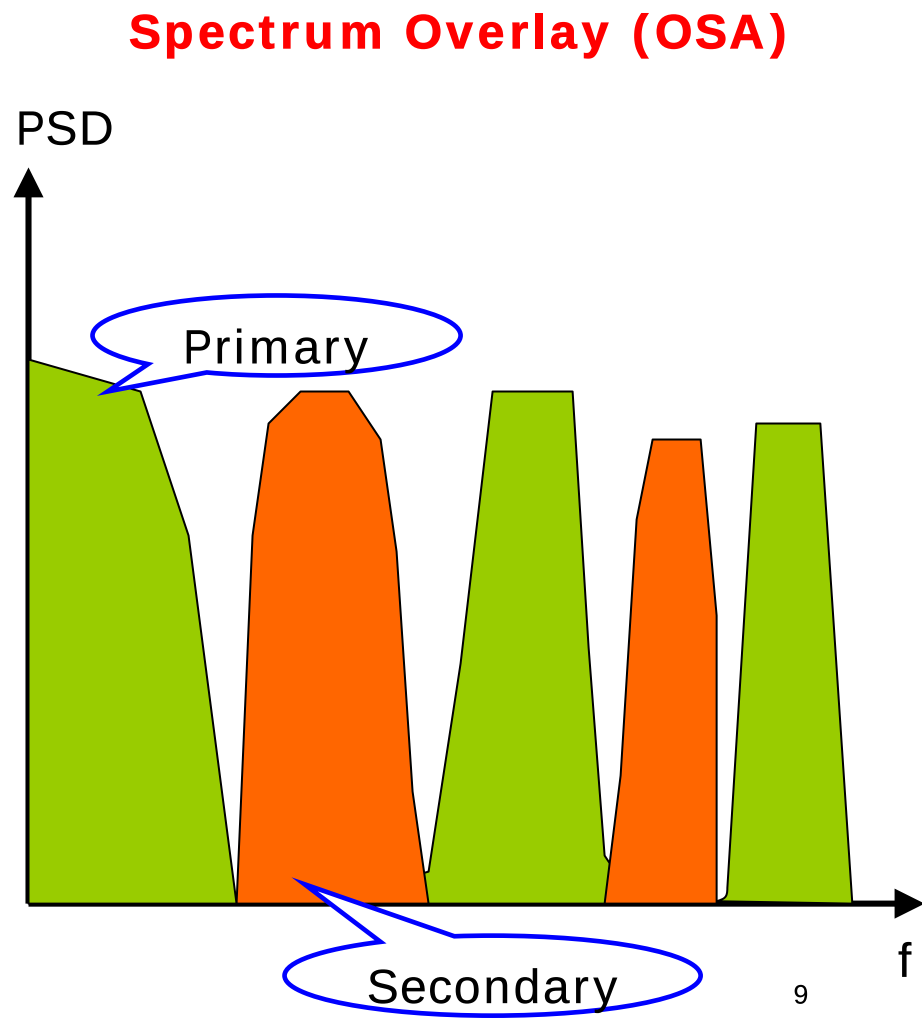
Hierarchical Access Model



- Spectrum underlay: constraint on transmission power
- Spectrum overlay: constraint on when and where to transmit

Underlay vs. Overlay

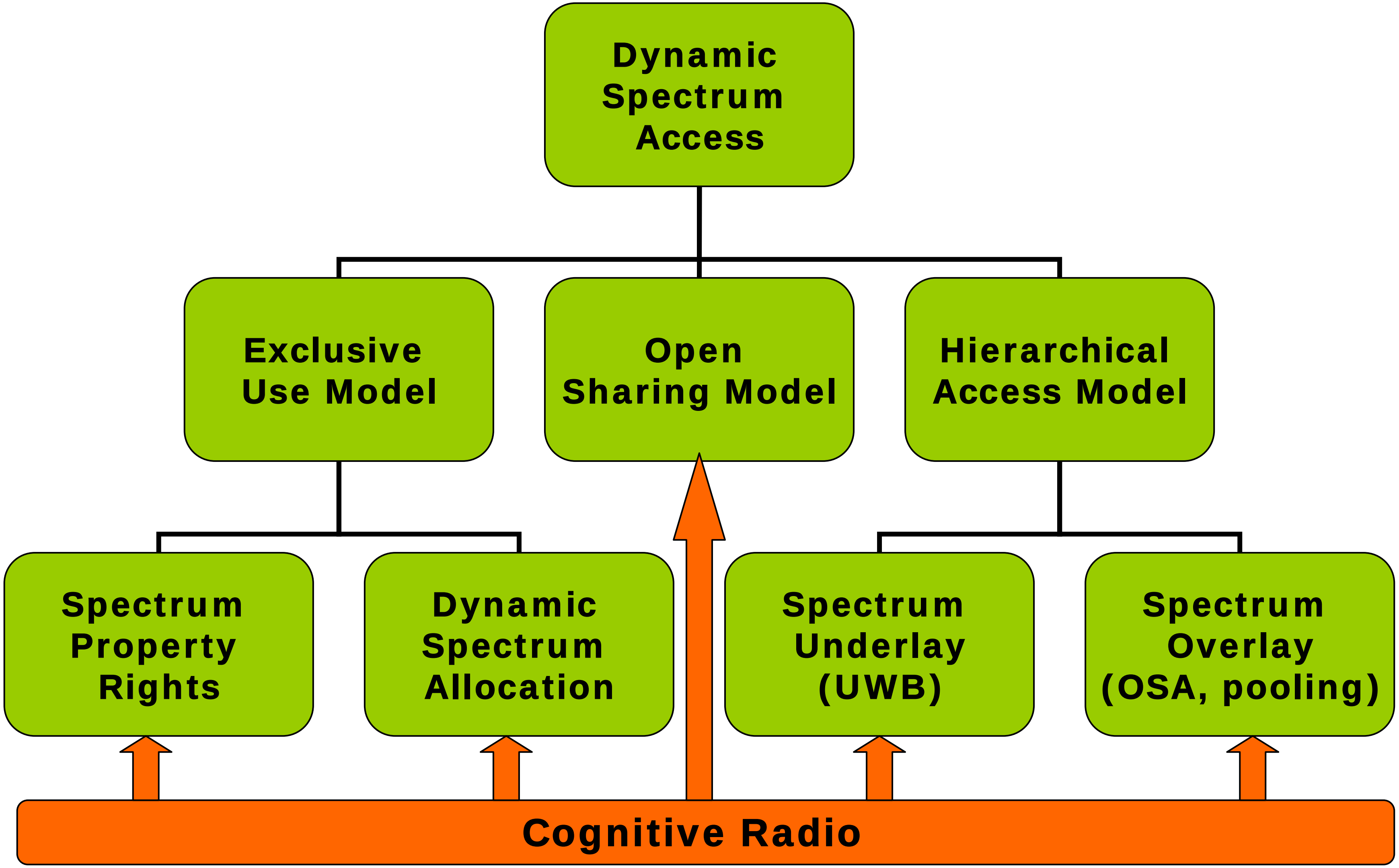




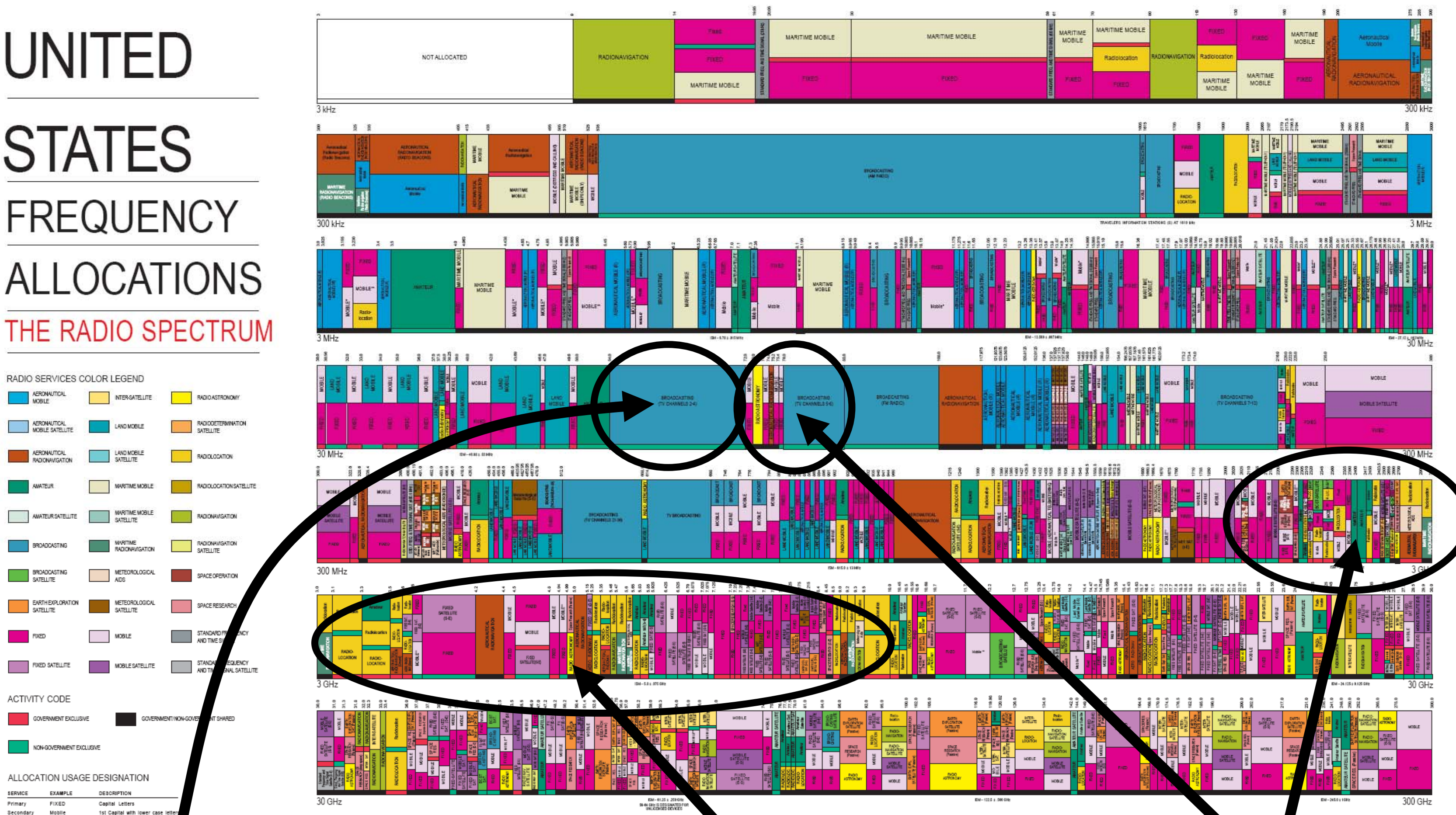
Cognitive Radio

- **Software Defined Radio**
  - Promoted by Mitola in 1991
  - A multiband radio supporting multiple air interfaces and reconfigurable through software
- **Cognitive Radio**
  - Promoted by Mitola in 1998
  - Built upon a software defined radio platform
  - Context-aware, autonomous reconfigurable
  - Learning from and adapting to environment
  - Applications not limited to DSA

Cognitive Radio: The Physical Platform



Toward Dynamic Spectrum Access



Overlay
(54-700M)

Underlay
(3.1-10.6G)

Auction
(A-TV,PCS,C)

Spectrum Overlay: Technical Issues

- Physical Layer
  - Opportunity sensing
  - Interference Aggregation
- MAC Layer
  - Opportunity tracking and learning
  - Opportunity exploitation with imperfect sensing
  - Opportunity sharing
- Network Layer
  - Power control and routing
  - Connectivity

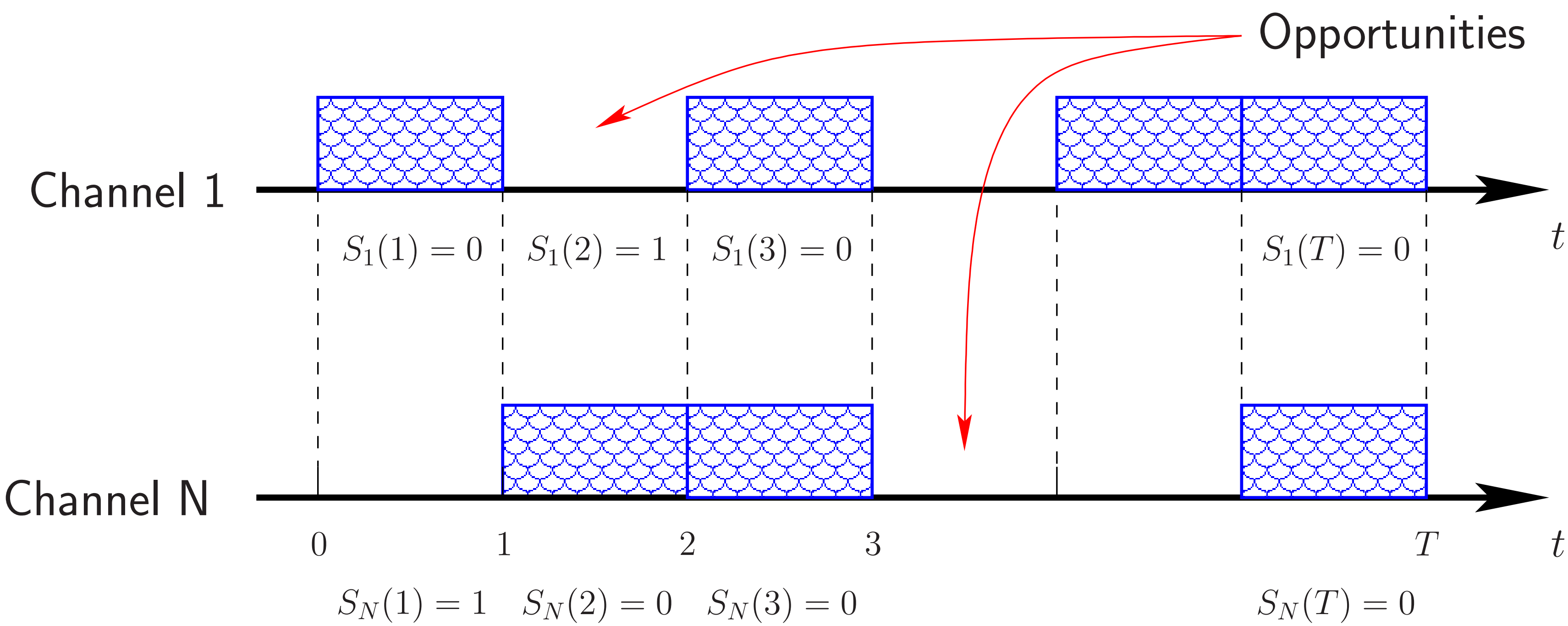
Spectrum Sensing and Opportunity Identification
PHY Layer Issues

- Model and detection problem
- How should we sense?
- Interference Constraints
- Cooperative Sensing
- Hardware Challenges
- Waveform Design & Modulation

References

[1] Q. Zhao and A. Swami, "Spectrum Sensing and Identification", in *Cognitive Radio Communications and Networks*, Elsevier Inc., 2009.

Channel Sensing Model: Slotted Primary Users



- N independent channels, each with bandwidth B_i.
- Secondary users search for opportunities independently.
- Every primary tx interferes with all secondary users (symmetric).
- How to detect whitespace?

802.22 Draft DFS Sensing Requirements

Parameter	Digital TV	Wireless Microphone (Part 74)
Channel Detection Time	$\leq$ 2 sec	$\leq$ 2 sec
Channel Move Time	2 sec	2 sec
Detection Threshold (required sensitivity)	- 116 dBM (over 6 MHz)	- 107 dBm (over 200 KHz)
Probability of detection	0.9	0.9
Probability of false alarm	0.1	0.1
SNR	**- 21 db**	**- 12 dB**

- Low SNR regime

FCC ET Docket no. 03-122, November 18, 2003, Cordeiro et al, Ghosh et al, Shellhammer

Spectrum Sensor at PHY

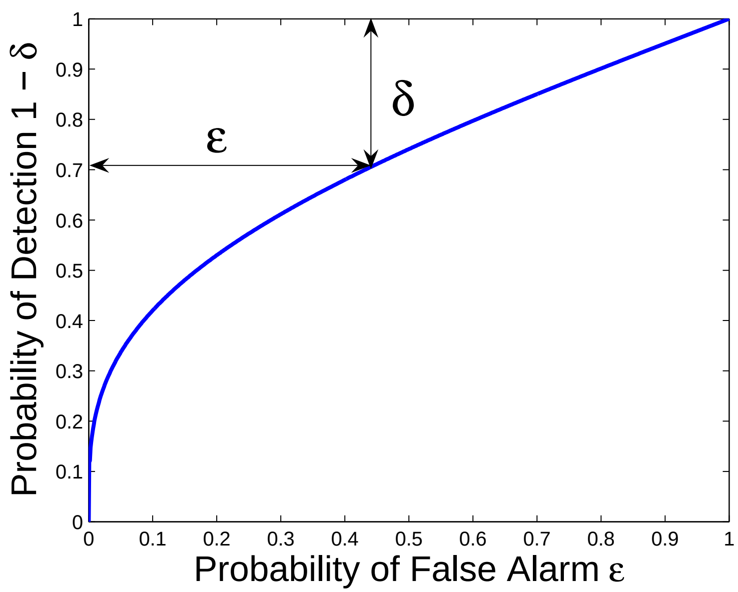
Binary Hypotheses Test:

$$\mathcal{H}_0 \text{ (idle)} \quad \text{vs.} \quad \mathcal{H}_1 \text{ (busy)}$$

Two Types of Sensing Errors:

- opportunity overlook: $\mathcal{H}_0 \rightarrow \mathcal{H}_1$ $\epsilon \triangleq$ prob. of overlook
- opportunity misidentification: $\mathcal{H}_1 \rightarrow \mathcal{H}_0$ $\delta \triangleq$ prob. of misidentification

Receiver Operating Characteristics (ROC): $1 - \delta$ vs. ϵ



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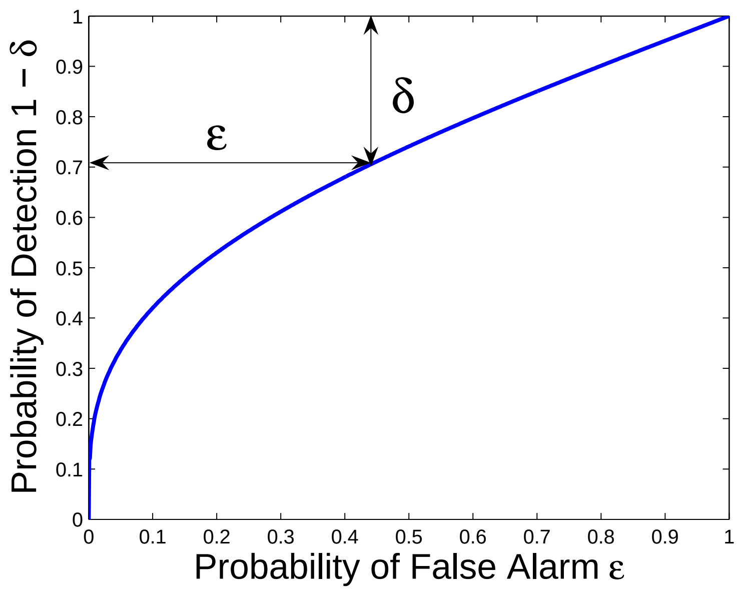


How to choose operating point δ?

- Overlook vs. Misidentification

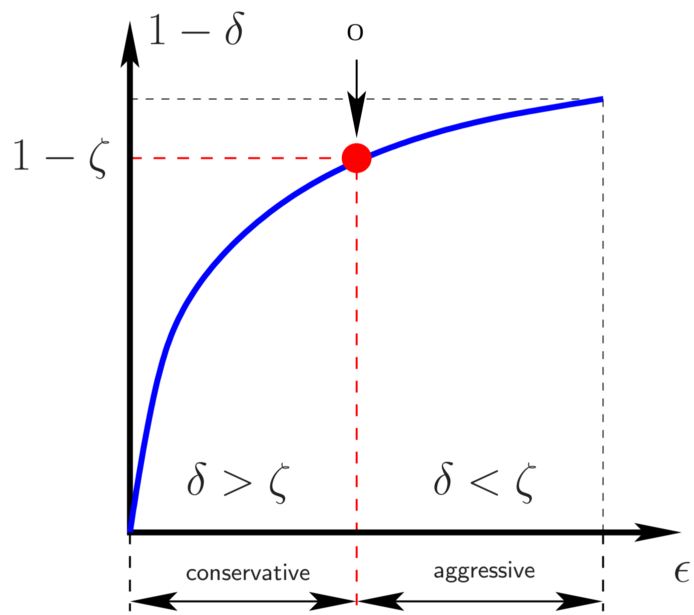
Which is worse:

- false alarm or miss detection?

Spectrum Sensor at PHY: MAC performance

Binary Hypotheses Test:

$$\mathcal{H}_0 \text{ (idle)} \quad \text{vs.} \quad \mathcal{H}_1 \text{ (busy)}$$

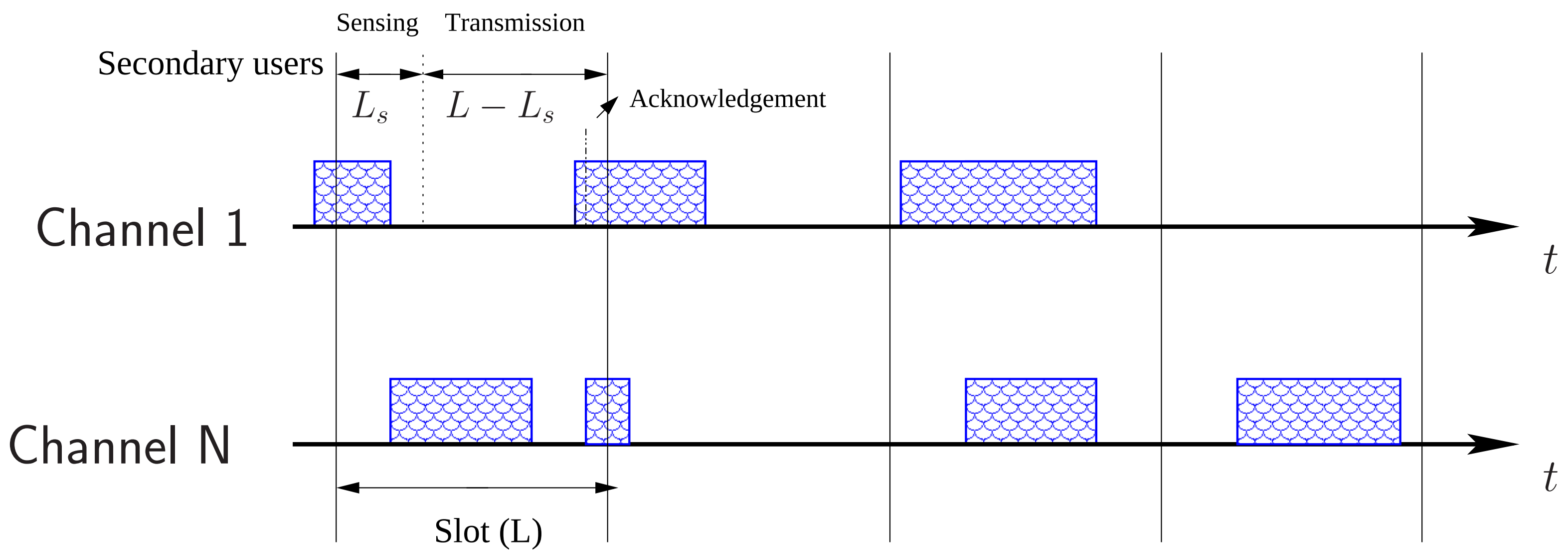


MAC Layer Performance

- Probability of success P_S (throughput)
- Probability of collision P_C
- Objective: $\max P_S \quad s.t. \quad P_C \leq \zeta$

How to choose operating point δ?

Channel Sensing Model: unslotted primary users



- Slotted secondary usage, with sensing, data, and ACK periods
- Problem: Given measurements during sensing time, detect the channel state during transmission time.
  Is a sensed idle channel an opportunity?
- Challenge: Even with perfect sensing, opportunity detection is subject to errors.
  How to choose the operating point $(\epsilon_n(k), \delta_n(k))$ **for each channel at each slot?**

Spectrum Sensing: Some key questions

- Model and detection problem
- **How should we sense?**
  - Choice of detectors
    - Bayesian vs. Neyman-Pearson
    - Energy detector vs. Cyclic detector vs. Matched filter
  - Tradeoff SU QoS with PU protection
  - Detecting spectrum opportunities
- Interference Constraints

Energy Detection

- Pros: easily implemented; minimal assumptions
- Cons: poor performance with noise uncertainty
  and with multiple secondary users
  Performance $\sim 1/\mathrm{SNR}^2$ at low SNR

$$H_0 : (\text{idle}) \quad y(n) = w(n), \quad n = 1, ..., N, \text{AWGN}$$

$$H_1 : (\text{busy}) \quad y(n) = w(n) + s(n)$$

$$\text{Decide} \quad H_1 \text{ if } z = \frac{1}{N}\sum_{n=1}^{N} |y(n)|^2 > \tau(N, \sigma_w^2)$$

$$\text{Under } H_0 : \qquad z \sim \mathcal{N}(\sigma_w^2, \sigma_w^4/N)$$

$$\text{Under } H_1 : \qquad z \sim \mathcal{N}(\sigma_y^2, \sigma_y^4/N), \quad \sigma_y^2 := \sigma_w^2 + \sigma_s^2$$

$$\mu_1 - \mu_0 \;=\; \sigma_0 Q^{-1}(P_{FA}) - \sigma_1 Q^{-1}(P_D)$$

$$\sqrt{N}\mathrm{SNR} = Q^{-1}(P_{FA}) - (1 + \mathrm{SNR})Q^{-1}(P_D)$$

- Problems if noise variance is not known
- Choosing sensing length to maximize throughput

How long should the sensing time be

- Channel coherence
- Primary's traffic patterns (e.g., fractional on-time)
- Interference constraints
- Primary and secondary user powers; noise power
- Fading, multipath, shadowing
- Multiple primaries? Spatial distribution
- Multiple secondary users? (aggregate interference)
- SU QoS (rate, reliability, latency) and constraints (power, cooperation)
- Can we exploit PU Modulation, pilots, sync signals,
- Complexity and specifics of algorithms
- Robustness

Detection problem cannot be solved in isolation

Spectrum Sensing: Some key questions

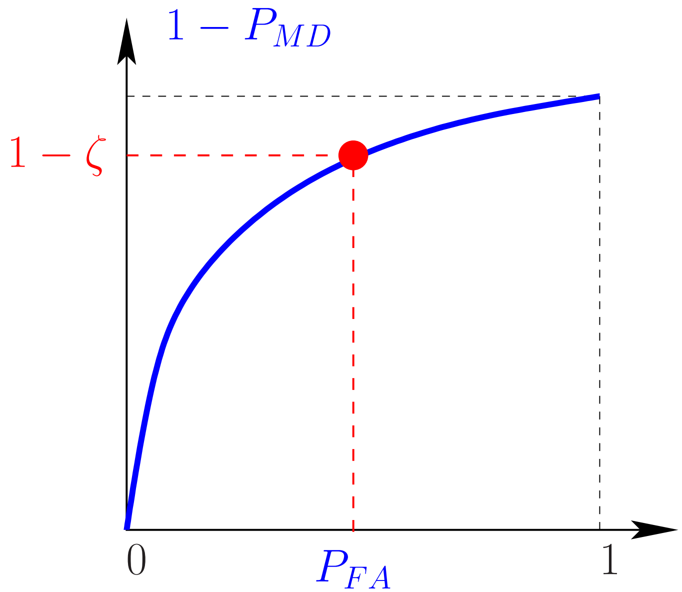
- Model and detection problem
- **How should we sense?**
  - Choice of detectors
  - Tradeoff SU QoS with PU protection
  - Detecting spectrum opportunities
    - Choosing 'sensing radius' or threshold
    - Tradeoffs with transmission power or range
    - Interaction with MAC
- Interference Constraints

Whitespace Detection to Opportunity Detection

- Is detecting primary signals = detecting spectrum opportunity?
- How does PHY performance translate to MAC performance?

We want to detect primary receivers!

PU locations are unknown

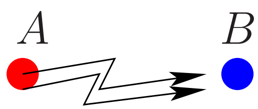


If PU is loud but SU is not listening, is it interference? SU-TX and SU-TX must jointly detect opportunities

$$P_S = (1 - P_{FA}) \Pr[\mathcal{H}_0]$$

$$P_C = P_{MD}$$

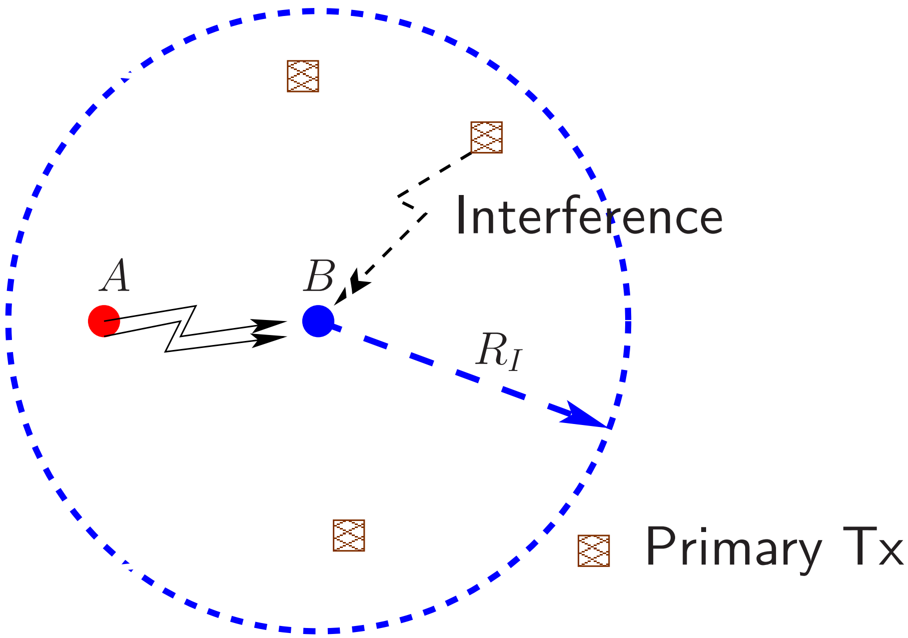
Spectrum Opportunity: Definition



A channel is an opportunity for $A \longrightarrow B$ if

- the transmission from A to B can succeed
- the interference power to primary is below a prescribed level

Spectrum Opportunity: Definition



- R_I: interference range of primary users

  $R_I \propto P_{tx}^{1/\alpha}$

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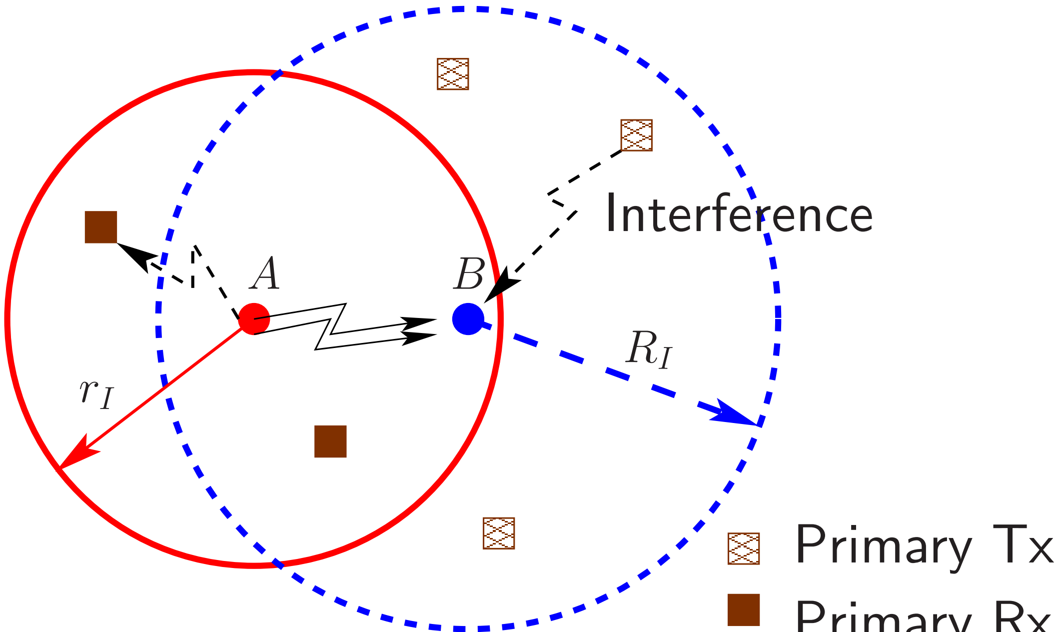

- R_I: interference range of primary users
  $R_I \propto P_{tx}^{1/\alpha}$
- r_I: interference range of secondary users
  $r_I \propto p_{tx}^{1/\alpha}$

A channel is an opportunity for $A \longrightarrow B$ if

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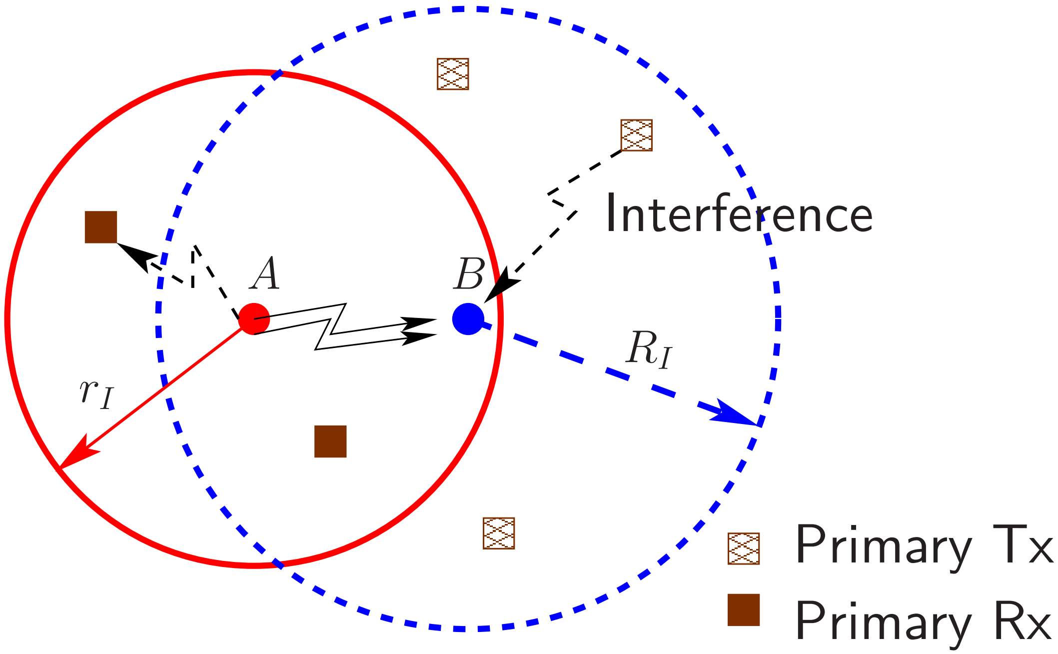
- the interference power to primary is below a prescribed level

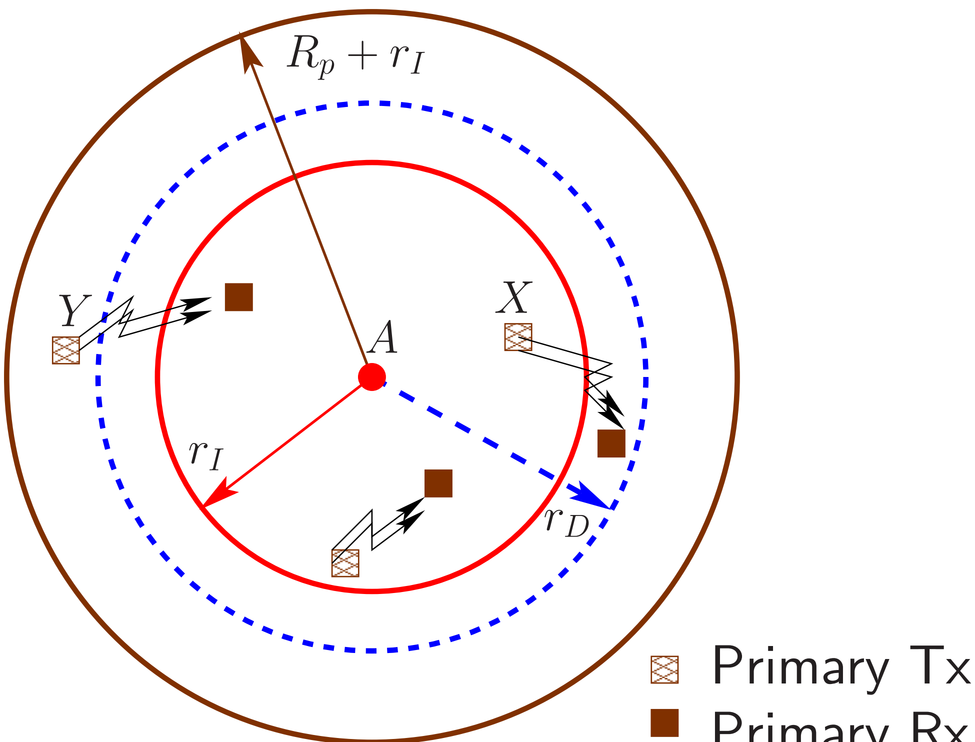
Spectrum Opportunity: Properties



- R_I: interference range of primary users
  $R_I \propto P_{tx}^{1/\alpha}$
- r_I: interference range of secondary users
  $r_I \propto p_{tx}^{1/\alpha}$

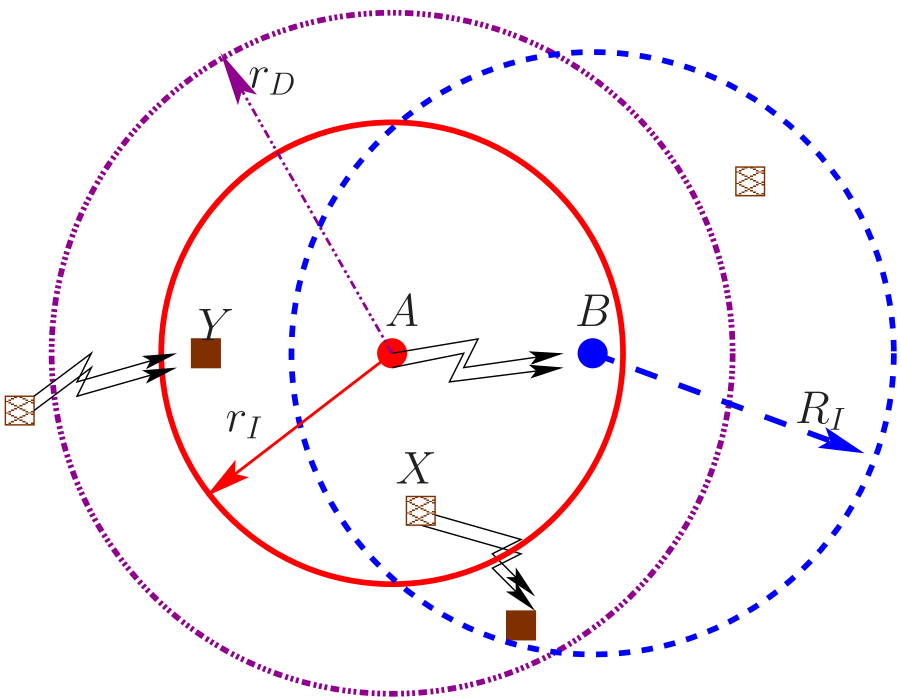
- determined by both transmitting and receiving activities of primary users.
- Asymmetric (an opportunity for $A \longrightarrow B$ may not be one for $B \longrightarrow A$).

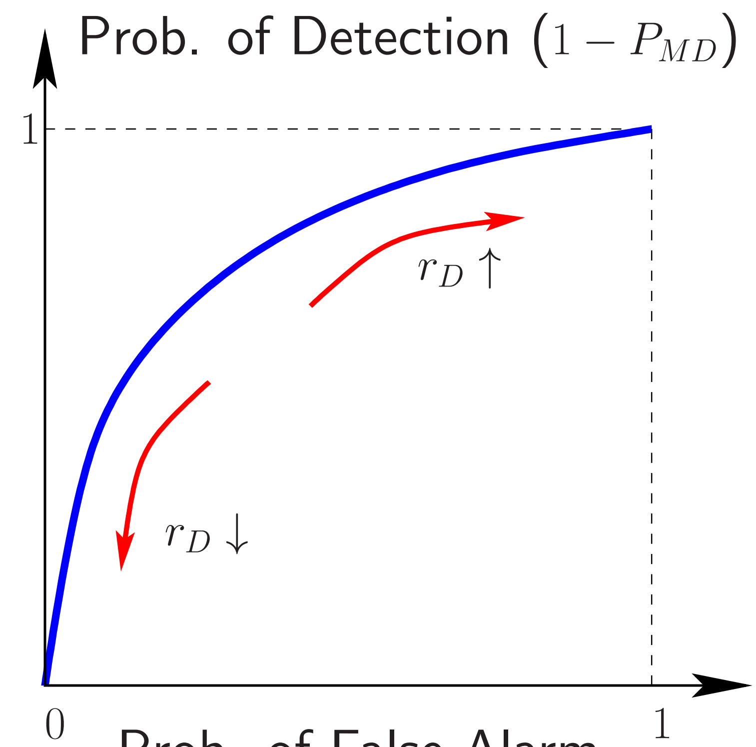
Detection of Primary Receivers (LBT)



- r_I: interference range, R_p: primary tx range, r_D: detection range
- Detecting primary Rx within r_I by detecting primary Tx within r_D
- False alarms and miss detections occur due to noise and fading

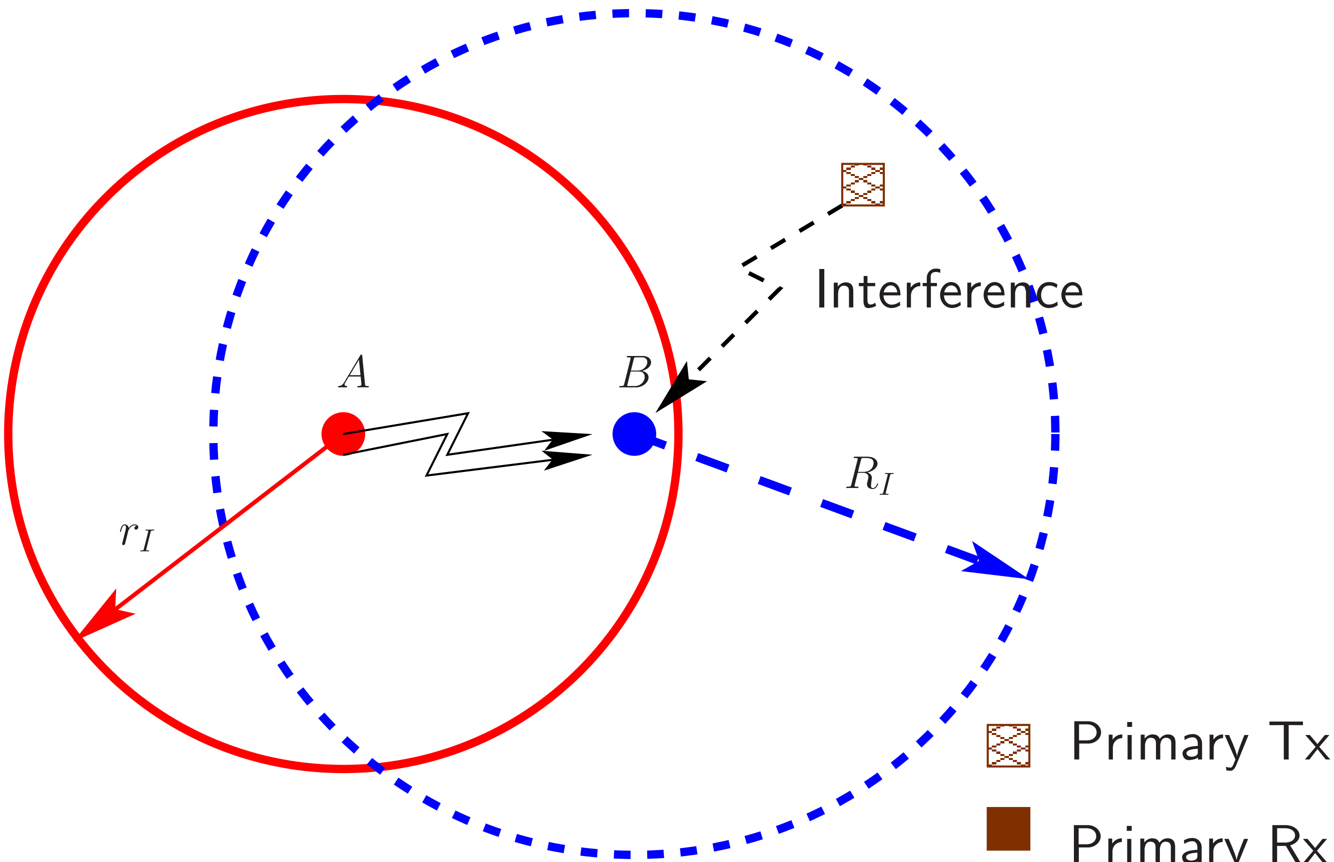
From Detecting Signal to Detecting Opportunity





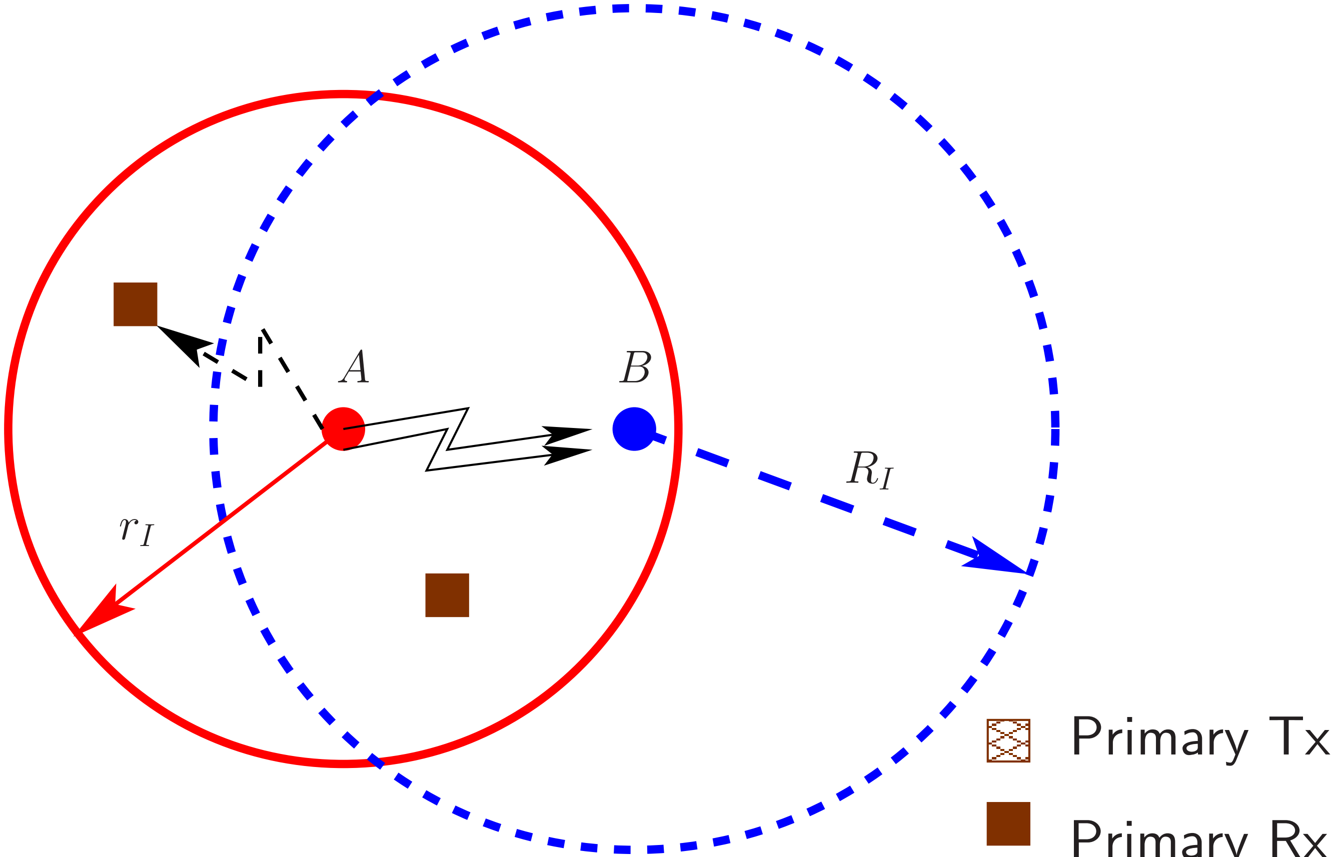
- $\mathcal{H}_0$: opportunity, $\mathcal{H}_1$: alternative.
- Even with perfect ears, exposed Tx $(X) \Rightarrow$ FA, hidden Rx $(Y) \Rightarrow$ MD.
- Adjusting detection range r_D leads to different operating points.

Miss Detection May not Lead to Collision



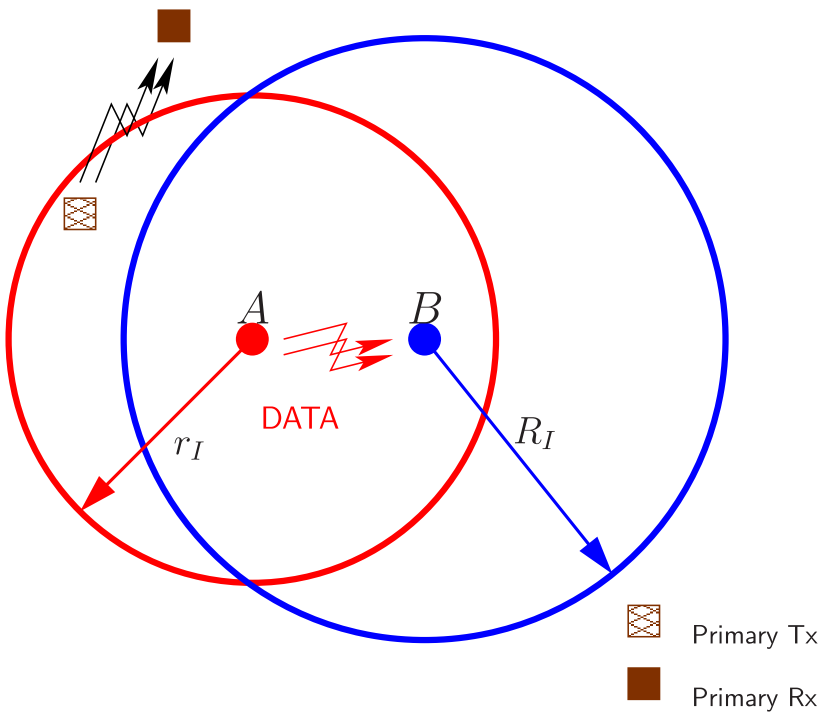
- There is no primary receiver around A
- There are primary transmitters around B

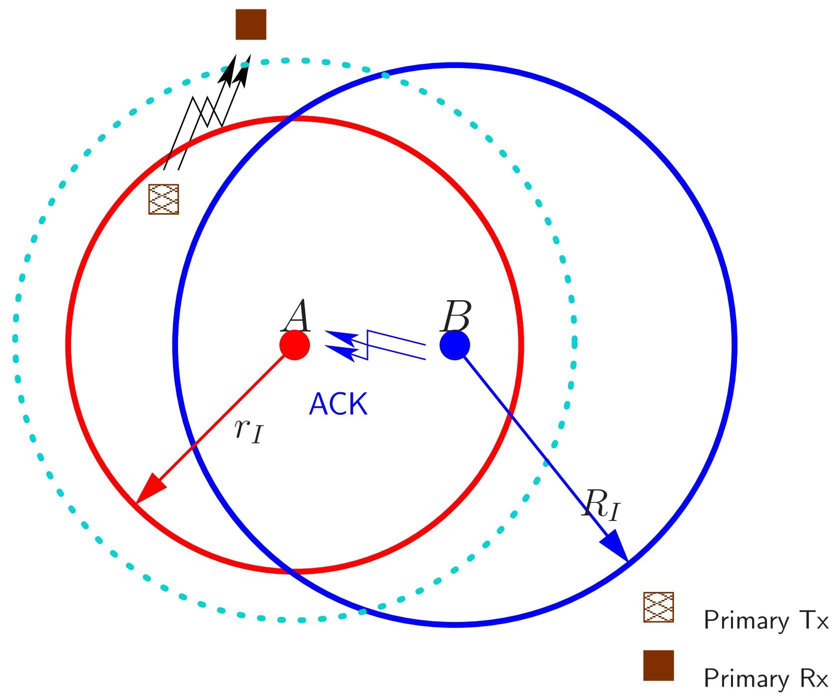
Miss Detection May Lead to Success



- There are primary receivers around A
- There is no primary transmitter around B

Correctly Identified Opportunity May Not Lead to Success

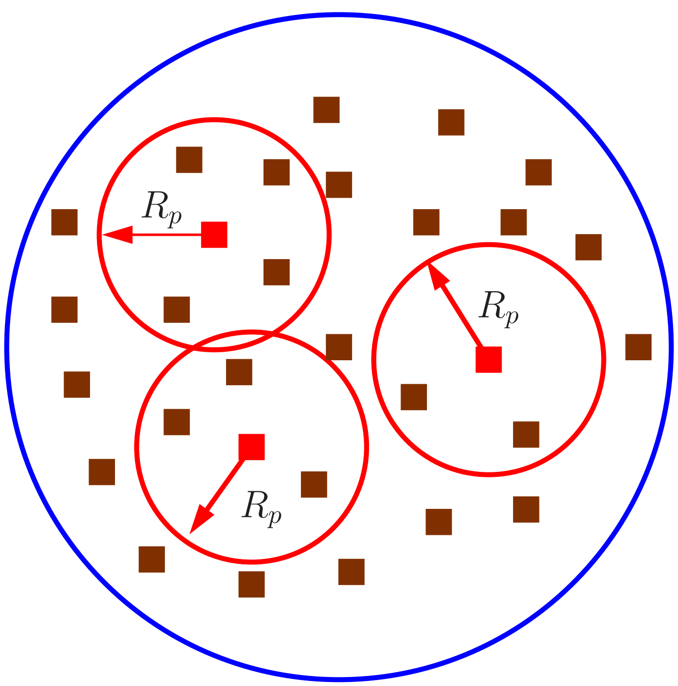




- Successful data transmission and failed ACK

Network Model

- Primary users form a Poisson point process with density λ.
- Each primary user transmits with probability p in a slot.
- Primary receivers are uniformly distributed within R_p of their transmitters.



- Analytical expressions for P_{FA}, P_{MD}, P_C, P_S
- For LBT and for RTS-CTS enabled LBT

Zhao-Ren-Swami, Asilomar '07

Summary of Opportunity Detection

Spectrum Opportunity

- Determined by both transmitting and receiving activities of primary users
- Asymmetric (an opportunity for $A \longrightarrow B$ may not be one for $B \longrightarrow A$)

Equivalence of Detecting Signal and Opportunity

- Inevitability of opportunity detection errors
- A necessary and sufficient condition

Translation from PHY Performance to MAC Performance

- Crucial for choosing optimal detector operating point
- Complex dependency on the application type and MAC

Choice of sensor operating point cannot be decoupled from sensing and accessing policies

Interference Constraints

Policy Issues: What to impose, How to monitor?

- How to impose?
- Need to specify allowed probability of interference ζ
  at prescribed interference level η to PU
- $[\eta, \zeta]$ is a PU-protection / SU-QoS tradeoff
- Conditional or joint probability of collision ?
- Impose on per-slot basis, or on average ?

- From aggregate to node-level parameters?
- Requires knowledge of node location, traffic, and channel models

- How to monitor?

Backups

Spectrum Sensor at PHY

Binary Hypotheses Test: (channel n in slot k)

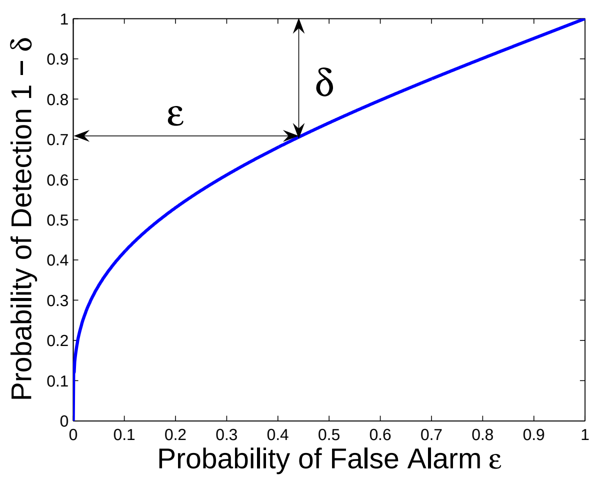
$$\mathcal{H}_0 \ (O_n(k) = 1 : \text{opportunity}) \quad \text{vs.} \quad \mathcal{H}_1 \ (O_n(k) = 0 : \text{no opportunity})$$

- Let $\hat{O}_n(k)$ denote the sensing outcome.

Two Types of Sensing Errors:

- false alarm: $\mathcal{H}_0 \to \mathcal{H}_1$ $\quad \epsilon_n(k) \stackrel{\Delta}{=} Pr\{\hat{O}_n(k) = 0 | O_n(k) = 1\}$
- miss detection: $\mathcal{H}_1 \to \mathcal{H}_0$ $\quad \delta_n(k) \stackrel{\Delta}{=} Pr\{\hat{O}_n(k) = 0 | O_n(k) = 1\}$

Receiver Operating Characteristics (ROC): $1 - \delta$ **vs.** ϵ



How to choose the operating point $(\epsilon_n(k), \delta_n(k))$

for each channel at each slot?

Choice of Detectors - Cyclic Detectors (2)

- Exploit guard bands in frequency, known carriers, data rates, modulation type
- Pros: f_c, T_s easy to detect via square-law devices, or cyclic approaches
  Cyclic approaches useful when σ_n^2 is unknown (avoid SNR wall)

$$\text{Test Statistic}: \; S(f;\tau) = \frac{1}{N}\sum_n y(n)y(n+\tau)e^{-j2\pi fn}$$

  Easily implemented via FFTs
- Cons: Timing and frequency jitter can be detrimental
  Requires long integration times
  RF non-linearities; Spectral leakage (ACI).

Cabric *et al*, Asiloamr'04
Ghozzi *et al*, Crowncom'06
Lee-Yoon-Kim,ICIPC'07
Ye *et al*, SPS Wkshp '07
Cabric-Brodersen, PIMRC'05
da Silva-Choi-Kim,ITA Wkhsp '07
Kim *et al*, Dyspan'07
Tu *et al*, PIMRC'07
Sutton-Nolan-Doyle, JSAC'08

General references on cyclic detection: Giannakis; Gardener

Choice of Detectors: Matched Filter (3)

- Exploit pilots or sync (PN) sequences in primary (WRAN 802.22)

$$\text{Test Statistic}: \quad z = \frac{1}{N}\sum_{n=1}^{N} y(n)s(n)$$

- Pros: Correlation detection is usually better than energy detection.
  Performance $\sim 1/\text{SNR}$ at low SNR

$$Q^{-1}(P_{FA}) - Q^{-1}(P_D) = \sqrt{N\text{SNR}}$$

- Cons: fading may null pilot; need to cope with time and freq sync

Li *et al*, JSAC'07 - Exploits pilots, for interference detection
Kundargi-Tewfik, ICASSP'08 - sequential tests with pilots
Yu-Sung-Lee, ICASSP'08 - exploit PU pilots

Other Detectors based on

Receiver leakage	Wild-Ramachandran, Dyspan'05	HMM classifier	Kyouwoong *et al*, Dyspan'07
Signal correlation	Zeng *et al*, PIMRC'07	Wavelet-based	Tian-Giannakis, CrownCom'06
Fast fading	Larson-Regnoli, CommLett'07	Multi-resolution	Neihart-Roy-Allstot, ISCAS'07
Multiple antennas	Pandhripande-Linnartz, ICC'07	Compressed sensing	Tian-Giannakis, ICASSP'07

Optimizing sensing time for detection

$$N \approx 2(\text{SNR})^{-2}[Q^{-1}(P_{FA}) - Q^{-1}(P_D)]^2$$

- What if we do not know the noise variance?
- Could use sample estimate of noise variance,

$$\hat{\sigma}_w^2 \in [a\sigma_w^2, b\sigma_w^2], \quad a, b \sim 1/\sqrt{N}$$

- To ensure desired performance with uncertainty, need

$$N \approx 2(\text{SNR} - \Delta)^{-2}[bQ^{-1}(P_{FA}) - (\text{SNR} + a)Q^{-1}(P_D)]^2$$

- Energy Detector breaks down when SNR $\approx \Delta = b - a$, uncertainty

Tandra and Sahai's SNR wall, JSTSP, 2008

- Example: 6 MHz BW, 1 sec. obs time, $\Delta \approx 0.0022$, SNR threshold $= -23$dB, close to operating SNR of -21 dB in the 802.22 standard
- Robustness to model imperfections important at low SNR

Optimizing sensing time for throughput

- Trade off sensing accuracy of throughput
- Slot size of length N - devote n samples for sensing
- Maximize throughput efficiency

$$\eta(n) := \frac{N-n}{N} \quad [1 - P_{FA}(n)]$$

- For specified P_D (interference constraint)

$$P_{FA}(n) = Q\left((1+\mathrm{SNR})Q^{-1}(P_D) + \mathrm{SNR}\sqrt{n}\right)$$

- $\mathbf{n}^*$ and η increase as $N \uparrow$
- $\mathbf{n}^* \quad \downarrow$ and $\eta \ \uparrow$ as SNR $\uparrow$
- $\mathbf{n}^* \quad \uparrow$ and $\eta \ \downarrow$ as interference constraint $\downarrow$
- Does this represent SU performance?

Wang *et al*, WCNC 2007

Kattepur *et al*, ICICSP 2007

Cooperative Schemes

- Benefits: combat fading, shadowing, poor sensors
- Overhead: control channel? broker?
- Trust issues: - jammed links, malicious nodes
- Fairness
- Time scales - latency
- Increased uncertainty due to aggregate interference
- Many based on 'distributed estimation detection' ideas

Cabric-Mishra-Brodersen, Asilomar'04
Ghasemi-Sousa, Dyspan'05
Mishra-Sahai-Brodersen, ICC'06 - correlated fading; detecting malicious users
Qihang *et al*, PIMRC'06 - uses Dempster-Shafer theory
Yi *et al*, PIMRC'07 - relies on multi-hop cooperation
Gandetto-Regazzoni, JSAC'07 - distributed detection
Tahrepour *et al*, IET Commun, 07 - asymptotic theory, sequential detection
Ma-Li, Globecom'07 - extensions of MRC, EGC
Chen-Wang-Li, ISWCS'07 - learns local ROC parameters
Peh-Liang, WCNC'07 - select users for cooperation
Ganesan *et al*, TWC'07, JSAC'08- optimal pairing of SU's to improve detection
Quan-Sayed,JSTSP'08 - linear combining
Unnikrishnan-Veeravalli, JSTSP'08 - linear-quadratic fusion of LLR's

Hardware Challenges

- Large bandwidth and sampling rates
  PU load dictates scanning architecture
- Dynamic range
- Linearity of analog circuits (mixers, etc)
- Adjacent channel interference
- Adaptive notch filtering
- Active interference cancellation

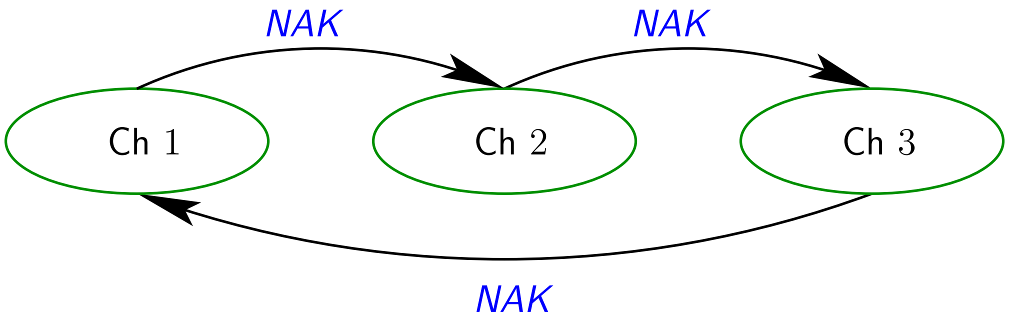
Cabric-Mishra-Brodersen, Asilomar'04
Cabric-Brodersen, PIMRC'05
Mayer *et al*, ECWT'07, PIMRC'07
Luu-Daneshrad, JSAC 2007
Jia-Zhang-Shen, JSAC 2008

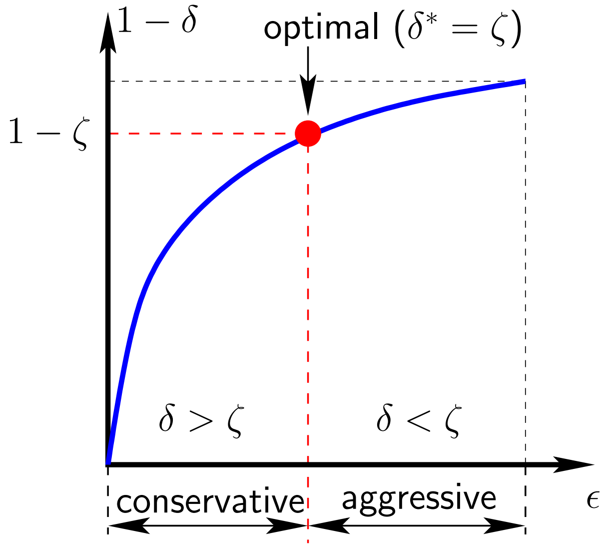
Waveform Design / Modulation

- OFDMA has emerged as natural standard
- Time-frequency granularity well-suited to filling holes
- ACI in sensing
- Hardware non-linearities and ACI in transmit
- Null subcarriers to protect PU from ACI
  (1440 data carriers out of 2048 in 802.22)
- PAPR issues
- Dictates pulse shape design
- Symbol period dictated by channel and SO coherence times
- SU transmit power dictated by allowed interference to PU

Weiss-Jondral, Comm Mag, 2004
Berthold-Jondral, Dyspan 2005
Tang, Dyspan 2005
Wright, AccessNets 07

MAC Issues in Opportunistic Spectrum Access





Searching for Opportunities with Limited Sensing

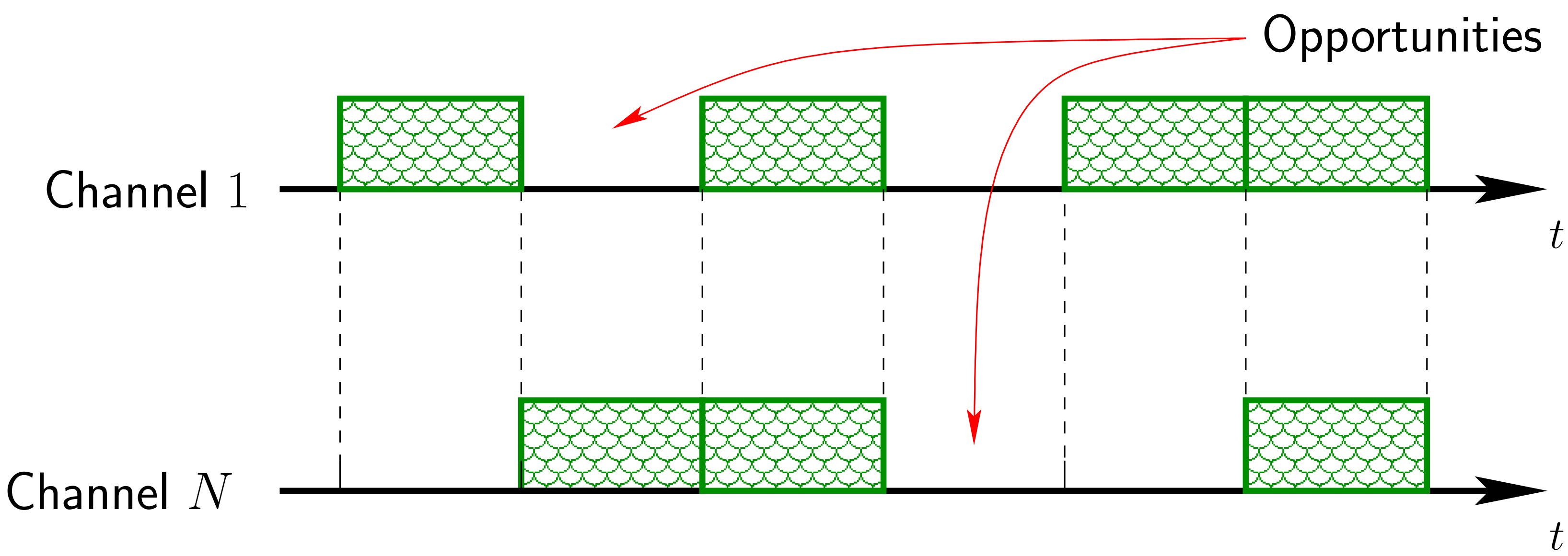
References:

* K. Liu, Q. Zhao, "Indexability of Restless Bandit Problems and Optimality of Whittle's Index for Dynamic Multichannel Access," submitted to *IEEE Trans. Information Theory*, available at http://arxiv.org/abs/0810.4658 (conference version: SECON'2008).

* Q. Zhao, B. Krishnamachari, and K. Liu, "On Myopic Sensing for Multi-Channel Opportunistic Access," in *IEEE Trans on Wireless Communications*, Dec., 2008.

* Y. Chen, Q. Zhao, and A. Swami, "Joint Design and Separation Principle for Opportunistic Spectrum Access in the Presence of Sensing Errors," *IEEE Transactions on Information Theory*, May, 2008.

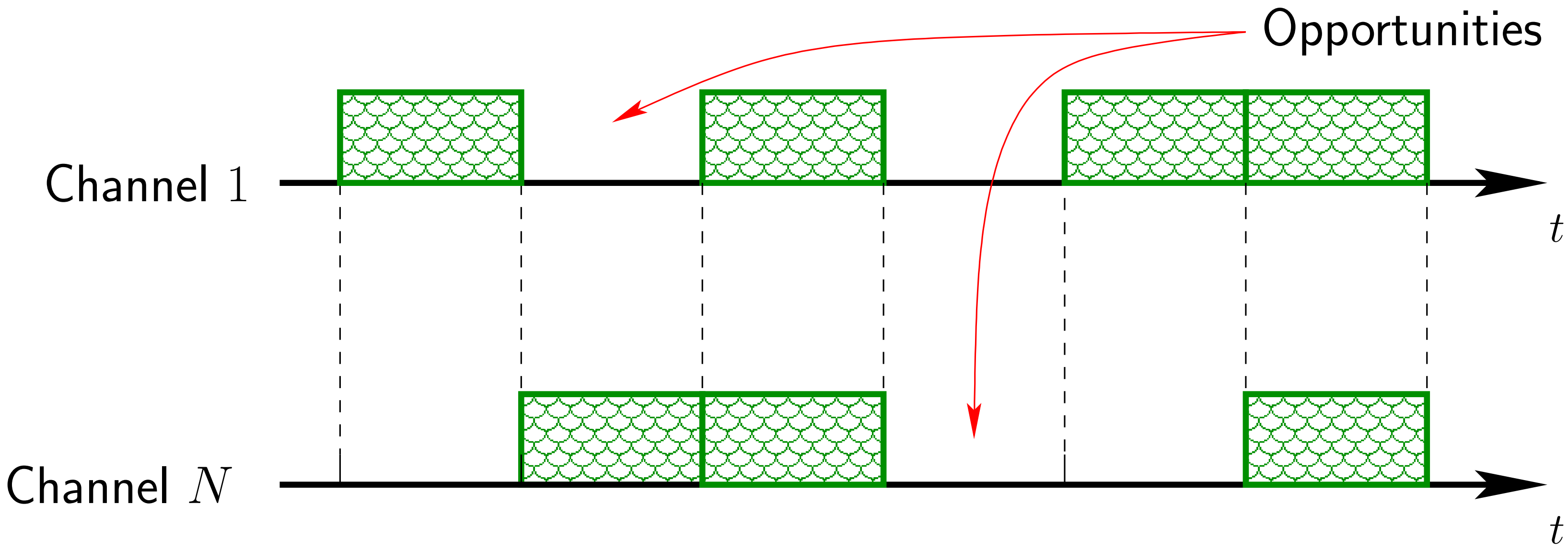
Searching for Opportunities with Limited Sensing



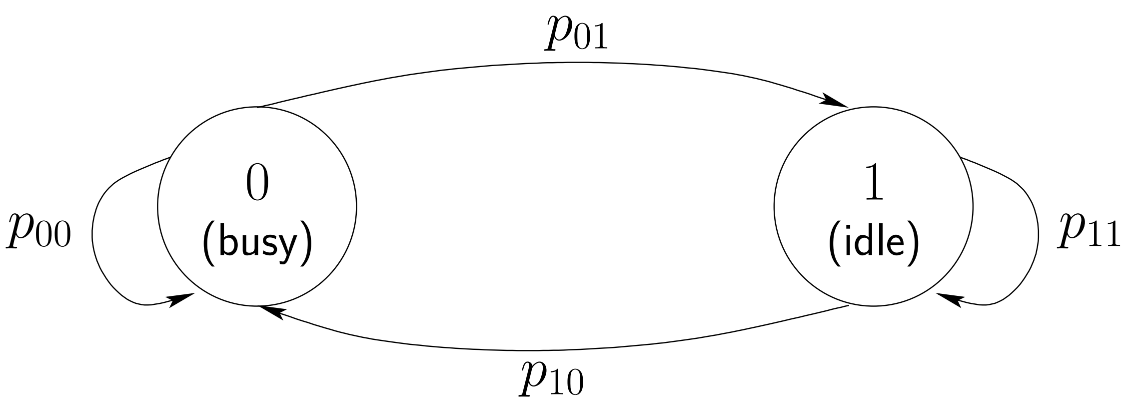
Tracking opportunities (dynamically choose K out of N channels) by learning from:

- statistical information on channel occupancy;
- observation history.

A Markovian Occupancy Model



- **N homogeneous Gilbert-Elliot channels:**



Multi-Armed Bandit

Multi-Armed Bandit:

- N *independent* arms with *fully observable* states $[Z_1(t), \cdots, Z_N(t)]$.
- *One* arm is activated at each time.
- Active arm changes state*(known Markov process)*; offers reward $R_i(Z_i(t))$.
- Passive arms are frozen and generate no reward.

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- Passive arms are frozen and generate no reward.

Solution via Dynamic Programming:

- Exponential complexity w.r.t. N.

Gittins' Index

The Index Structure of the Optimal Policy: *(Gittins:1960's)*

- Assign each state of each arm a *priority* index.
- Activate the arm with the highest current index value.

Complexity:

- Reduce an N-dim problem to N independent 1-dim problems.
- *Linear* complexity with N.
- Polynomial (cubic) with the state space size of an *individual* arm *(Varaiya&Walrand&Buyukkoc'85, Katta&Sethuraman'04)*.

Restless Bandit

Restless Multi-Armed Bandit: *(Whittle'88)*

- Activate K arms simultaneously.
- Passive arms also change state and offer reward.

Structure of the Optimal Policy:

- Not yet found.

Complexity:

- PSAPCE-hard *(Papadimitriou&Tsitsiklis'99)*.

Whittle's Index

Whittle's Index: *(Whittle'88)*

- Provide a subsidy for passivity m whenever the arm is made passive.
- Whittle's index: the subsidy m that makes active and passive actions equally attractive at the current state.

Performance:

- Optimal under relaxed constraint on the average number of active arms.
- Asymptotically (in N) optimal under certain conditions *(Weber&Weiss'90)*.
- Near optimal performance observed from extensive numerical examples.

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Performance:

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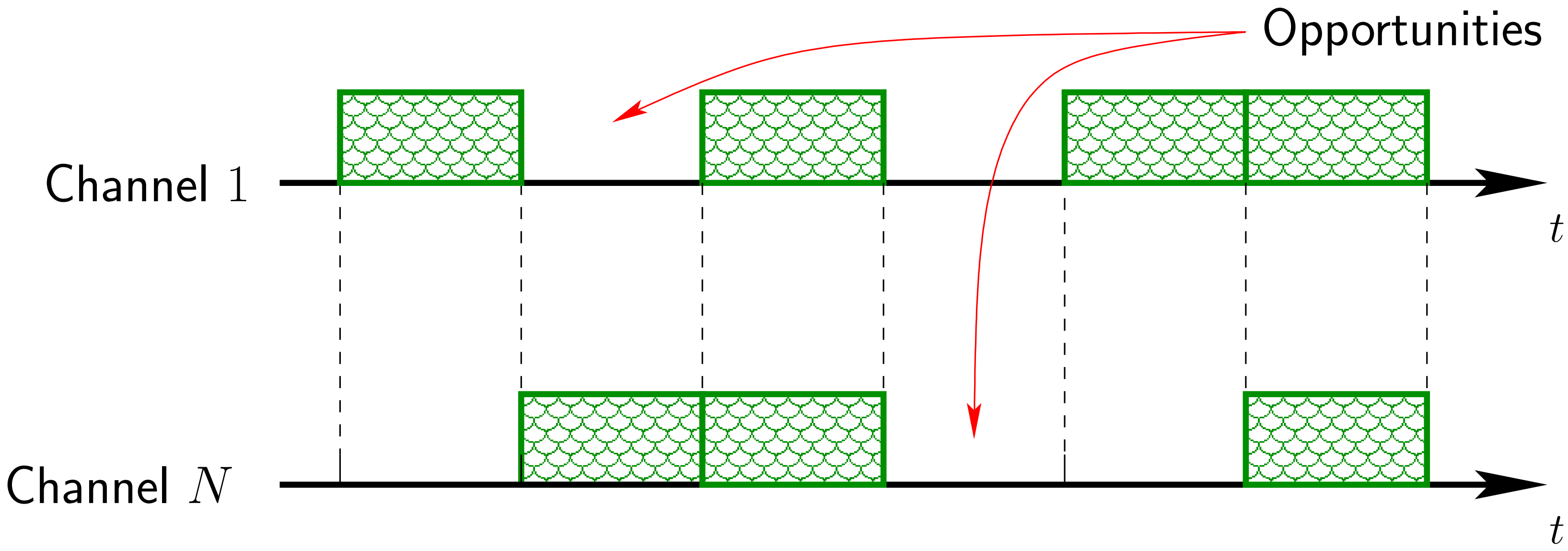
- Asymptotically (in N) optimal under certain conditions *(Weber&Weiss'90)*.
- Near optimal performance observed from extensive numerical examples.

Difficulties:

- Existence (indexability) not guaranteed and difficult to check.
- Numerical index computation infeasible for uncountable state space.
- Optimality in finite regime difficult to establish.

Searching for Spectrum Opportunities

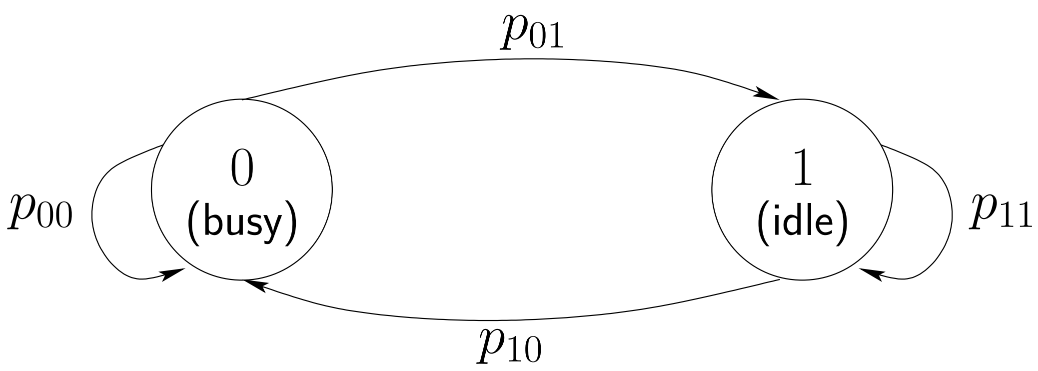


- Each channel is considered as an arm.
- State of arm i: *a posterior* probability that channel i is idle.

$$\omega_i(t) = \Pr[\text{channel } i \text{ is idle in slot } t \mid \underbrace{O(1), \cdots, O(t-1)}_{\text{observations}}]$$

- The expected immediate reward for activating arm i is $\omega_i(t)$

Markovian State Transition



- If channel i is activated in slot t:

$$\omega_i(t+1) = \begin{cases} p_{11}, & \text{if} \quad O_i(t) = 1 \\ p_{01}, & \text{if} \quad O_i(t) = 0 \end{cases}.$$

- If channel i is made passive in slot t:

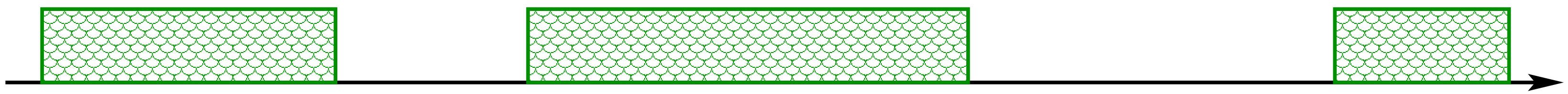
$$\omega_i(t+1) = \omega_i(t)p_{11} + (1 - \omega_i(t))p_{01}.$$

Structure of Whittle's Index Policy

The Semi-Universal Structure of Whittle's Index Policy:

- No need to compute the index.
- No need to know $\{p_{01}, p_{11}\}$ except their order.

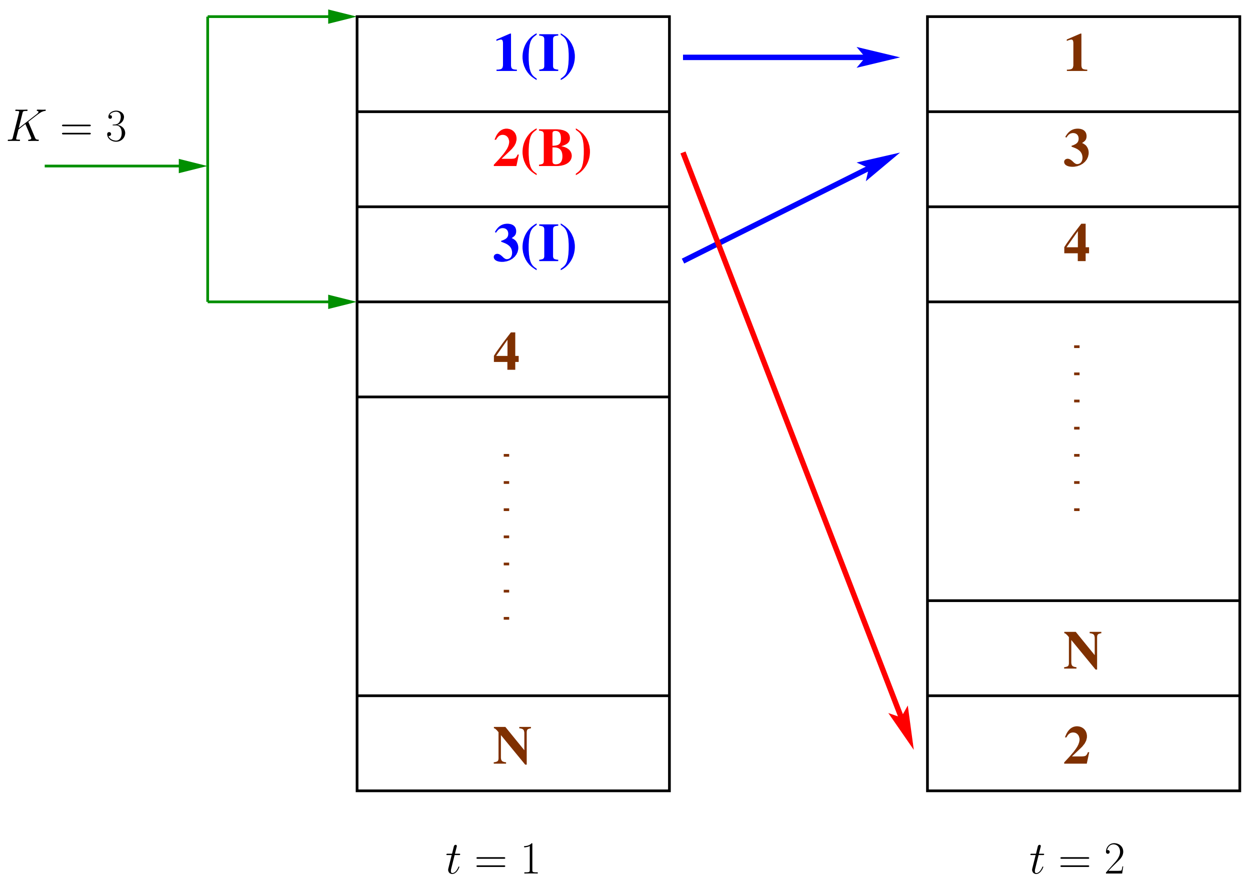
$p_{11} \geq p_{01}$ *(positive correlation):*



$p_{11} < p_{01}$ *(negative correlation):*

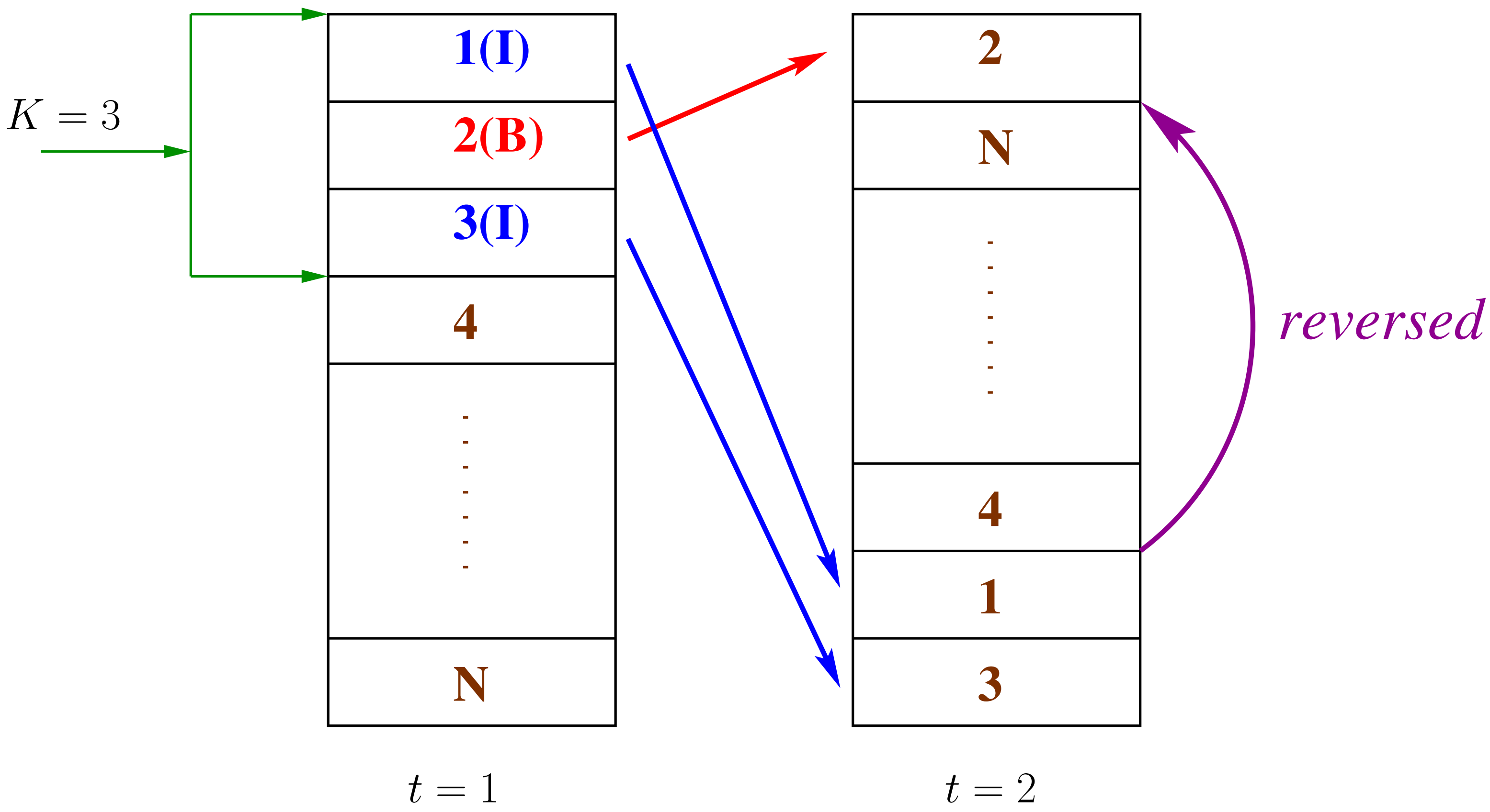
Structure of Whittle's Index Policy: Positive Correlation

- Stay with idle **(I)** channels and leave busy **(B)** ones to the end of the queue.



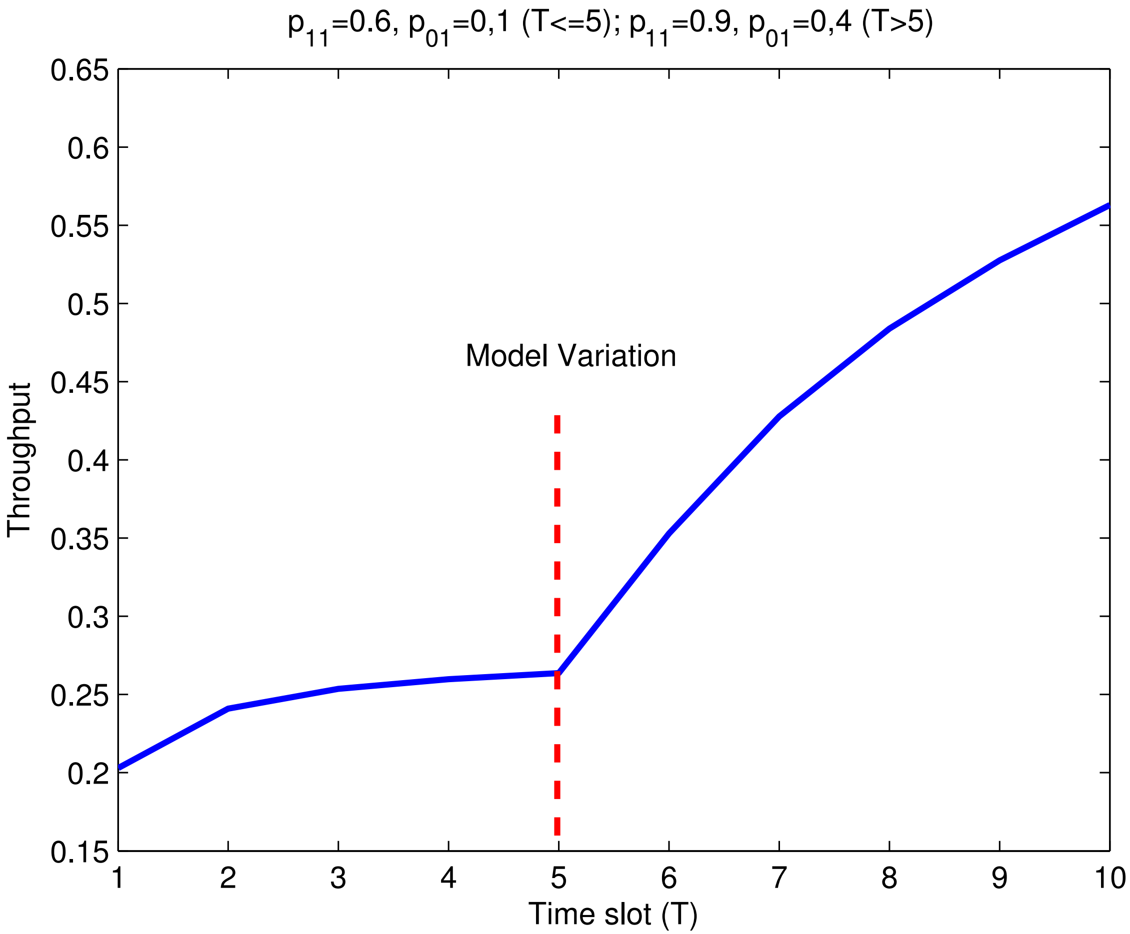
Structure of Whittle's Index Policy: Negative Correlation

- Stay with busy **(B)** channels and leave idle **(I)** ones to the end of the queue.
- *Reverse* the order of unobserved channels.



Robustness of Whittle's Index Policy

- Automatically tracks model variations:



Optimality of Whittle's Index Policy

Optimality for positively correlated channels:

- holds for general N and K.
- holds for both finite and infinite horizon (discounted/average reward).

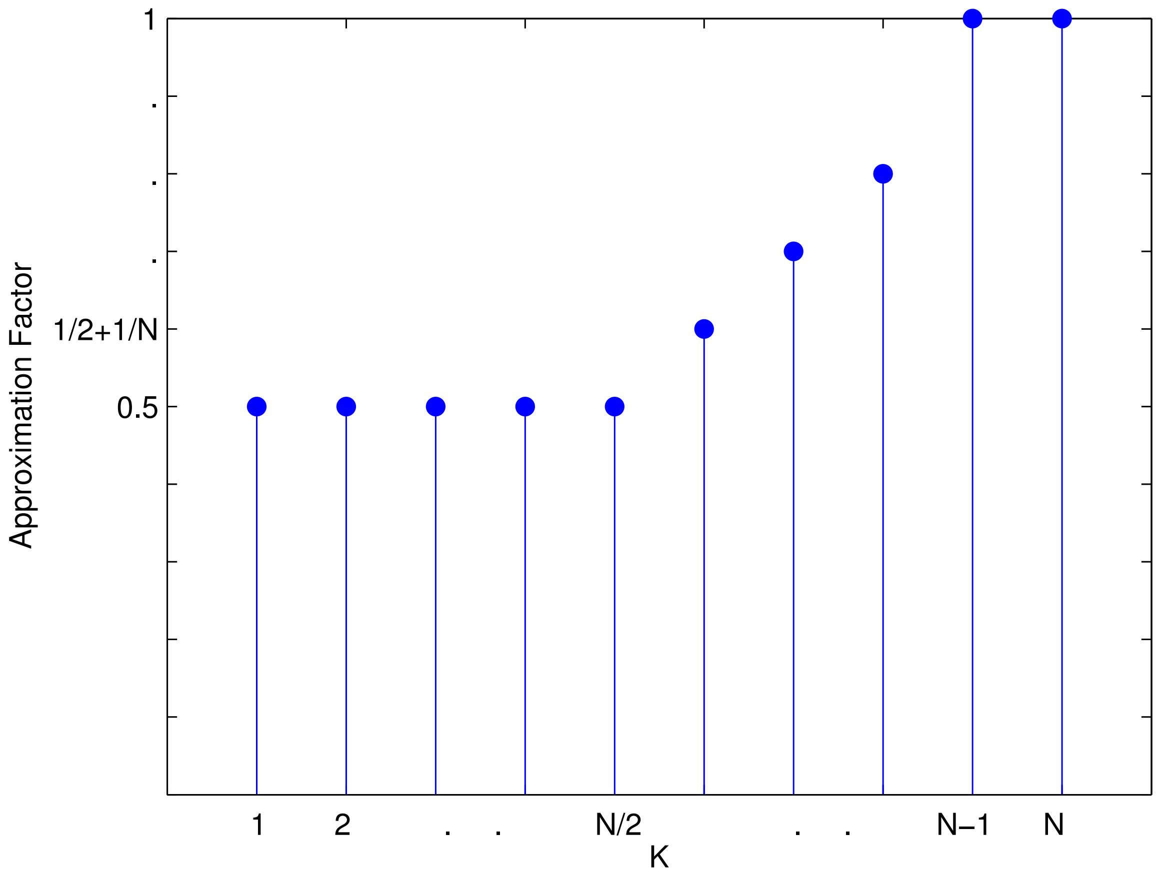
Optimality for negatively correlated channels:

- holds for all N with $K = N - 1$.
- holds for $N = 3$.

Performance of Whittle's Index Policy w.r.t. K

Constant approximation factor $\eta = \frac{\text{Performance of Whittle's index policy}}{\text{Optimal performance}}$

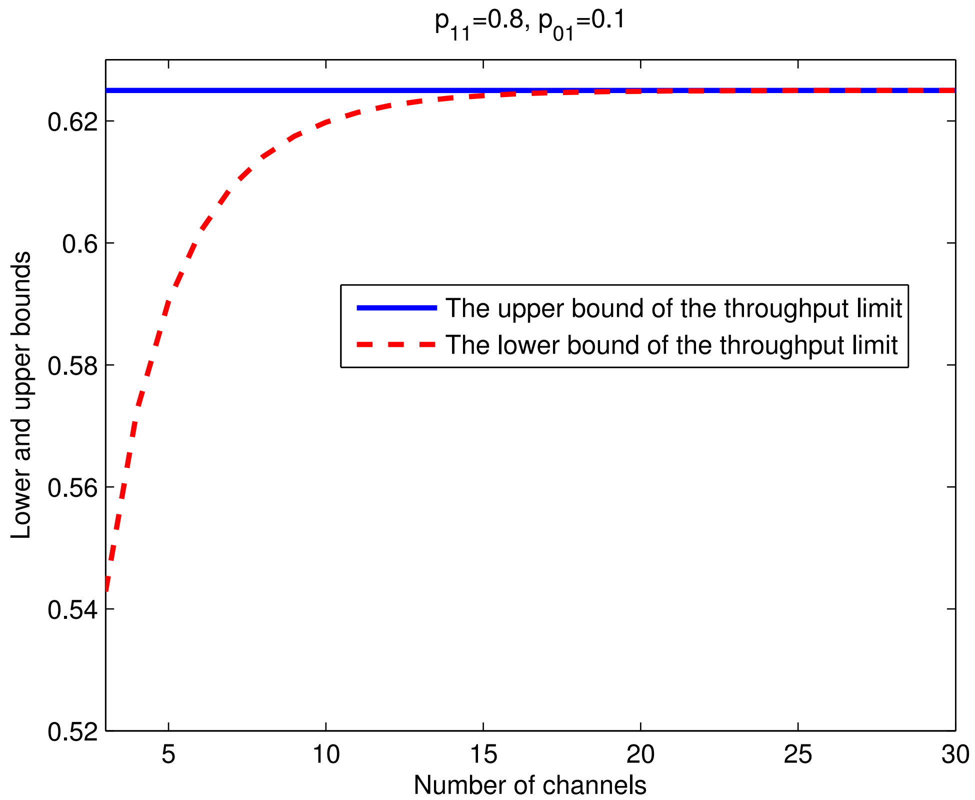
$p_{11} < p_{01}$ *(Negative Correlation)*



$$\begin{cases} \eta = 1, & K = N-1, N \\ \eta \geq \max\{\frac{1}{2}, \frac{K}{N}\}, & \text{otherwise} \end{cases}$$

Performance of Whittle's Index Policy w.r.t. N

- $V(N)$: the average reward achieved by Whittle's index policy ($K = 1$).
- For $p_{11} \geq p_{01}$, $V(N)$ converges to a constant $\frac{\omega_o}{1-p_{11}+\omega_o}$ at geometric rate $p_{11} - p_{01}$.
- For $p_{11} < p_{01}$, $V(N)$ approaches a constant $\frac{p_{10}^{(2)}}{E-p_{01}G}$ at geometric rate $(p_{11} - p_{01})^2$.



Heterogeneous Channels

Whittle's Index in Closed Form:

- Positive correlation ($p_{11} \geq p_{01}$):

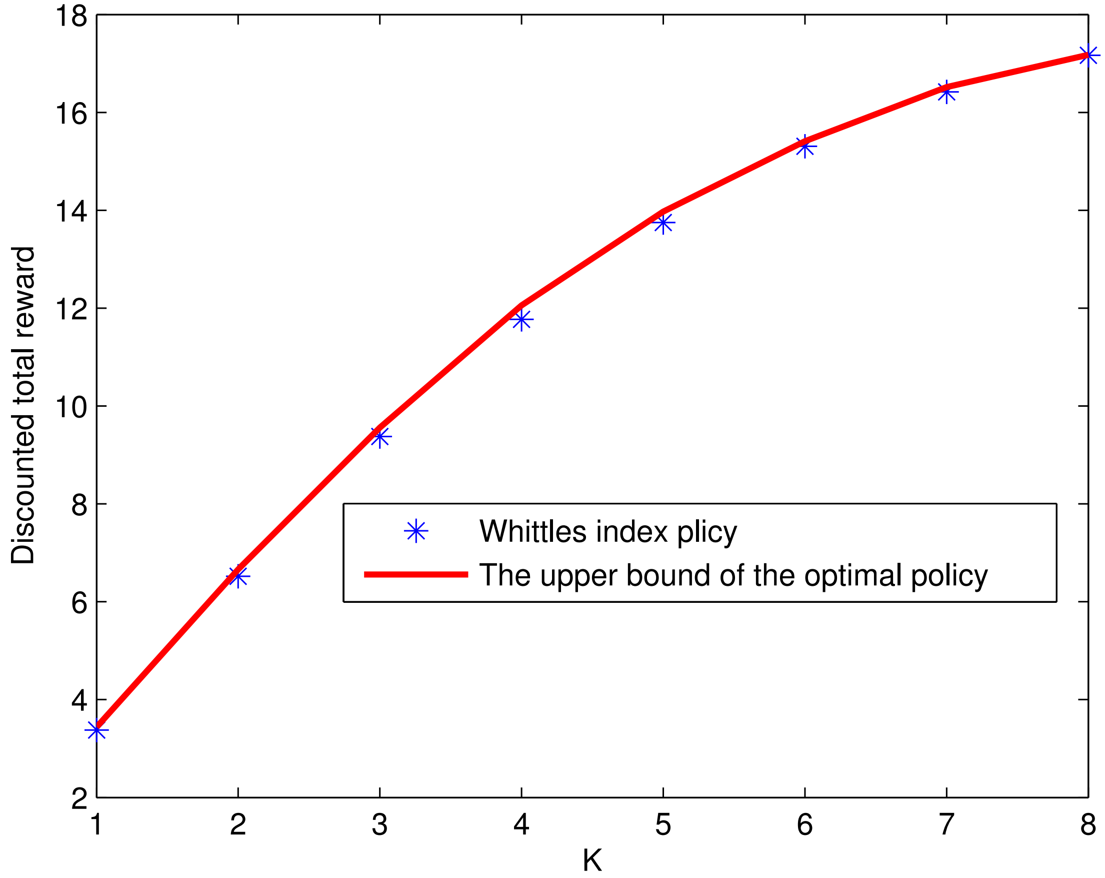
$$I(\omega) = \begin{cases} \omega, & \omega \leq p_{01} \text{ or } \omega \geq p_{11} \\ \frac{\omega}{1-p_{11}+\omega}, & \omega_o \leq \omega < p_{11} \\ \frac{(\omega-\mathcal{T}^1(\omega))(L+2)+\mathcal{T}^{L+1}(p_{01})}{1-p_{11}+(\omega-\mathcal{T}^1(\omega))(L+1)+\mathcal{T}^{L+1}(p_{01})}, & p_{01} < \omega < \omega_o \end{cases}$$

- Negative correlation ($p_{11} < p_{01}$):

$$I(\omega) = \begin{cases} \omega, & \omega \leq p_{11} \text{ or } \omega \geq p_{01} \\ \frac{p_{01}}{1+p_{01}-\omega}, & \mathcal{T}^1(p_{11}) \leq \omega < p_{01} \\ \frac{p_{01}}{1+p_{01}-\mathcal{T}^1(p_{11})}, & \omega_o \leq \omega < \mathcal{T}^1(p_{11}) \\ \frac{\omega+p_{01}-\mathcal{T}^1(\omega)}{1+p_{01}-\mathcal{T}^1(p_{11})+\mathcal{T}^1(\omega)-\omega}, & p_{11} < \omega < \omega_o \end{cases}$$

Performance for Heterogeneous Channels

- The tightness of the performance upper bound ($\mathcal{O}(N(\log N)^2)$ running time).
- The near-optimal performance of Whittle's index policy



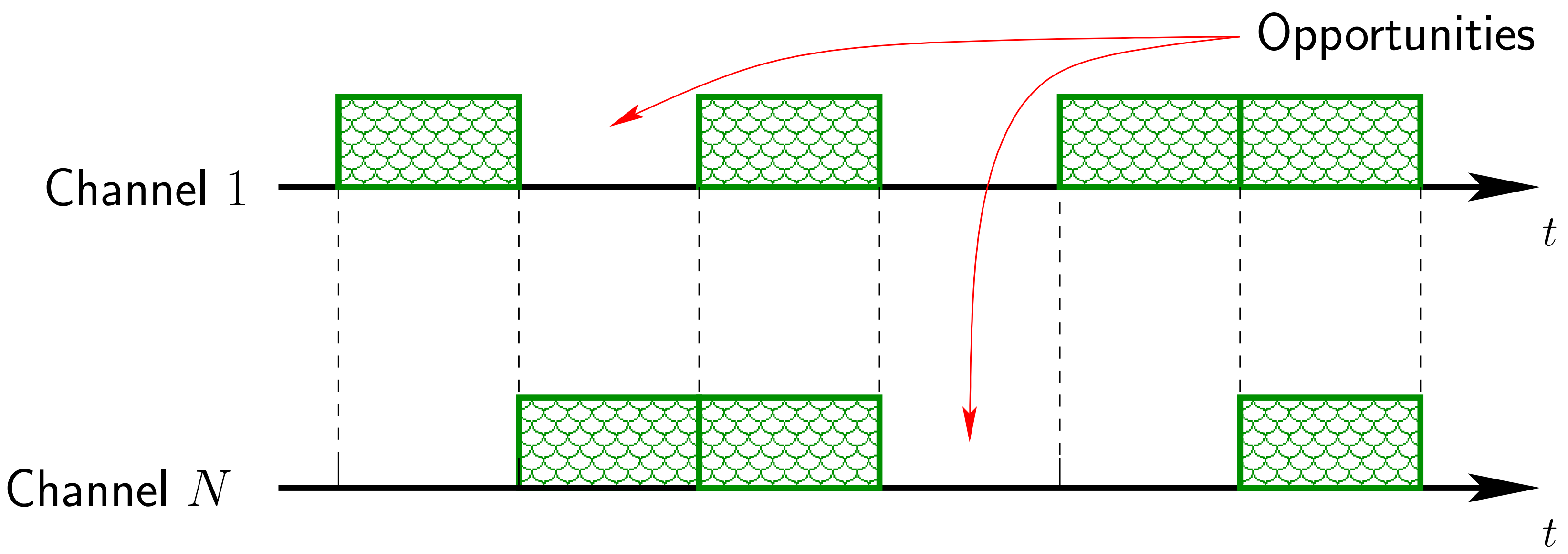
Imperfect Channel Sensing

References:

* Y. Chen, Q. Zhao, and A. Swami, "Joint Design and Separation Principle for Opportunistic Spectrum Access in the Presence of Sensing Errors," *IEEE Trans. on Information Theory*, May, 2008.

* K. Liu, Q. Zhao, and B. Krishnamachari, "Dynamic Multichannel Access with Imperfect Channel State Detection," *IEEE Trans. on Signal Processing*, May, 2010.

Cognitive Radio



Reward and Collision:

- A reward is accrued when access an idle channel
- A collision with primary users occurs when access a busy channel

Objective: joint design of sensing, access, and channel selection to

$$\max \mathbb{E}[\text{throughput}] \quad s.t. \quad \text{collision probability } P_c \leq \zeta$$

Channel State Detector

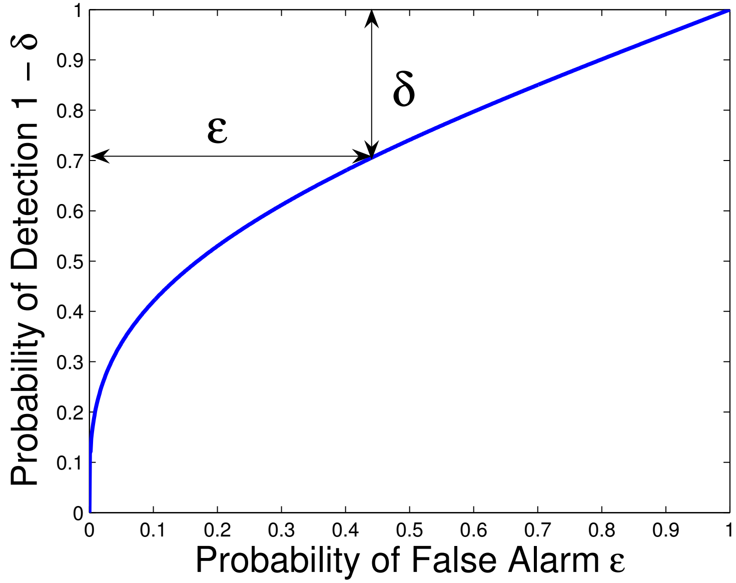
Binary Hypotheses Test:

$$\mathcal{H}_0 \text{ (idle)} \quad \text{vs.} \quad \mathcal{H}_1 \text{ (busy)}$$

Two Types of Sensing Errors:

- false alarm: $\mathcal{H}_0 \rightarrow \mathcal{H}_1$ — $\epsilon \triangleq$ prob. of false alarm
- miss detection: $\mathcal{H}_1 \rightarrow \mathcal{H}_0$ — $\delta \triangleq$ prob. of miss detection

Receiver Operating Characteristics (ROC): $1 - \delta$ vs. ϵ



Which point on the ROC to operate at?

Access Policy: Opportunity Overlook vs. Collision

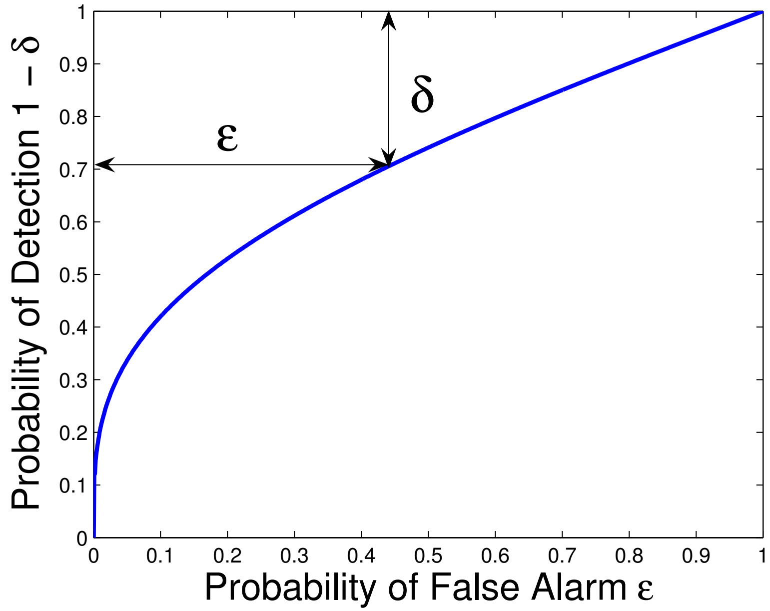
$$\max \mathbb{E}[\text{throughput}] \quad s.t. \quad \text{collision probability } P_c \leq \zeta$$

Consequences of trusting the detector:

- false alarm (idle sensed as busy) $\Longrightarrow$ opportunity overlook
- miss detection (busy sensed as idle) $\Longrightarrow$ collision

Access Policy: when and how much to trust the detector

$$\text{tx probability} = \begin{cases} p_0 & \text{if idle} \\ p_1 & \text{if busy} \end{cases}$$



A Constrained POMDP and The Separation Principle

A Constrained POMDP:

$$\max \mathbb{E}[\sum_{t=1}^{T} R(t)], \quad \text{subject to } P_c \leq \zeta$$

The Separation Principle:

1. The optimal detector and access policy are *myopic*:

$$\max \mathbb{E}[R(t)] \quad \text{subject to } P_c = \zeta$$

2. *Unconstrained* design of the optimal channel selection policy:

$$\max \mathbb{E}\left[\sum_{t=1}^{T} R(t)\right]$$

The Optimal Detector and Access Policy

- when $\delta > \zeta$ (conservative)

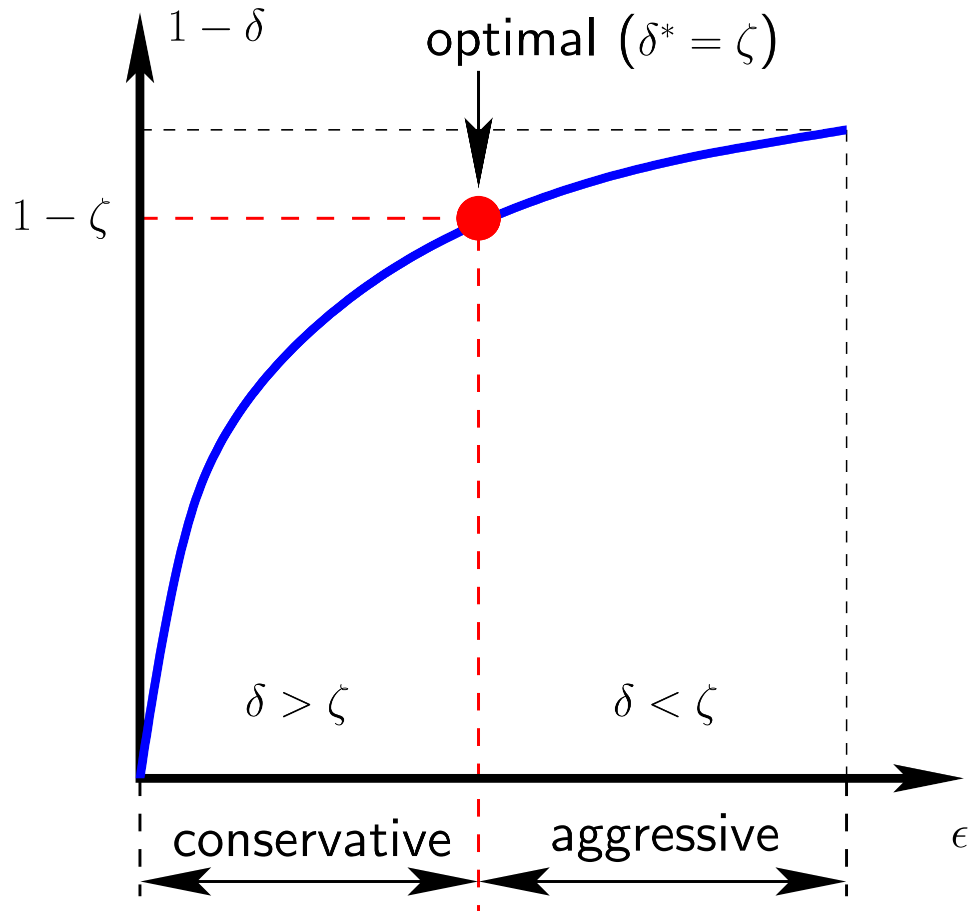
$$\text{tx probability} = \begin{cases} 0 & \text{if busy} \\ \frac{\zeta}{\delta} & \text{if idle} \end{cases}$$

- when $\delta < \zeta$ (aggressive)

$$\text{tx probability} = \begin{cases} \frac{\zeta-\delta}{1-\delta} & \text{if busy} \\ 1 & \text{if idle} \end{cases}$$

- when $\delta = \zeta$ (optimal)

$$\text{tx probability} = \begin{cases} 0 & \text{if busy} \\ 1 & \text{if idle} \end{cases}$$



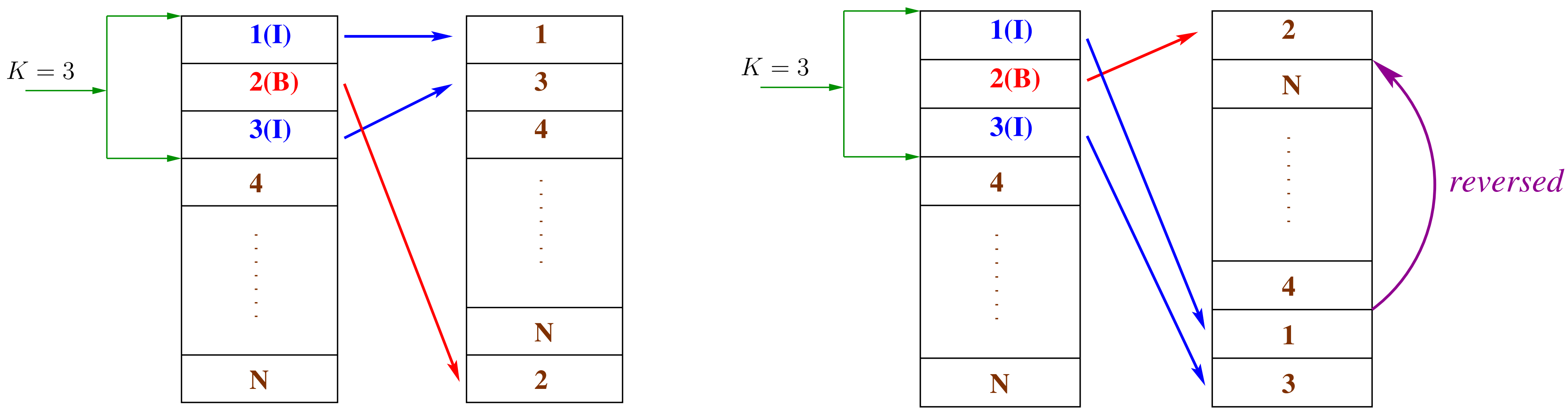
Optimal policies are universal: $\delta^* = \zeta$, π_c^* = trust the detector.

Myopic Channel Selection for Identical Channels

The Semi-Universal Structure:

Positive Correlation $(\epsilon^* < \frac{p_{1,0}p_{0,1}}{p_{1,1}p_{0,0}})$

Negative Correlation $(\epsilon^* < \frac{p_{0,0}p_{1,1}}{p_{0,1}p_{1,0}})$



The Optimality:

- proved for $N = 2$.

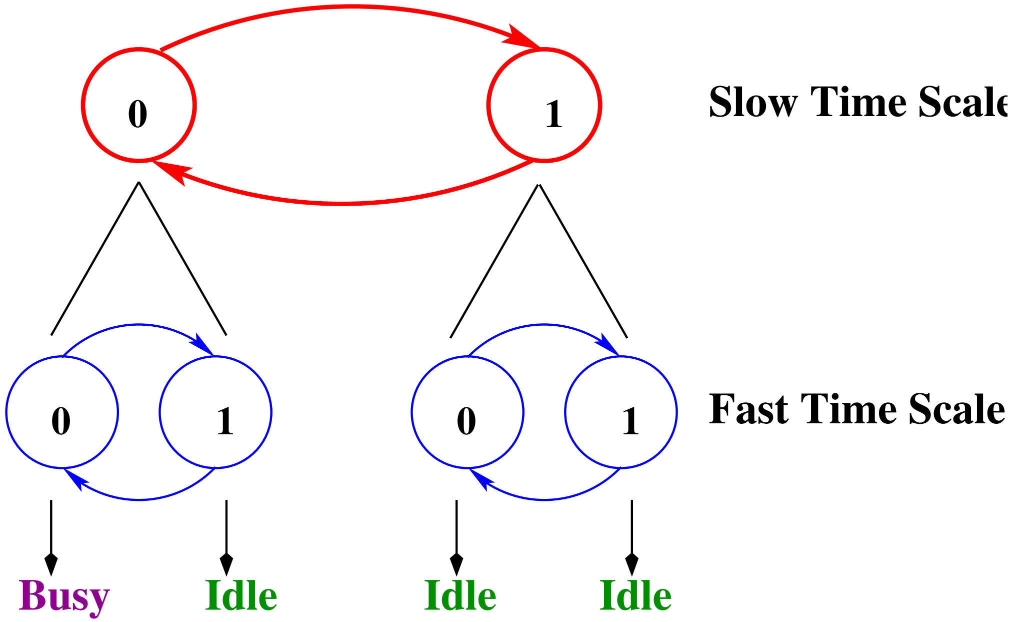
Self-Similar Primary Traffic

References:

* X. Xiao, K. Liu, and Q. Zhao, "Opportunistic Spectrum Access in Self Similar Primary Traffic," *EURASIP Journal on Advances in Signal Processing*, March, 2009.

Non-Markovian Models with Long Range Dependency

Multi-Scale Hierarchical Markovian Model for Self-Similar Traffic: *(Misra&Gong'98)*



- Channel occupancy is a hidden Markov process.
- Robust index policy with near optimal performance.

[0]X. Xiao, K. Liu, Q. Zhao, EURASIP Journal on Advances in Signal Processing, March, 2009.

Unslotted Primary System

References:

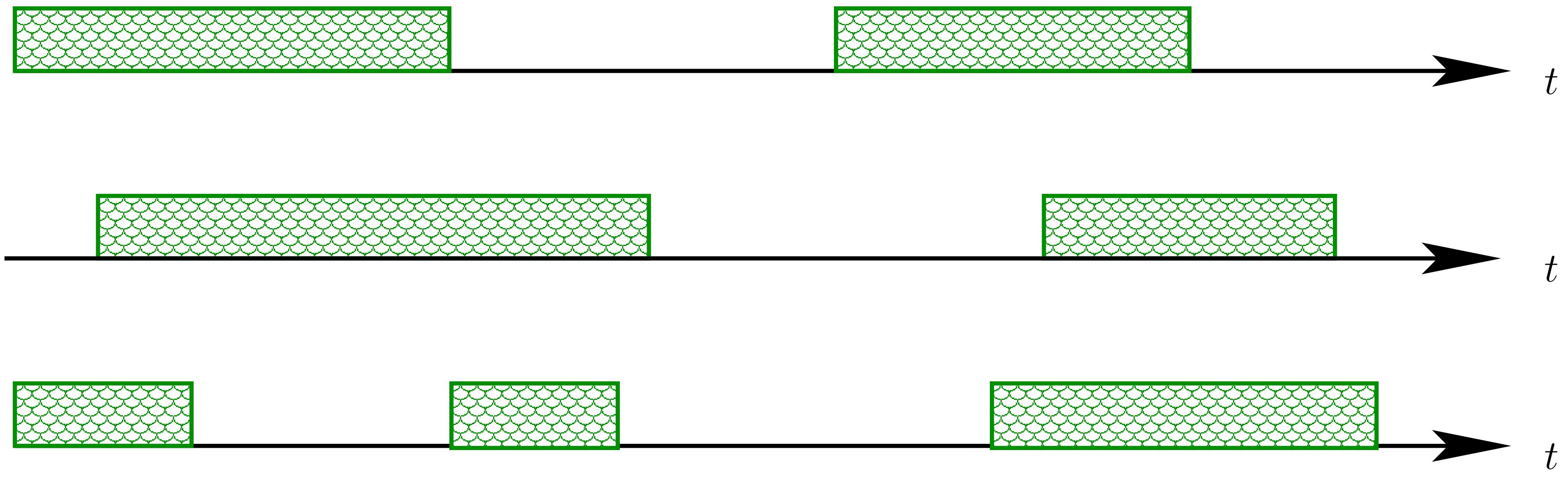
* Q. Zhao and J. Ye, "Quickest Change Detection in Multiple On-Off Processes," submitted to *IEEE Trans. on Signal Processing*, January, 2010.

  Conference versions: MILCOM'2008, ICASSP'2009, Allerton'2009.

* P. Tehrani, K. Liu, and Q. Zhao, "Opportunistic Spectrum Access in Unslotted Primary Systems," submitted to *Journal of The Franklin Institute*, January, 2010.

  Conference versions: RWS'2008, CISS'2009.

Searching for Opportunities: Unslotted Case



Quickest Detection of Idle Periods in Multiple On-Off Processes:

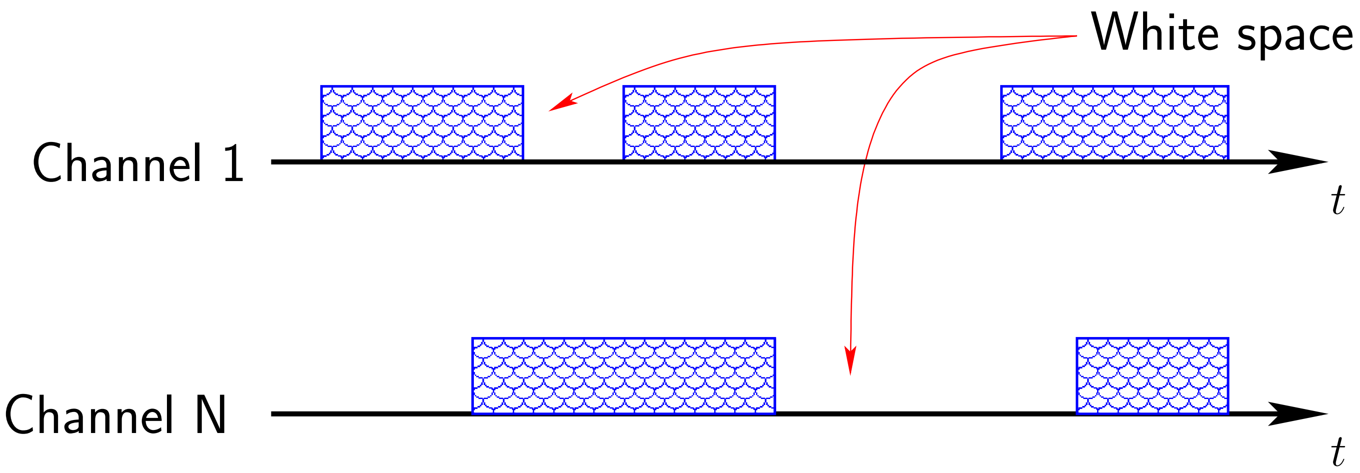
- Continue, switch, or declare?

Tradeoffs:

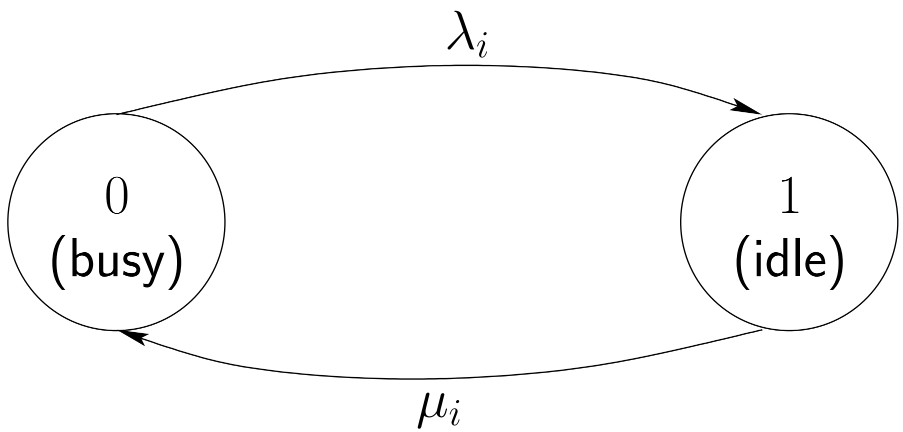
- Whether to declare: delay vs. reliability.
- Whether to switch: loss of data vs. avoiding bad realizations.

[0]Q. Zhao, J. Ye, MILCOM 2008, ICASSP 2009, Allerton 2009.

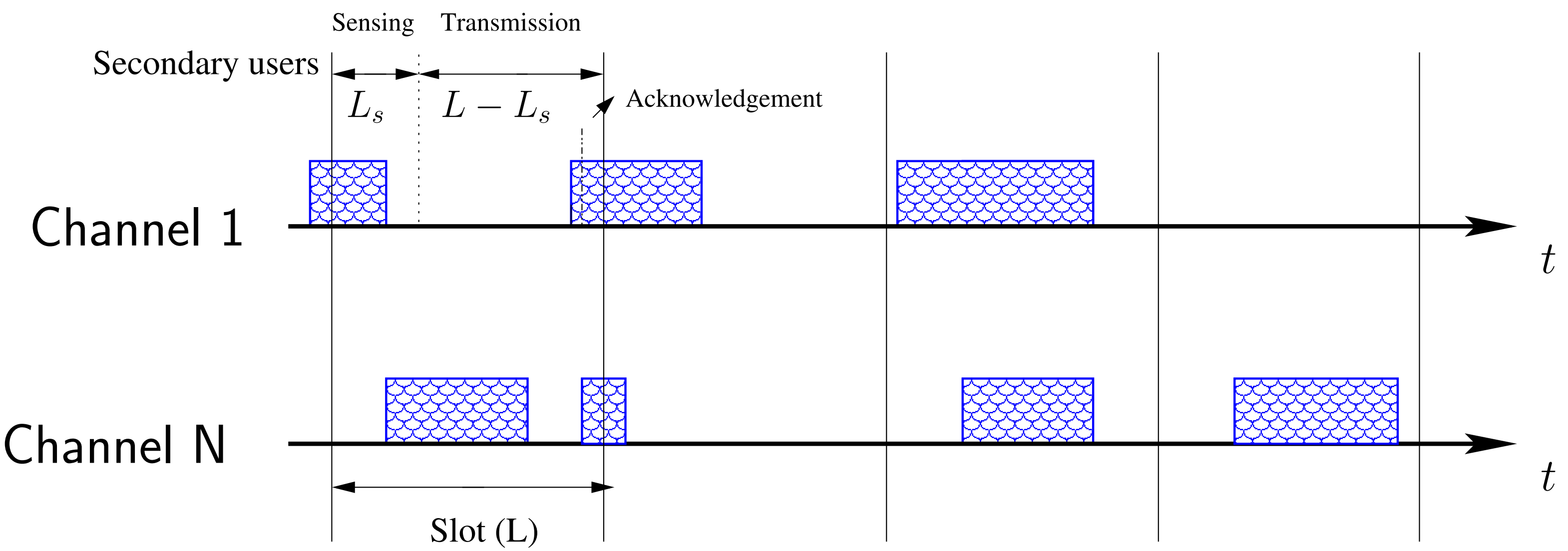
Unslotted Primary Systems



- N channels, each with bandwidth B_i.
- Channel i: two-state continuous Markov process with transition rates μ_i, λ_i.



Reduce to OSA in Slotted Primary Systems



- Secondary users adopt a slotted transmission structure with slot length L.
- A slot is partitioned into sensing time (L_s) and transmission time $(L - L_s)$.
- The chosen channel is an opportunity if it stays idle during the tx period.
- Unslotted tx of primary users absorbed by sensing errors.
- The problem can be reduced to that in a slotted primary system.

[0]Q. Zhao, K. Liu, RWS 2008; P. Tehrani, Q. Zhao, CISS 2009.

Energy-Constrained OSA

References:

* Y. Chen, Q. Zhao, and A. Swami, "Distributed Spectrum Sensing and Access in Cognitive Radio Networks with Energy Constraint" *IEEE Trans. Signal Processing*, Feb., 2009.

Energy-Constrained OSA in Fading

Energy Constraint

- Both sensing and access cost energy
- Finite initial energy

Optimal Sensing and Access Policies

- may choose not to sense when the belief vector indicates all channels are unlikely to be idle
- may choose not to access when channels are in deep fade

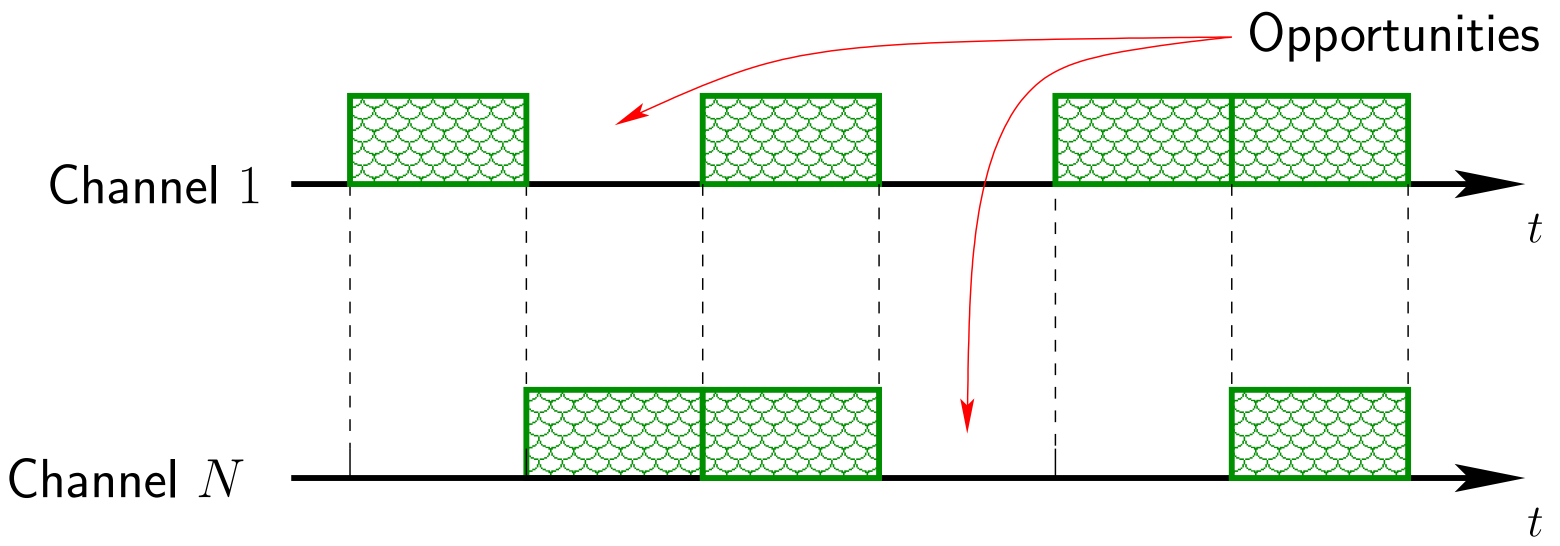
Distributed Learning under Unknown Model

References:

* K. Liu and Q. Zhao, "Distributed Learning in Multi-Armed Bandit with Multiple Players," submitted to *IEEE Trans. on Signal Processing*, Dec., 2009. Available at http://arxiv.org/abs/0910.2065

Conference versions: ITA'2010, ICASSP'2010.

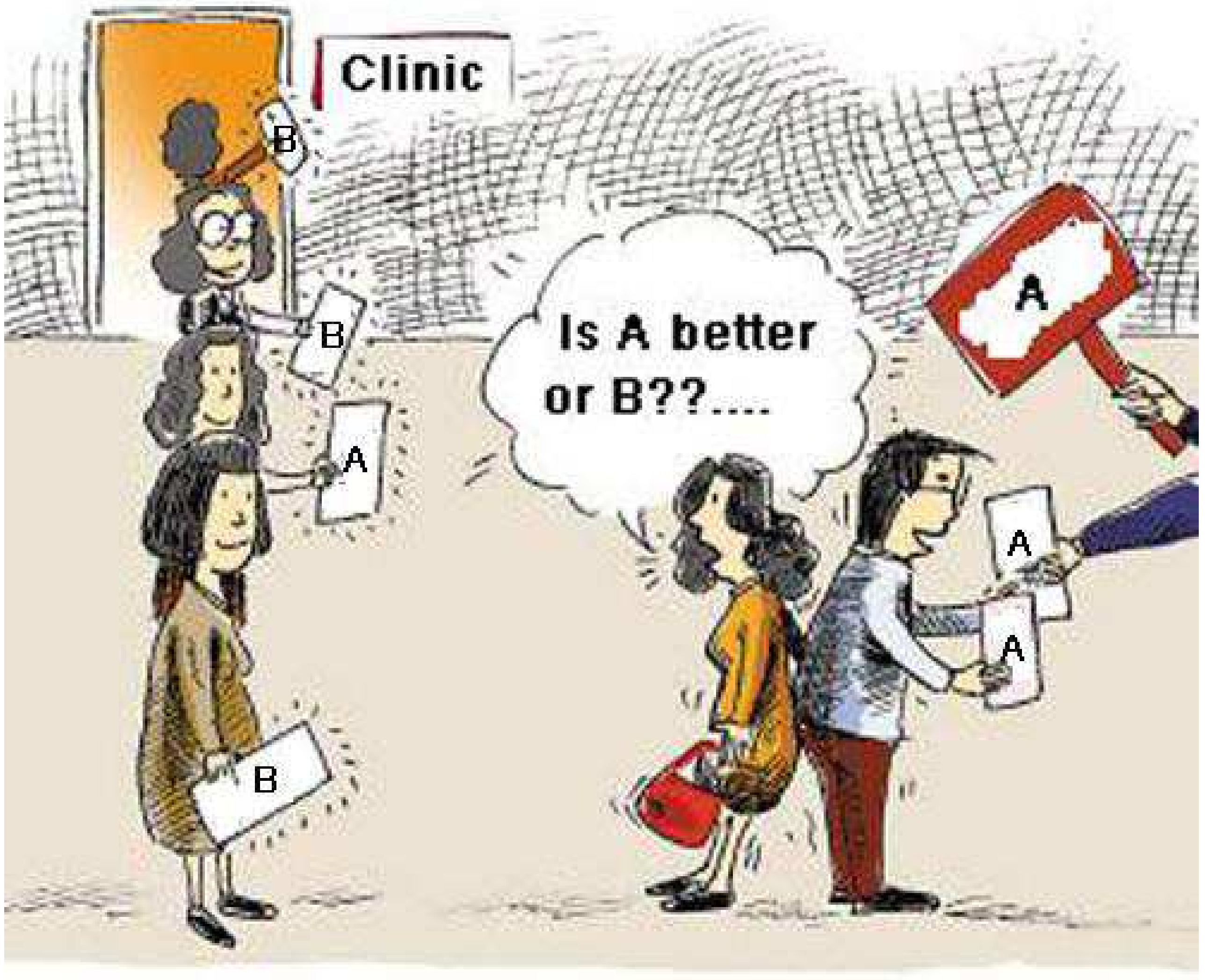
Sharing under Unknown Model



- N channels, M $(M < N)$ **distributed** secondary users (no info exchange).
- Primary occupancy of channel i: i.i.d. Bernoulli with unknown mean θ_i:
- Accessing an idle channel results in a unit reward.
- Users accessing the same channel collide; no one or only one receives reward.
- Objective: decentralized policy for optimal **network-level** performance.

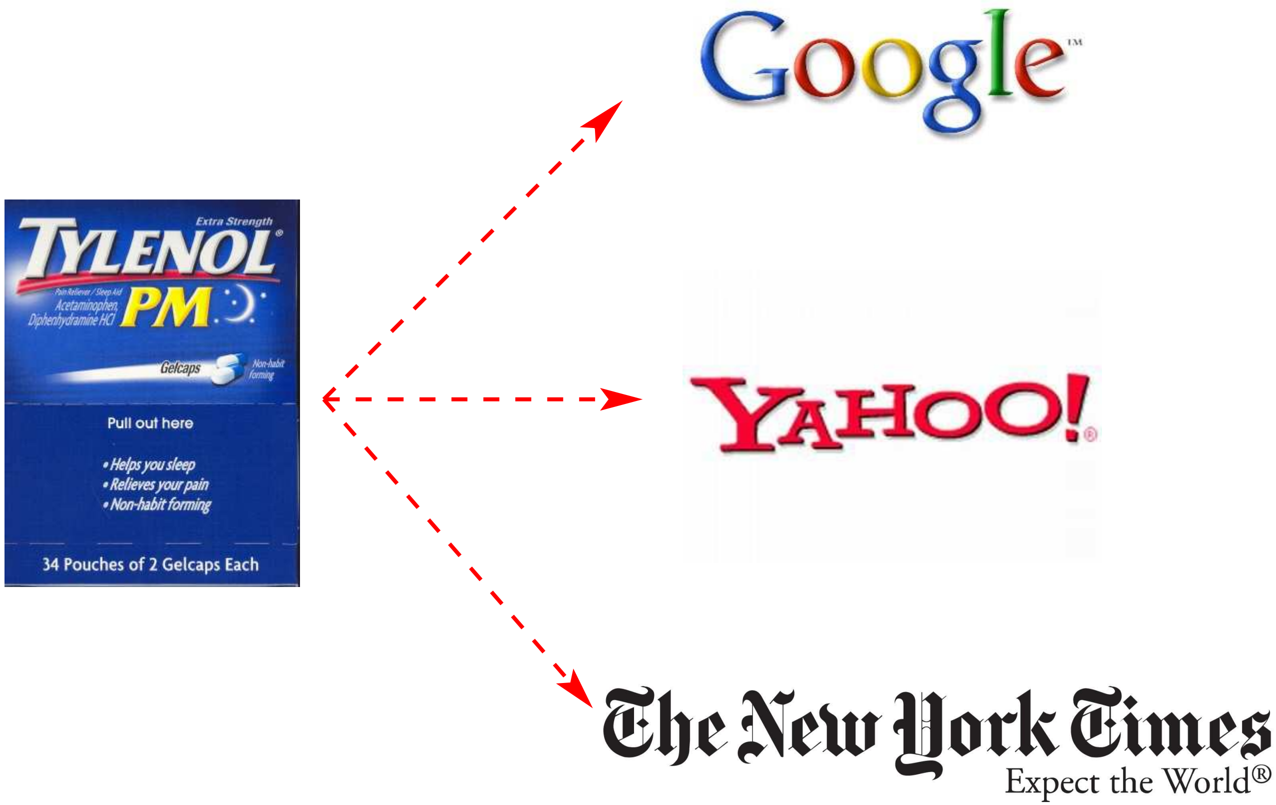
Classic MAB: Clinical Trial *(Thompson'33)*

Two treatments with unknown effectiveness:



Classic MAB: Web Search and Internet Advertising

Where to place ads?



An Example: Bernoulli Reward

A Two-Armed Bandit:

- Two coins with unknown bias θ_1, θ_2.
- Head: reward $= 1$; Tail: reward $= 0$.
- Objective: maximize long-term total reward.

Non-Bayesian Formulation

- (θ_1, θ_2) are treated as unknown deterministic parameters.
- $V_T^\pi(\theta_1, \theta_2)$: total reward of policy π over a horizon of length T.
- $T \underbrace{\max\{\theta_1, \theta_2\}}_{\theta_{max}}$: total reward if (θ_1, θ_2) were known.
- The cost of learning (regret):

$$R_T^\pi(\theta_1, \theta_2) \stackrel{\Delta}{=} T\theta_{max} - V_T^\pi(\theta_1, \theta_2) = (\theta_{max} - \theta_{min})\mathbb{E}[\text{time spent on } \theta_{min}]$$

- Objective: minimize the rate that $R_T^\pi(\theta_1, \theta_2)$ grows with T.

Classic Results under Non-Bayesian Formulation

- Lai&Robbins'85:

$$R_T^*(\theta_1, \theta_2) \sim \underbrace{\frac{\theta_{max} - \theta_{min}}{I(\theta_{min}, \theta_{max})}}_{\text{KL distance}} \log T \quad \text{as } T \to \infty$$

- Anantharam&Varaiya&Walrand'87:
    - extension from single play to multiple plays.
- Agrawal'95, Auer&Cesa-Bianchi&Fischer'02:
    - simpler order-optimal policies.

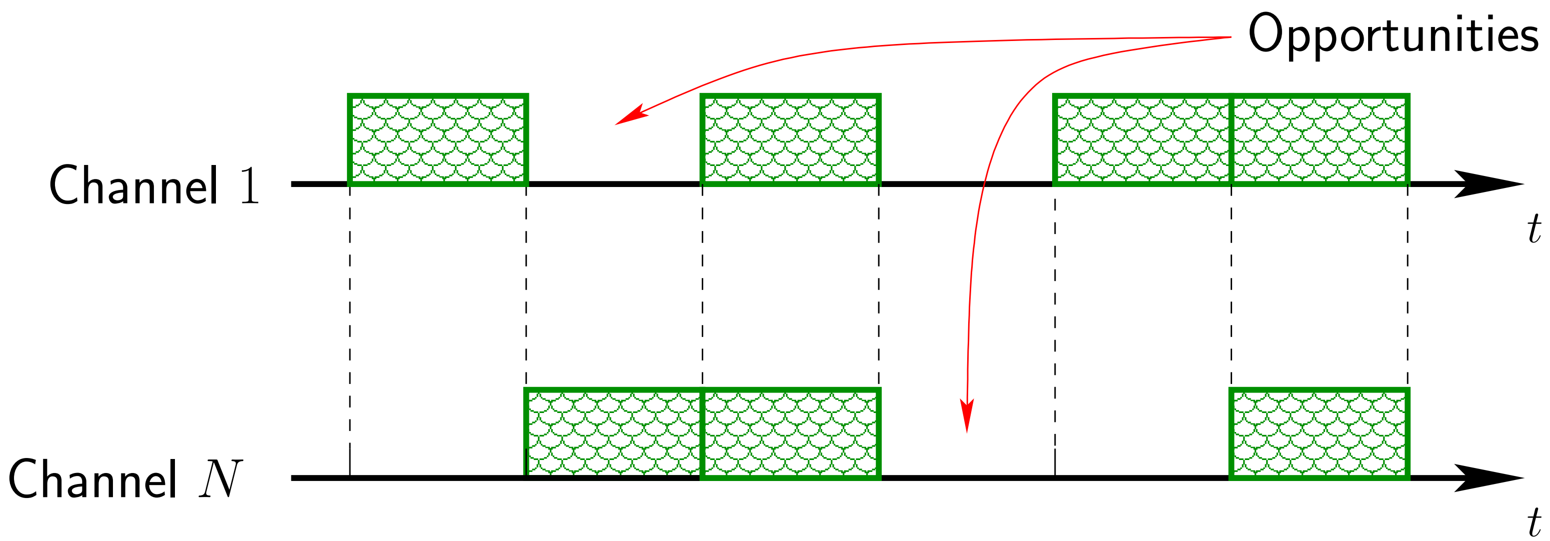
Recent Results on Decentralized MAB

- Lai&Robbins'85:

$$R_T^*(\theta_1, \theta_2) \sim \underbrace{\frac{\theta_{max} - \theta_{min}}{I(\theta_{min}, \theta_{max})}}_{\text{KL distance}} \log T \quad \text{as } T \to \infty$$

- Anantharam&Varaiya&Walrand'87:
  - extension from single play to multiple plays.
- Agrawal'95, Auer&Cesa-Bianchi&Fischer'02:
  - simpler order-optimal policies.
- Liu&Zhao'10:
  - extension to **distributed** multiple players
    (distributed decision-making using only local observations).
  - decentralized policy achieving **the same** $\log T$ order of the regret.
  - fairness among players.

Cognitive Radio Networks



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- Accessing an idle channel results in a unit reward.
- Users accessing the same channel collide; no one or only one receives reward.
- Objective: decentralized policy for optimal **network-level** performance.

Decentralized Multi-Armed Bandit

Decentralized Multi-Armed Bandit:

- N arms, M $(M < N)$ distributed players.
- Each player selects one arm to play and observes the reward.
- Distributed decision making using only **local** observations.
- Colliding players either share the reward or receive no reward.

System Regret:

- $V_T^\pi(\Theta)$: total system reward under a decentralized policy π.
- Total system reward with **known** $\Theta \stackrel{\Delta}{=} (\theta_1, \cdots, \theta_N)$ and **centralized scheduling**:

$$T \; \Sigma_{i=1}^{M} \underbrace{\theta^{(i)}}_{i\text{th best}}$$

- System regret:

$$R_T^\pi(\Theta) = T\Sigma_{i=1}^{M}\theta^{(i)} - V_T^\pi(\Theta)$$

The Minimum Regret Growth Rate

The Minimum regret rate in Decentralized MAB is logarithmic.

$$R_T^*(\Theta) \sim C(\Theta)\ \log T$$

A Framework for Constructing Decentralized Policies

The TDFS (Time Division Fair Sharing) Framework:

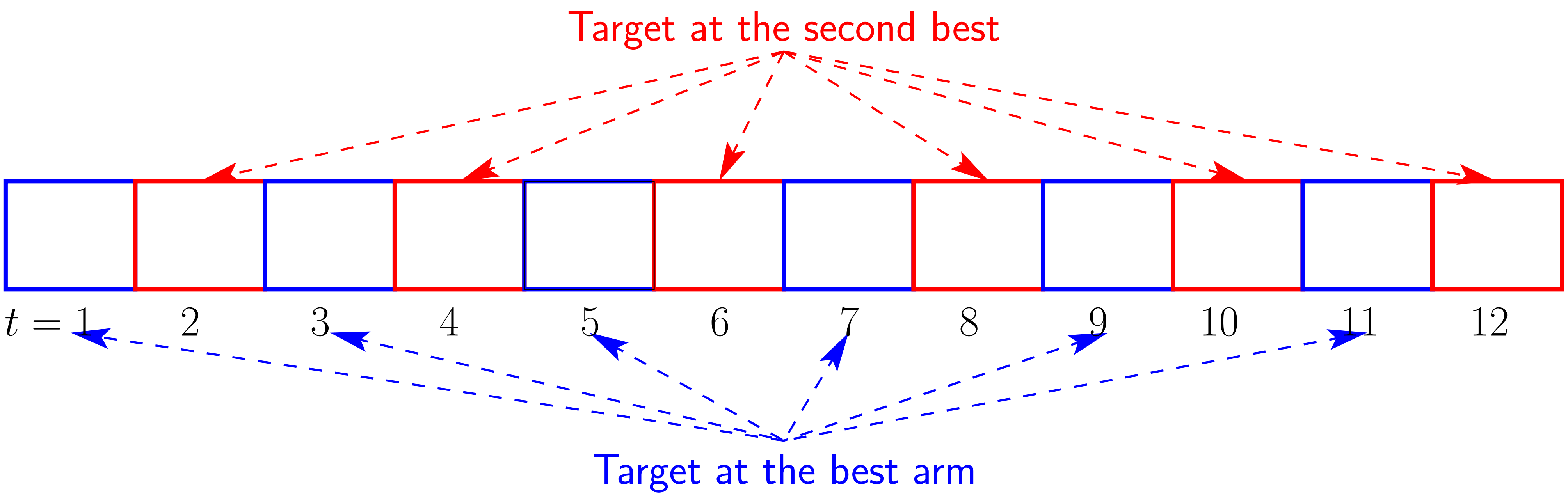
- Players use round-robin selection of the M best arms with different offset.
- Each player learns the M best arms based on local observations.

Challenges in Achieving $\log T$ Order:

- Each player needs to learn the entire rank of the M best arms based on single-arm observations.
- Players do not always agree on the arm rank; collisions occur.

An Example: $N = 3$, $M = 2$

Assume that Arm 1 $>$ Arm 2 $>$ Arm 3



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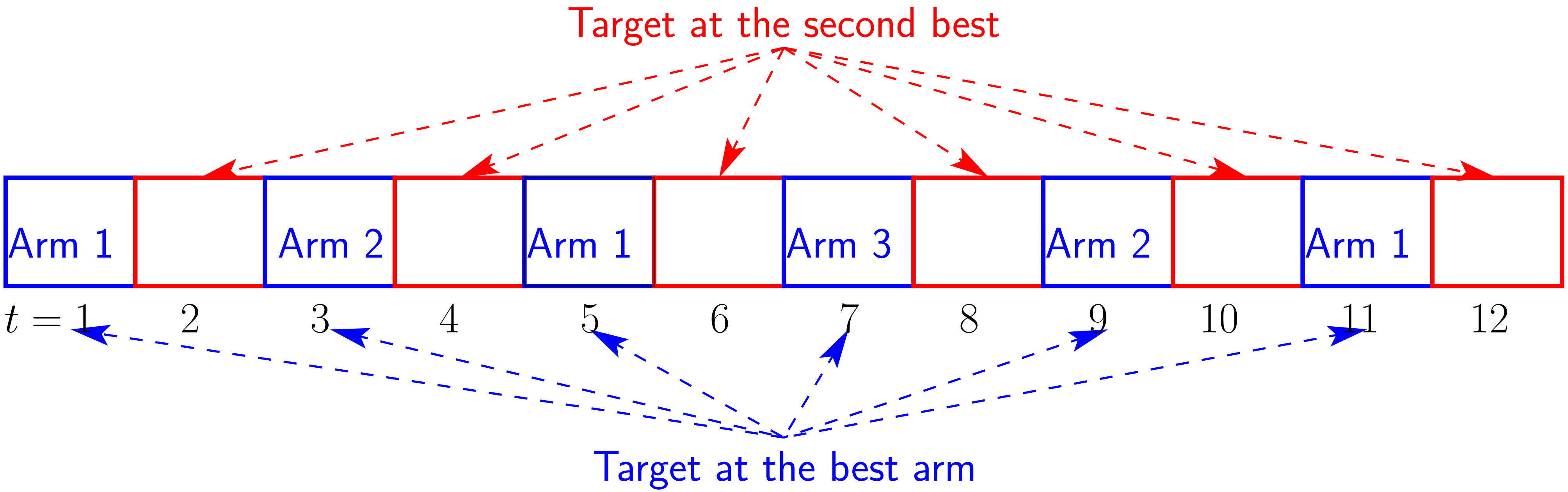

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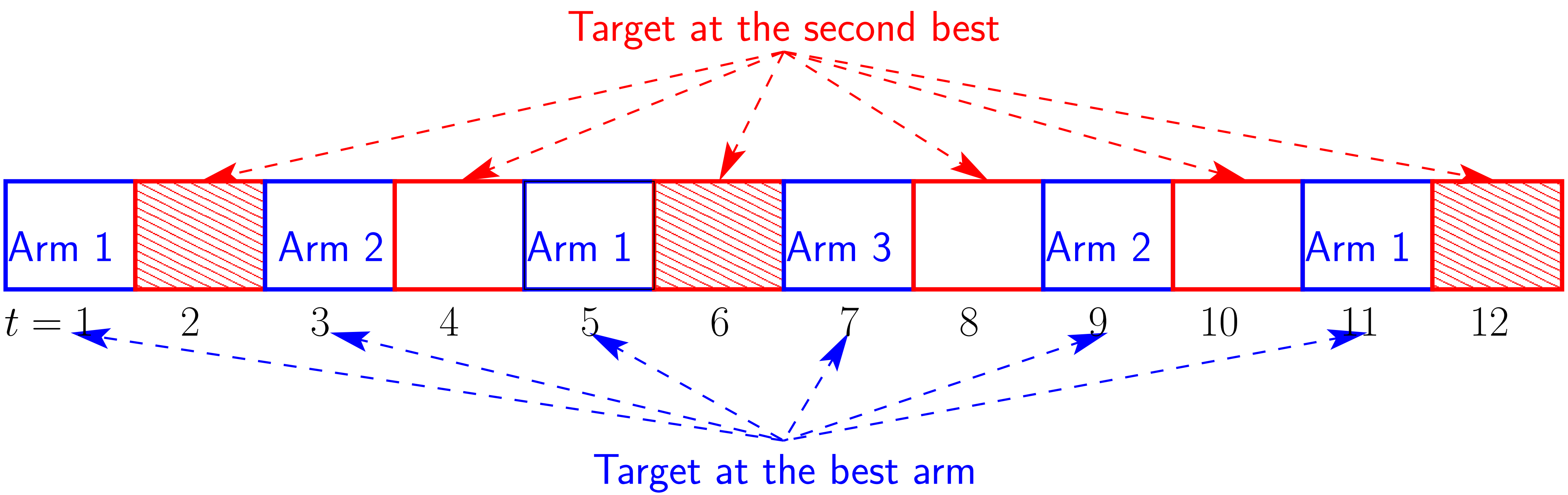

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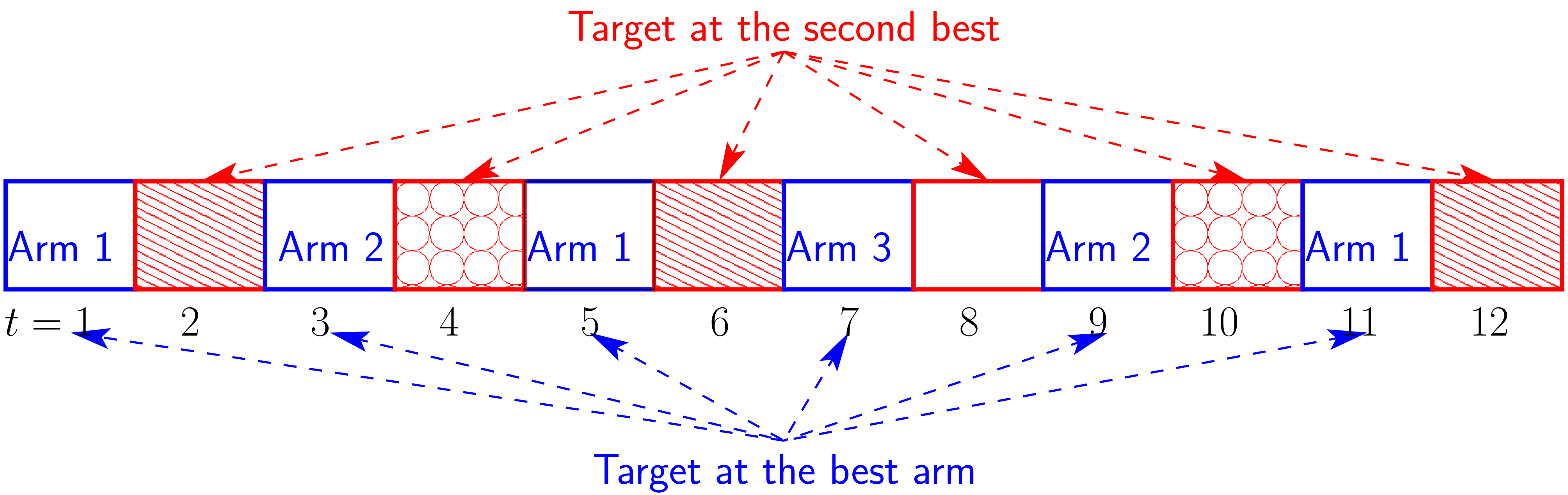

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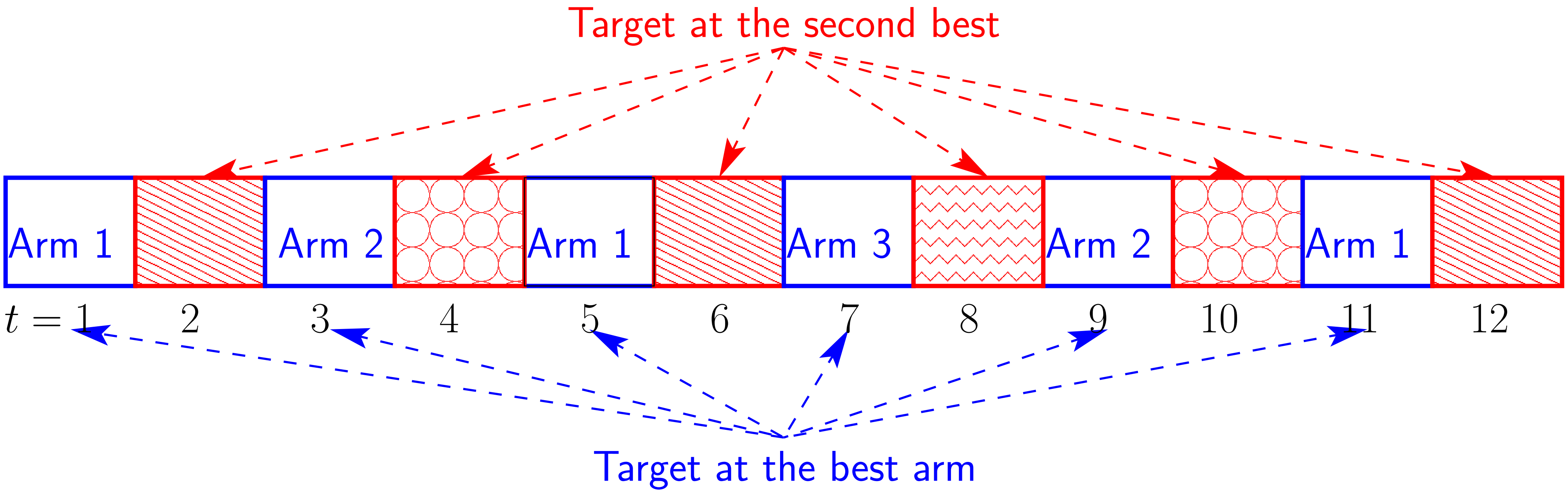

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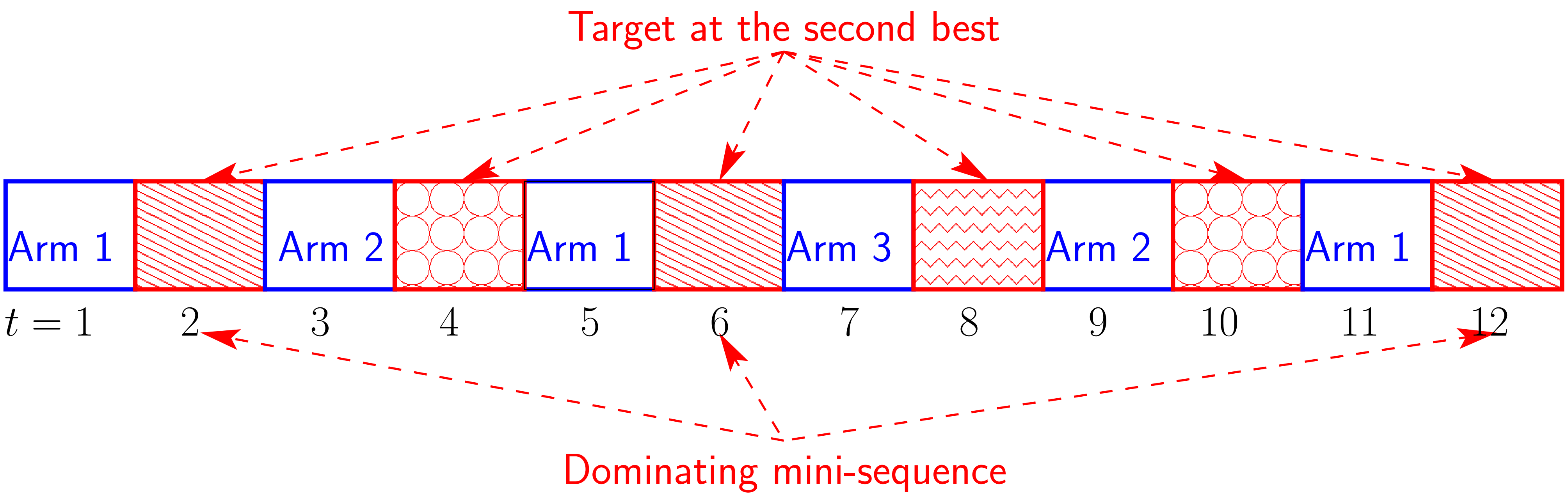
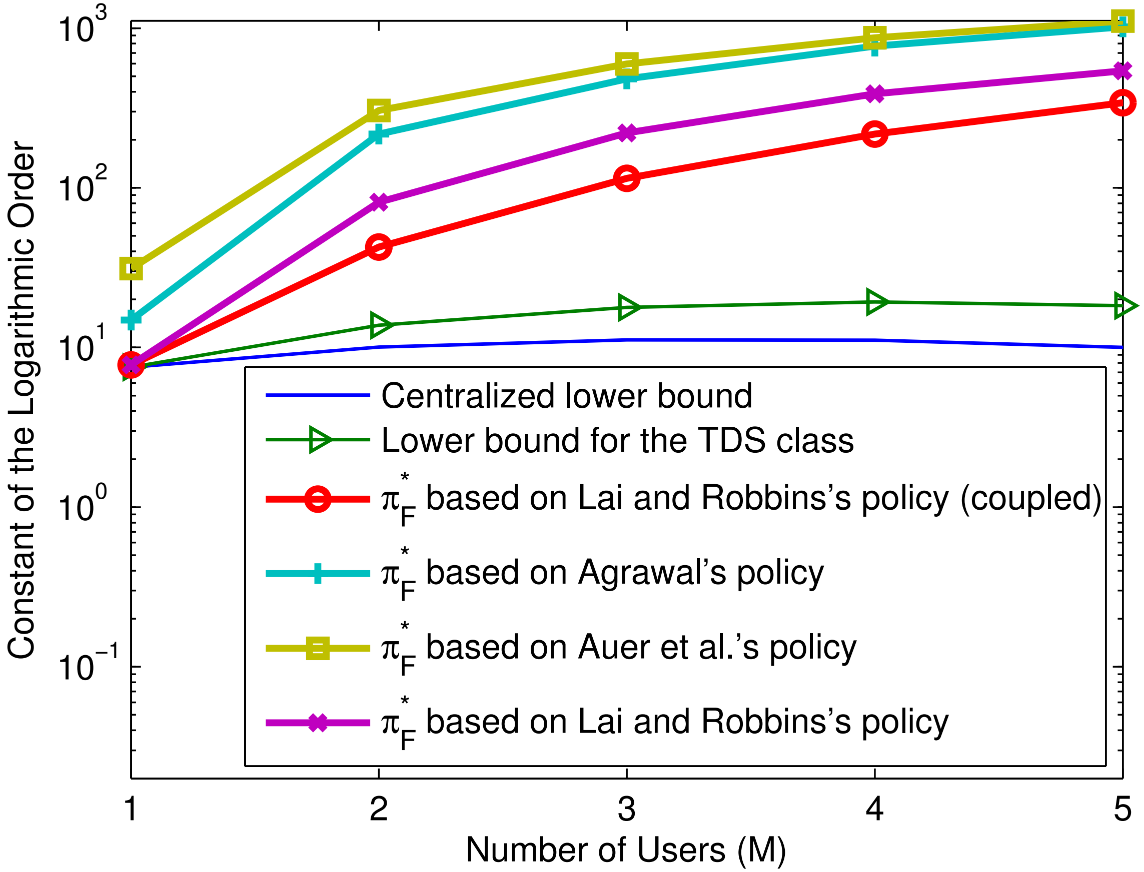


Properties of TDFS

- **Order-Optimal:** if the single-player policy adopted in the TDFS framework is order-optimal, then the corresponding TDFS policy is order-optimal.
- **Fair:** each user achieves the maximum average reward at the same rate.
- **General:** order-optimality and fairness preserved
  - □ for general reward model;
  - □ when players use different order-optimal single-player policies;
  - □ when reward offered by each arm has different distributions and/or different realizations across players provided that all players have the common set of the M best arms and each of the M best arms has the same mean across players.

Cognitive Radio: Bernoulli Reward

- $N = 9$ and $\Theta = [0.1,\ 0.2,\ \cdots,\ 0.9]$.



Conclusion

Research Issue: *Sensing, Tracking, Sharing Spectrum Opportunities*

- Ad hoc architecture w/o central controller or dedicated control channel.
- Fast-varying spectrum opportunities in multiple channels.
- Both Markovian and long range dependent primary traffic.
- Both slotted and unslotted primary transmission structure.
- Sensing errors, limited sensing, energy constraint, and fading.
- Structural results, robust and low-complexity policies.

Technical Approach:

- Stochastic optimization and decision theory.
- Distributed learning under unknown channel occupancy models.
- Quickest change detection in multiple stochastic processes.
- Multi-time-scale traffic modeling.
- Bounding techniques based on stochastic dominance.

Network Layer Issues in Opportunistic Spectrum Access

References

[1] W. Ren, Q. Zhao, and A. Swami, "On the Connectivity and Multihop Delay of Ad Hoc Cognitive Radio Networks", *Proc. of IEEE ICC*, May 2010.

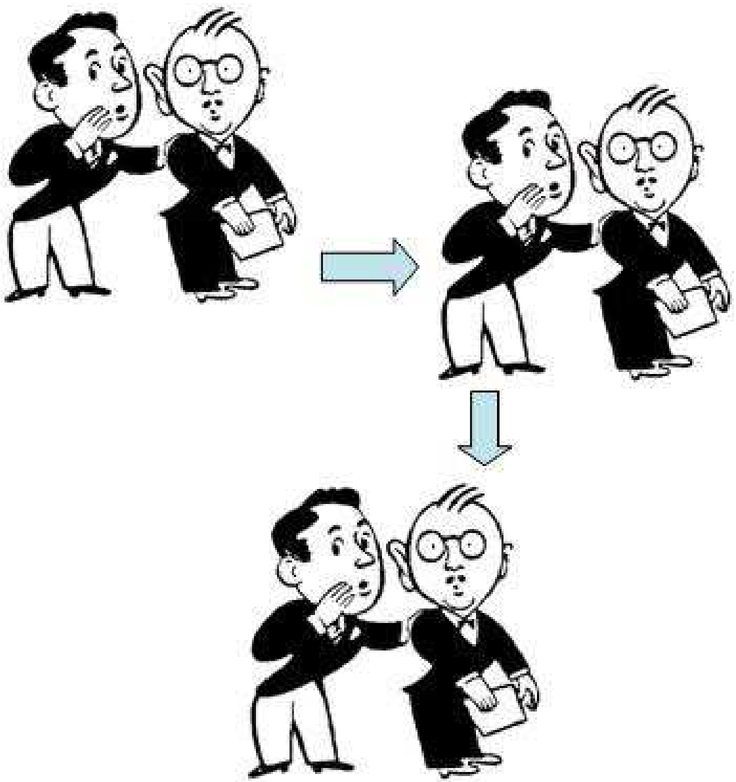
[2] W. Ren, Q. Zhao, and A. Swami, "Power Control in Spectrum Overlay Networks: How to Cross A Multi-Lane Highway," *IEEE JSAC: Special Issue on Stochastic Geometry and Random Graphs for Wireless Networks*, 27(7), 1283-1296, Sept 2009.

[3] W. Ren, Q. Zhao, and A. Swami "Connectivity of Cognitive Radio Networks: Proximity vs. Opportunity", *Proc. ACM MobiCom Workshop on Cognitive Radio Networks*, Sept 2009.

[4] Q. Zhao, W. Ren, and A. Swami, "Spectrum Opportunity Detection: How Good Is Listen-Before-Talk?" *Proc. of IEEE Asilomar Conference on Signals, Systems, and Computers*, November, 2007.

Long Hop vs. Relaying: We Know This

Whispering: Spatial Reuse



Shouting: Fewer Hops

How to Cross A Multi-Lane Highway?

One lane at a time or dash through?

How to Cross A Multi-Lane Highway?

Detecting traffic in multiple lanes is more difficult.

Unique Tradeoffs in Spectrum Overlay

- Transmission power affects how often opportunities occur.

- Transmission power affects the reliability of opportunity detection.

[0] W. Ren, Q. Zhao, and A. Swami, "Power Control in Spectrum Overlay Networks: How to Cross A Multi-Lane Highway," ICASSP 2008; JSAC Sept 2009.

Quantification for Poisson Primary Networks

- Transmission power affects how often opportunities occur.
  - □ Pr[opportunity] decreases exponentially with tx range squared ($p_{tx}^{2/\alpha}$).

- Transmission power affects the reliability of opportunity detection.
  - □ Reliable detection achieved when $p_{tx}/P_{tx} \rightarrow 0$ or $p_{tx}/P_{tx} \rightarrow \infty$.

[0] W. Ren, Q. Zhao, and A. Swami, "Power Control in Spectrum Overlay Networks: How to Cross A Multi-Lane Highway," ICASSP 2008; JSAC Sept 2009.

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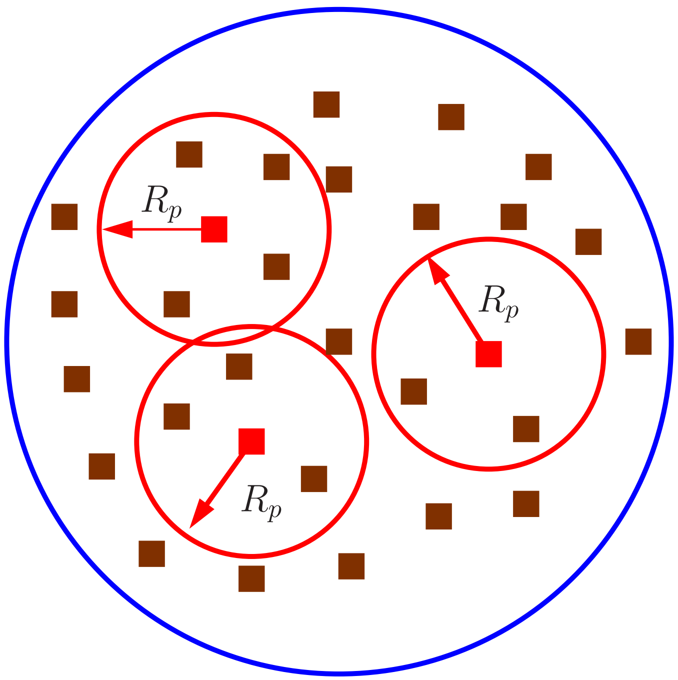
- Optimal transmission power for constrained transport throughput.
  - p_{tx}^* decreases with the traffic load of primary network.

[0] W. Ren, Q. Zhao, and A. Swami, "Power Control in Spectrum Overlay Networks: How to Cross A Multi-Lane Highway," ICASSP 2008; JSAC Sept 2009.

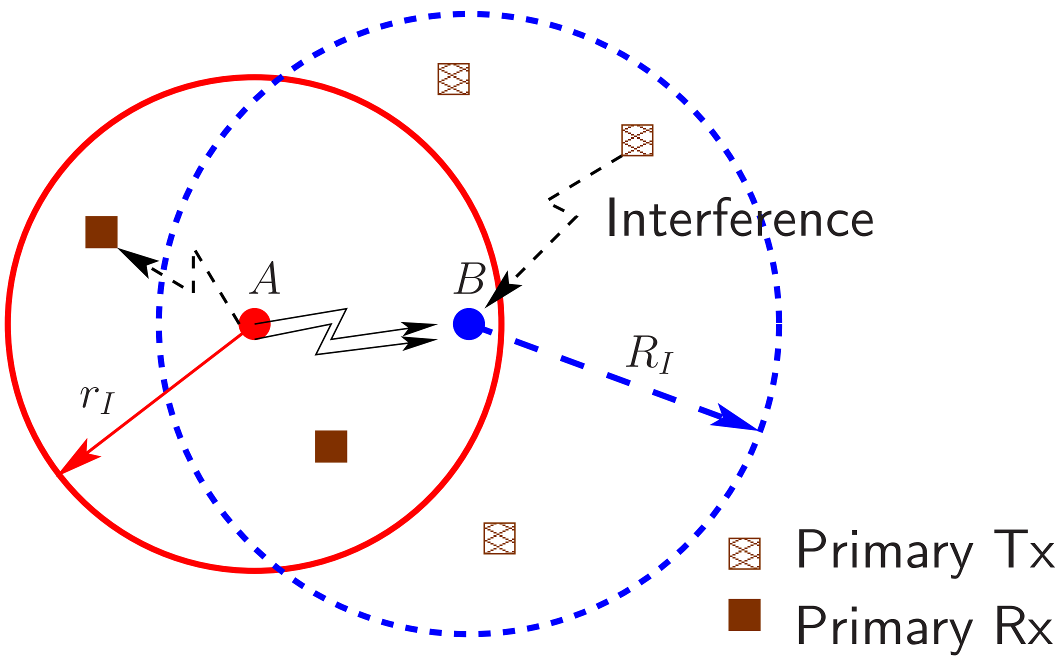
Poisson Primary Network

- Primary users form a Poisson point process with density λ.
- Each primary user transmits with probability p in a slot.
- Primary receivers are uniformly distributed within R_p of their transmitters.



- Thinning Thm $\Rightarrow$ Txs are Poisson.
- Displacement Thm $\Rightarrow$ Rxs are Poisson.

Spectrum Opportunity: Definition



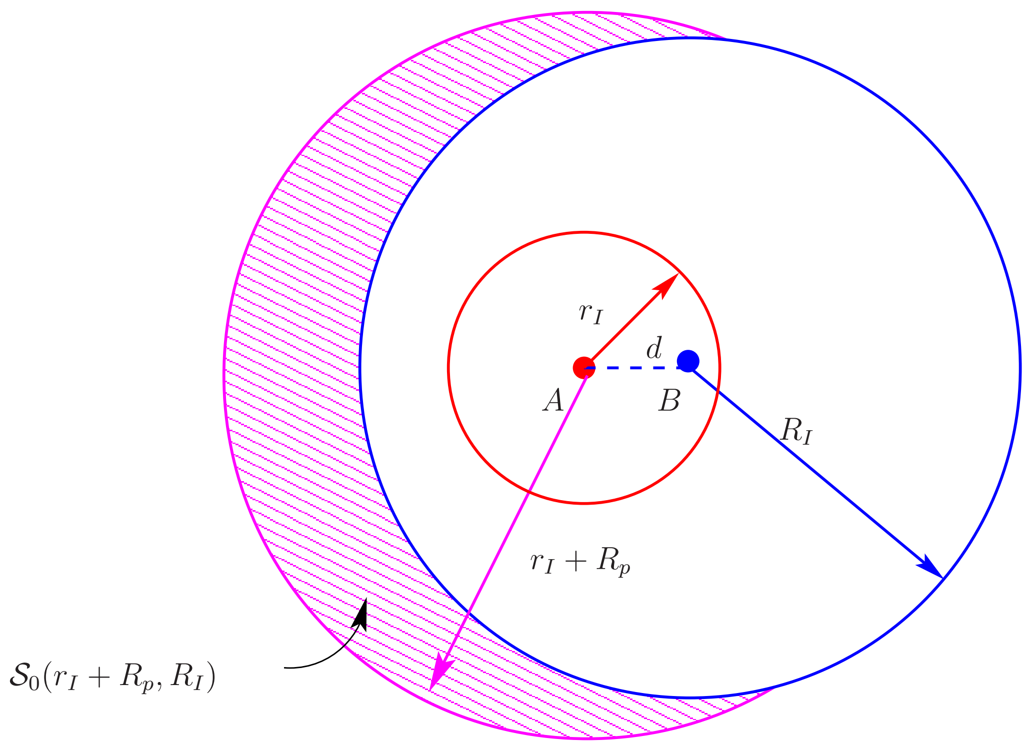
- R_I: interference range of primary users
  $R_I \propto P_{tx}^{1/\alpha}$
- r_I: interference range of secondary users
  $r_I \propto p_{tx}^{1/\alpha}$

A channel is an opportunity for $A \longrightarrow B$ if

- the transmission from A to B can succeed
- the interference power to primary is below a prescribed level

Probability of Spectrum Opportunity

$$
\begin{aligned}
\Pr[\text{opportunity}] &= \Pr\{\{\text{no rx} \leq r_I \text{ of } A\} \cap \{\text{no tx} \leq R_I \text{ of } B\}\} \\
&= \exp\left[-p\lambda\left(\iint_{\mathcal{S}_0(r_I+R_p,R_I)} \frac{\mathcal{S}_I(r,R_p,r_I)}{\pi R_p^2} r\,\mathrm{d}r\,\mathrm{d}\theta + \pi R_I^2\right)\right]
\end{aligned}
$$

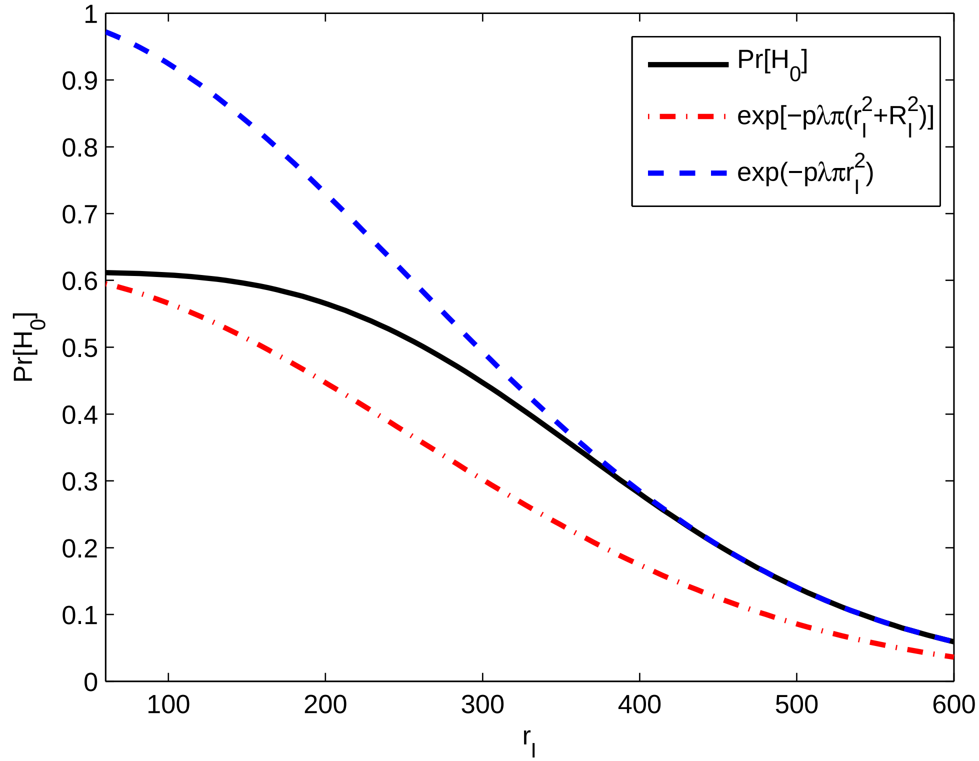


Impact of Transmission Power on Pr[opportunity]

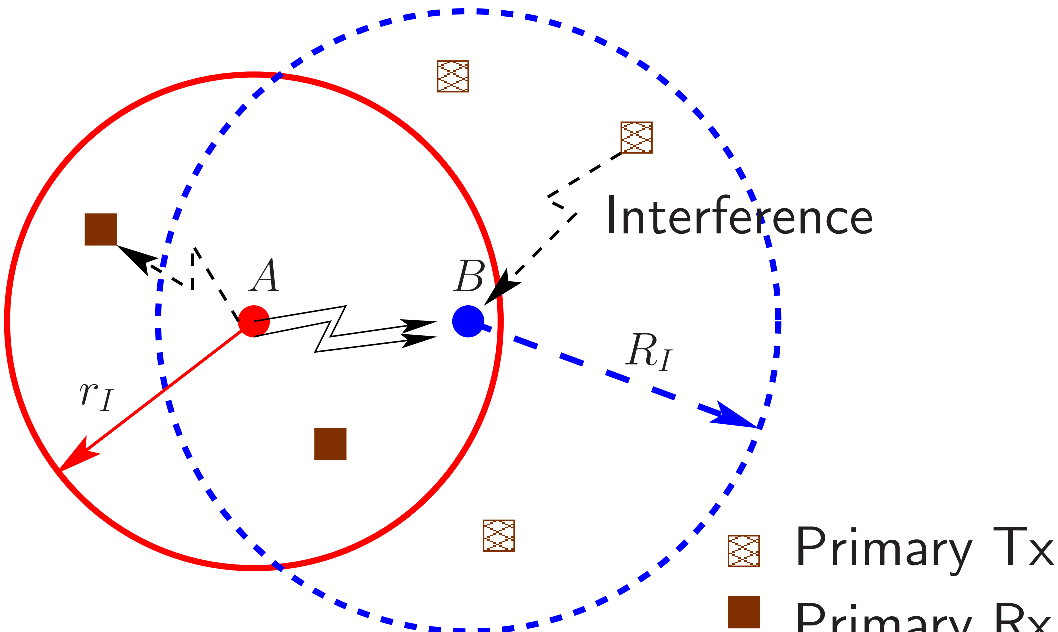
- Asymptotically Achievable Lower and Upper Bounds:

$$\exp[-p\lambda\pi(r_I^2 + R_I^2)] \;<\; \Pr[\text{ opportunity }] \;\leq\; \exp(-p\lambda\pi r_I^2)$$

- $\Pr$[opportunity] decreases exponentially with $r_I^2 \propto p_{tx}^{2/\alpha}$.



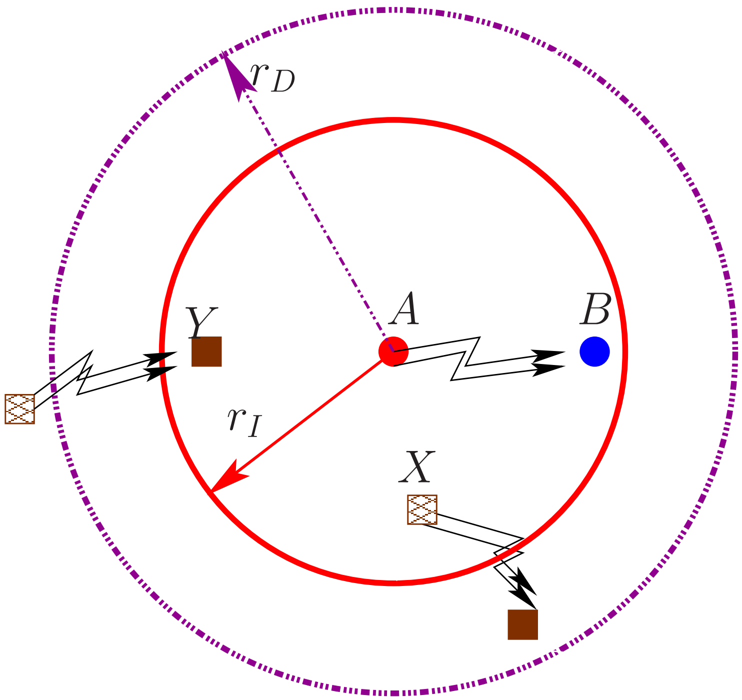
Spectrum Opportunity Detection



- R_I: interference range of primary users
  $R_I \propto P_{tx}^{1/\alpha}$
- r_I: interference range of secondary users
  $r_I \propto p_{tx}^{1/\alpha}$

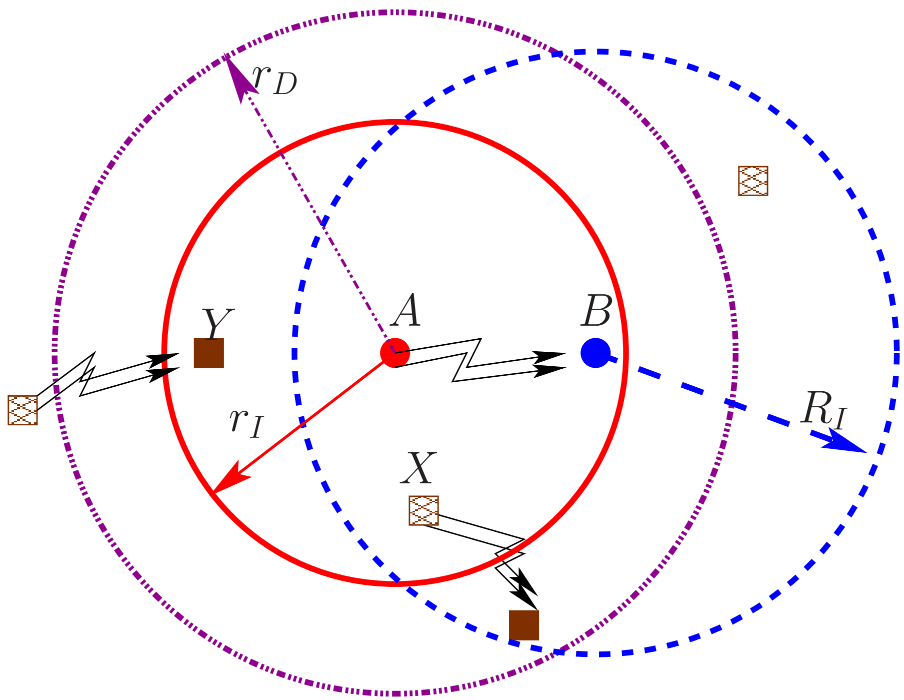
Detecting primary signals $\neq$ detecting spectrum opportunity.

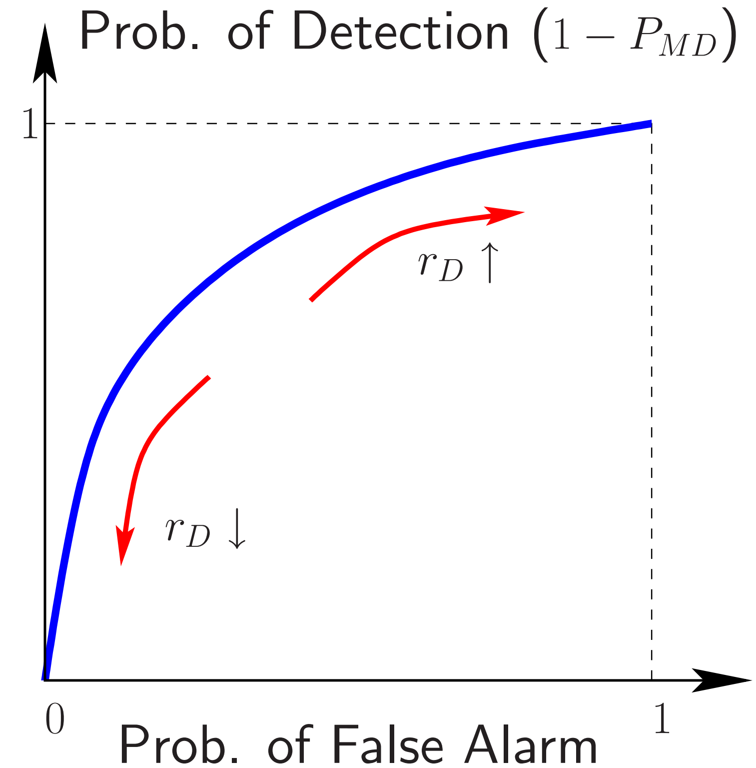
Detecting Primary Signals



- r_D: detection range.
- $\mathcal{H}_0$: no primary Tx within r_D, $\mathcal{H}_1$: alternative.
- False alarms and miss detections occur due to noise and fading.

From Detecting Signal to Detecting Opportunity

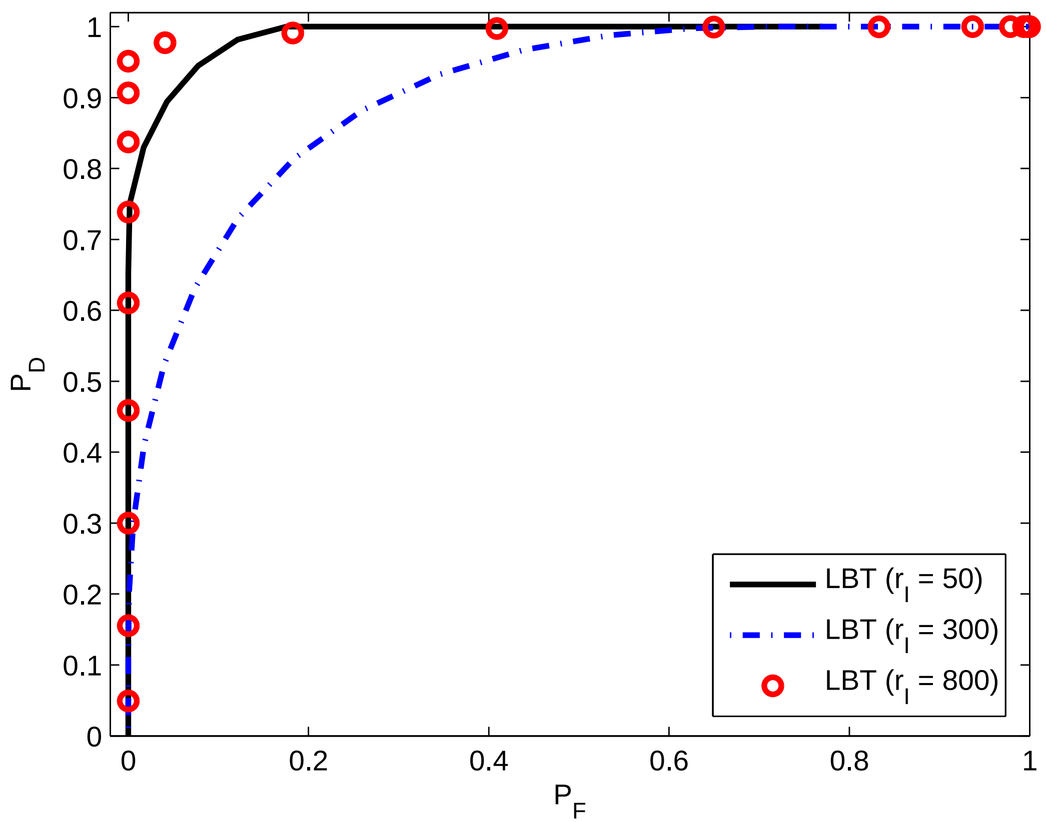




- $\mathcal{H}_0$: opportunity, $\mathcal{H}_1$: alternative.
- Even with perfect ears, exposed Tx $(X) \Rightarrow$ FA, hidden Rx $(Y) \Rightarrow$ MD.
- Adjusting detection range r_D leads to different operating points.

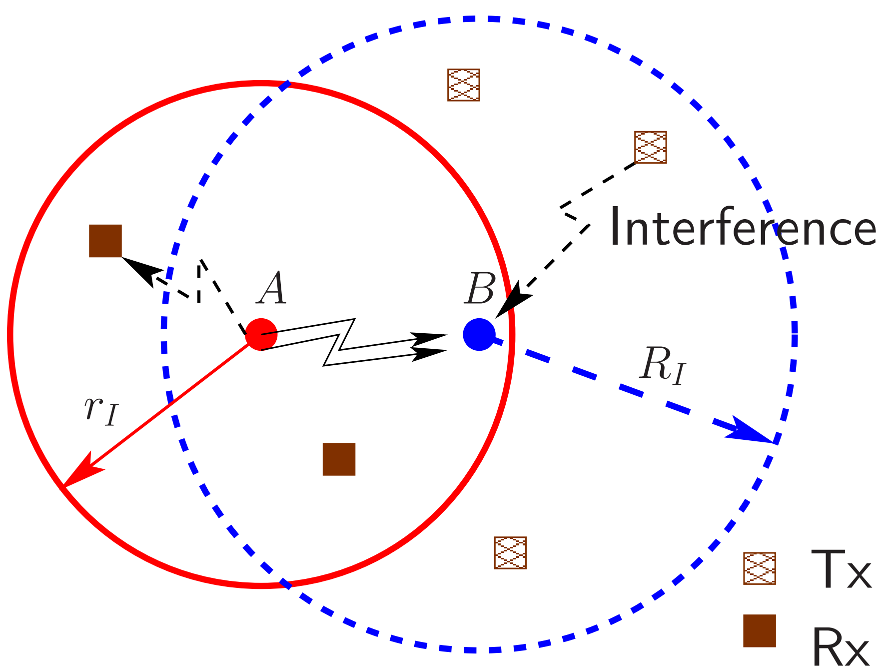
Asymptotic Properties of ROC

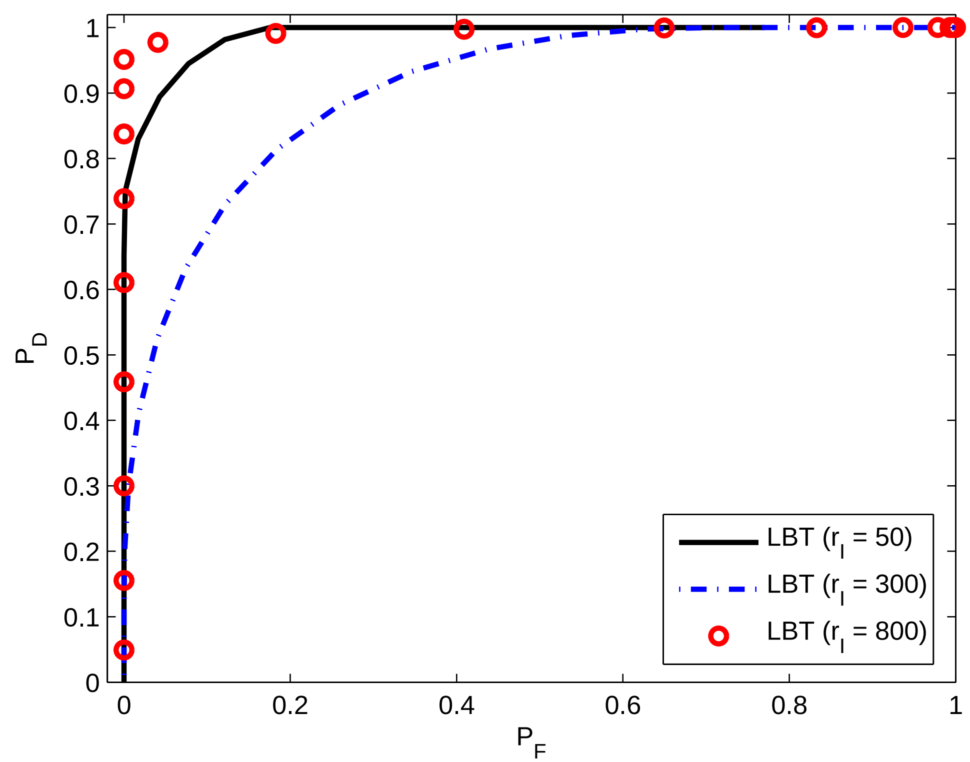
- Reliable opportunity detection is achieved in two extreme regimes:
  - The point $(P_F(r_D = R_I), P_D(r_D = R_I)) \rightarrow (0,1)$ when $p_{tx}/P_{tx} \longrightarrow 0$.
  - The point $(P_F(r_D = r_I - R_I), P_D(r_D = r_I - R_I)) \rightarrow (0,1)$ when $p_{tx}/P_{tx} \longrightarrow \infty$.



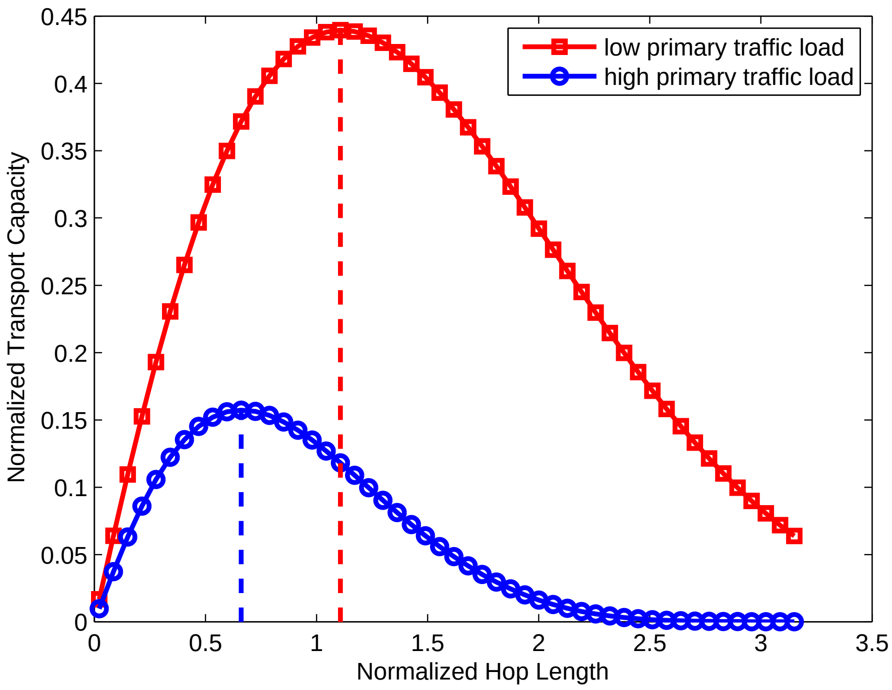
Optimal Power for Constrained Transport Throughput

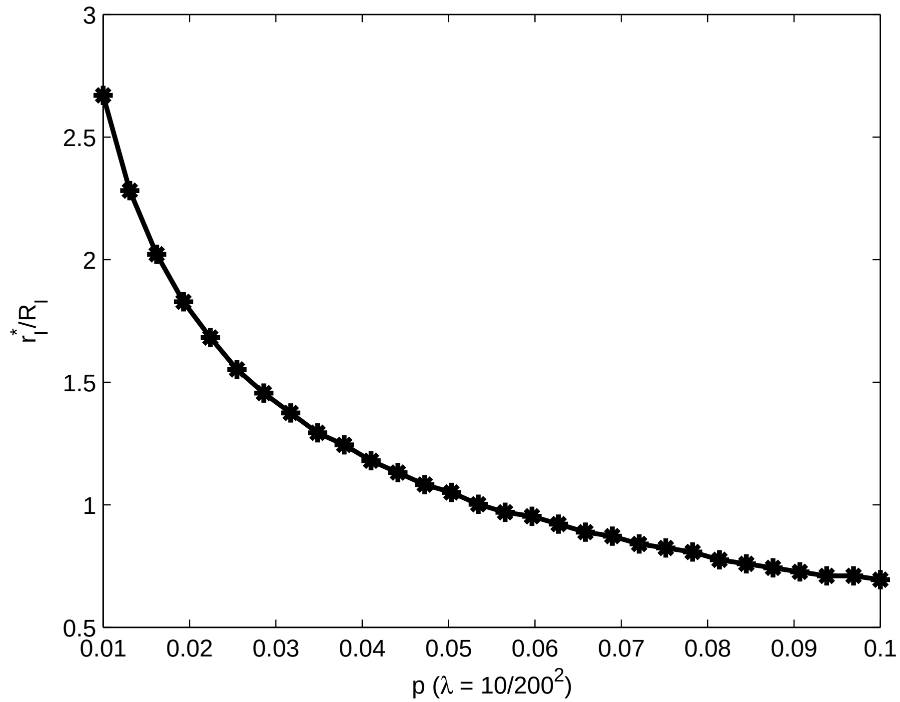
$$p_{tx}^* = \arg\max\{\ d(p_{tx})\ \Pr[\ \text{success} \mid p_{tx}]\} \quad \text{s.t.} \quad \Pr[\ \text{collision} \mid p_{tx}] \leq \zeta$$





Numerical Examples





Quantification for Poisson Primary Networks

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- Optimal transmission power for constrained transport throughput.
  - p_{tx}^* decreases with the traffic load of primary network.

Non-cooperative Power Control Game[1, 2]

- Network Model
  - Centralized primary network and centralized secondary network
  - Shared based station
- Net Utility Function = Utility Function − Pricing Function
  - Utility function: the throughput of each secondary users (SINR).
  - Pricing function: channel condition and interference to primary users.
  - Only up-link is considered.
- Objective and Solution
  - Objective: $\max_{p_i} \{\text{net utility}\}$, p_i – transmission power of secondary user i.
  - Solution: Nash Equilibrium.

[1]Yajun Zhu, Wei Wang, Tao Peng, Wenbo Wang, "A Non-cooperative Power Control Game Considering Utilization and Fairness in Cognitive Radio Network," *IEEE 2007 International Symposium on Microwave, Antenna, Propagation, and EMC Technologies for Wireless Communications*, Aug. 2007.

[2]Wang Xia, Zhu Qi, "Power Control for Cognitive Radio Base on Game Theory," *IEEE 2007 International Conference on Wireless Communications, Networking and Mobile Computing*, Sep. 2007.

Power Control Based on Soft Sensing Information[3, 4]

▶ Basic Idea

Use the soft information (e.g., likelihood ratio) given by the spectrum sensor to determine the transmission power.

▶ Network Model

- One pair of primary and one pair of secondary users with known distance.
- Primary user: coherence time T_c and an ON probability of α.

▶ Two Different Objectives and the Corresponding Power Control Schemes

- $\max$ SNR or capacity
- Two constraints: peak transmission power and average interference power to the primary receiver.
- maximize SNR $\longrightarrow$ binary power control scheme (0 or the peak power).
- maximize capacity $\longrightarrow$ continuous power adjustment.

[3] Karama Hamdi, Wei Zhang, and Khaled Ben Letaief, "Power Control in Cognitive Radio Systems Based on Spectrum Sensing Side Information," *IEEE 2007 International Conference on Communications*, June 2007.

[4] Sudhir Srinivasa and Syed Ali Jafar, "Soft Sensing and Optimal Power Control for Cognitive Radio," *IEEE 2007 Global Telecommunications Conference*, Nov. 2007.

Power Control in OSA in TV Bands[5]

- Network Model
  - Primary system: TV station with certain covering range.
  - Secondary system: N users outside the range of TV station.
  - Feedback from primary receivers is assumed.

- Objective and Constraint
  - Objective: minimize the sum of the transmission power of all N users.
  - Constraint: target SINR for both primary receivers and secondary receivers, minimum and maximum allowable transmission power of secondary users.

- Centralized and Distributed Solution
  - Centralized solution needs a central controller.
  - Distributed solution can not ensure the QoS of primary users.

[5] Lijun Qian, Xiangfang Li, John Attia, and Zoran Gajic, "Power Control for Cognitive Radio Ad Hoc Networks," *15th IEEE Workshop on Local & Metropolitan Area Networks*, June 2007.

Power Control Based on Cooperative Sensing[6, 7]

▶ Basic Idea

Employ independent secondary sensing stations to improve the performance of detecting the primary signals.

▶ Each secondary user determines its transmission power based on the CINR report from its nearby sensing stations. Here CINR is defined as the ratio of the received power of the primary signal to the received power of the secondary signal plus noise.

▶ Simulation Results

- Network model: a secondary transmitter with randomly distributed secondary sensing stations; one primary base station and several primary receivers.
- Performance metric: successful transmission probability and the ratio of primary receivers that are affected by the secondary transmitter.

[6] Youngjin Yu, Hidekazu Murata, Koji Yamamoto, and Susumu Yoshida, "Multi-hop Cooperative Sensing and Transmit Power Control Based on Interference Information for Cognitive Radio," *IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications*, Sep. 2007.

[7] Naotaka Shibata, Koji Yamamoto, Hidekazu Murata, and Susumu Yoshida, "Joint Effect of Power Control, Access Control, and Multi-hop Transmission on Area Spectra Efficiency of Cognitive Radio System," *IEEE 6th International Conference on Information, Communications & Signal Processing*, Dec. 2007.

Coexistence: Connectivity and Multi-hop Delay

Coexistence: Connectivity and Multi-hop Delay

Consider a large-scale ad hoc cognitive radio network:

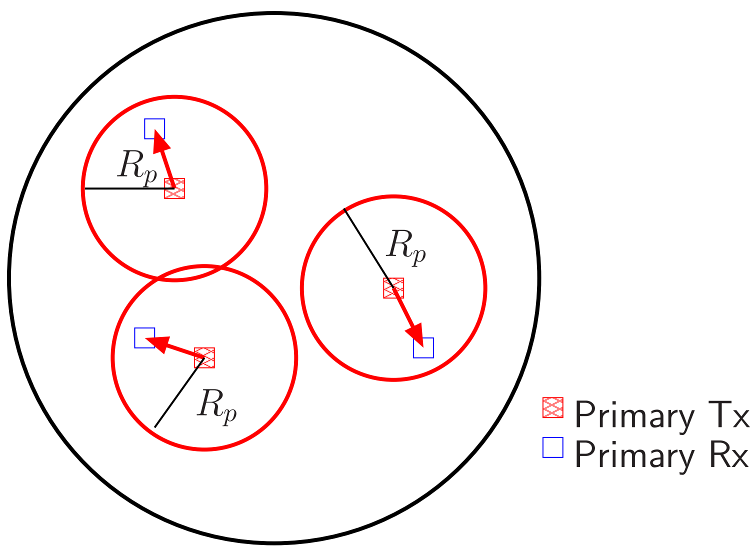
$$\text{spectrum overlay} \begin{cases} \text{a Poisson distributed primary network} \\ \text{a Poisson distributed secondary network} \end{cases}$$

- Analytical characterization of the connectivity of the secondary network as a function of its density and the traffic load of the primary network.

- Establishment of the scaling law of the multihop delay in the secondary network with respect to the source-destination distance.

Primary Network Model

- Primary network adopts a synchronous slot structure with a slot length T_S.
- The realizations of active primary transmitters vary from slot to slot and are assumed to be i.i.d. across slots.
- At the beginning of each slot, the primary transmitters are distributed according to a two-dimensional Poisson point process X_{PT} with density λ_{PT}. To each primary transmitter, its receiver is uniformly distributed within its transmission range R_p.



Displacement Theorem $\Rightarrow$ Primary receivers form another two-dimensional Poisson point process X_{PR} with density λ_{PT}.

Secondary Network Model

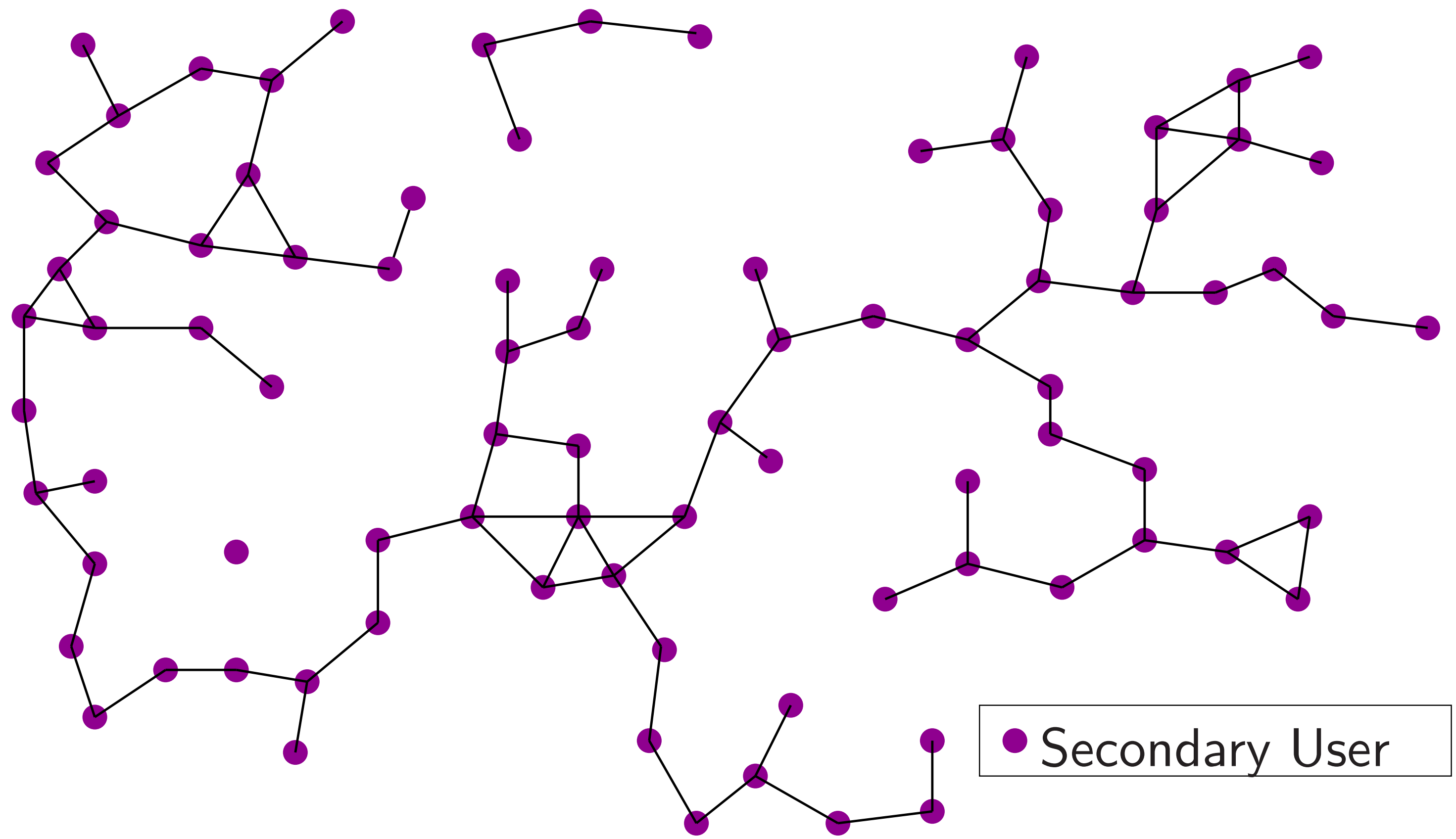
- Secondary users are distributed according to a two-dimensional Poisson point process X_S with density λ_S, independent of the primary network.

- The locations of the secondary users are static over time.

- Two types of links
  - topological link: distance $\leq r_p$.
  - communication link: distance $\leq r_p$ and a bidirectional opportunity exists.

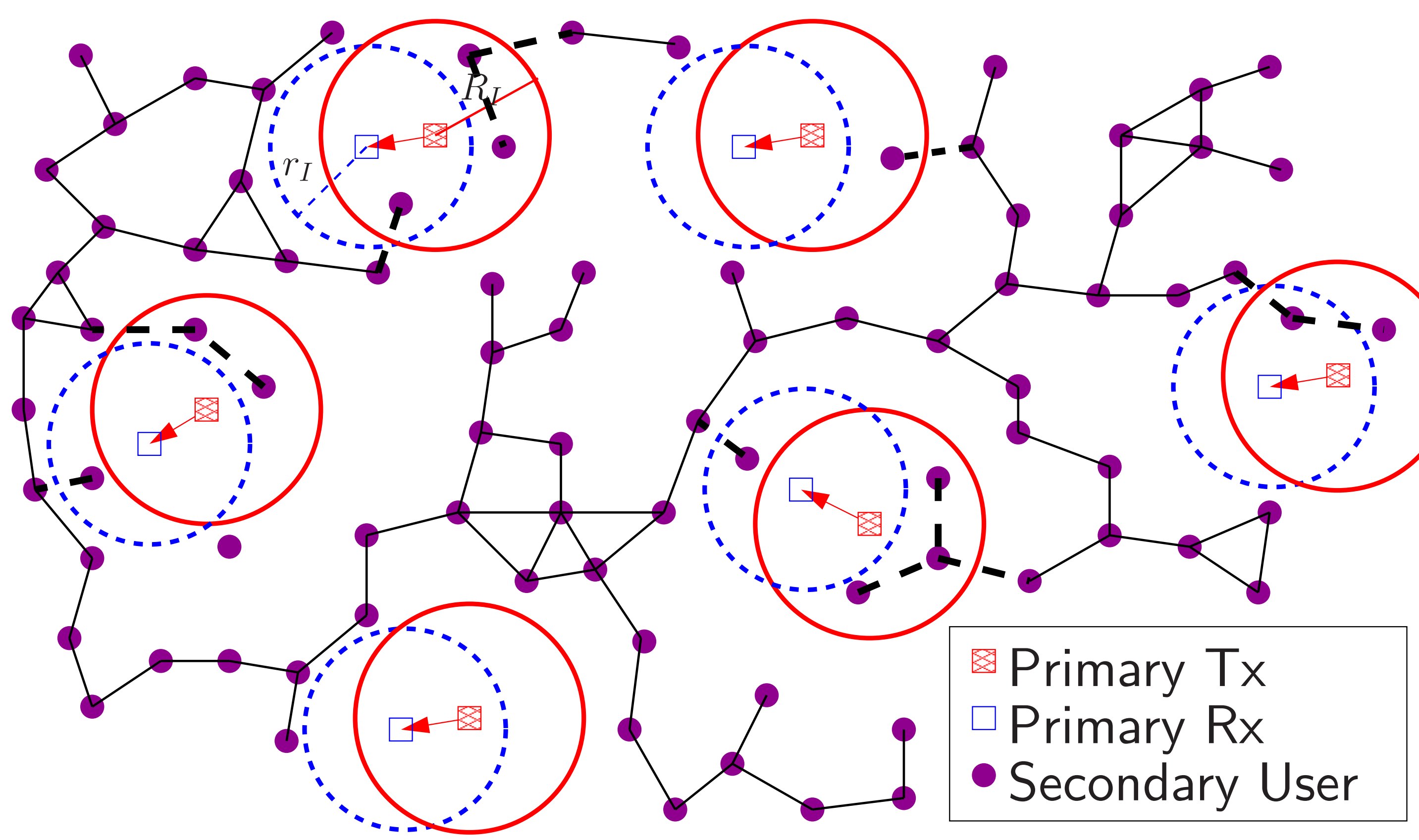
Topological Link vs. Communication Link

- A **communication link** is a **topological link** which sees a bidirectional opportunity.
- Random graph $\mathcal{G}_S(\lambda_S)$ formed by topological links



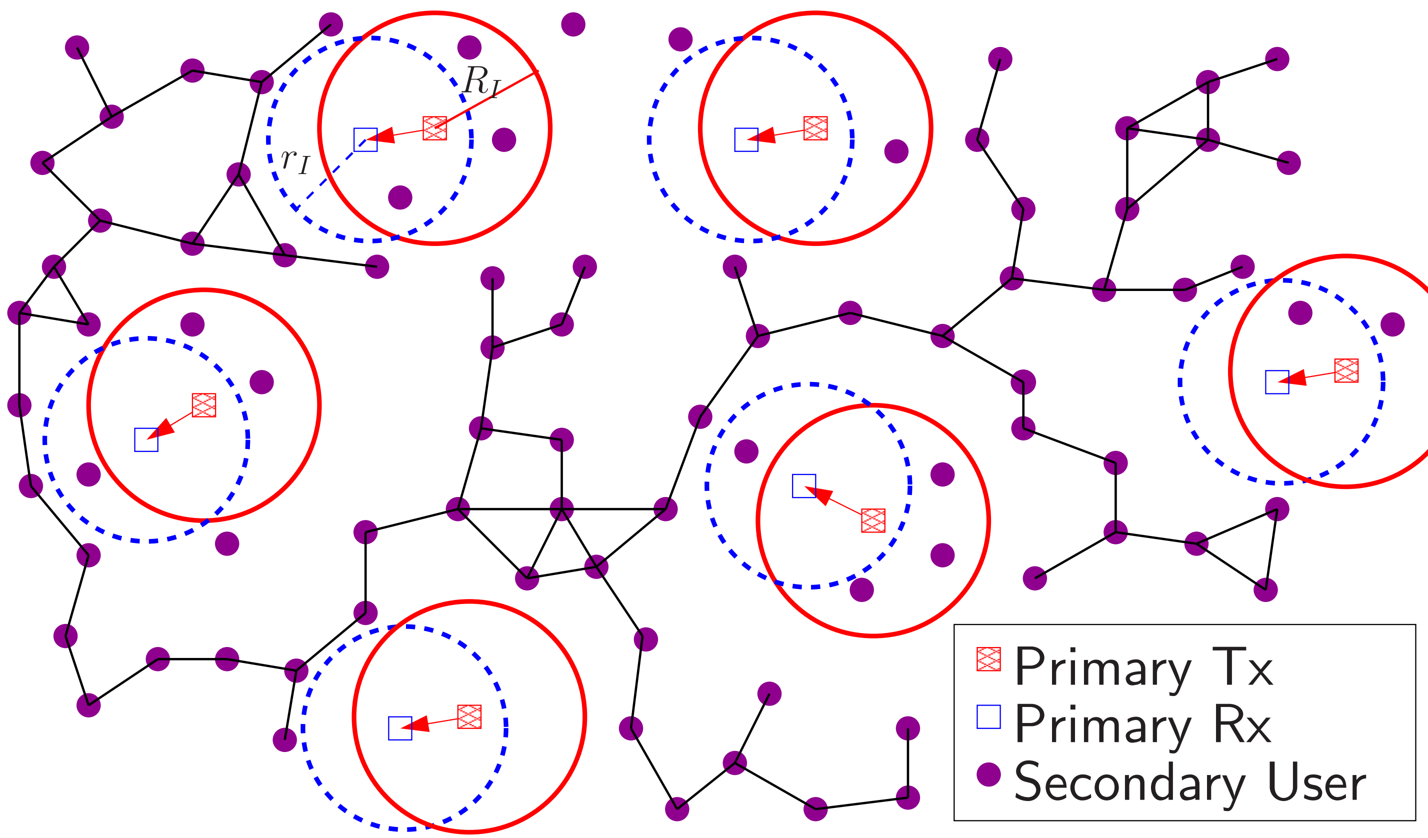
Topological Link vs. Communication Link

- A **communication link** is a **topological link** which sees a bidirectional opportunity.
- Remove the topological links which do not see opportunities.

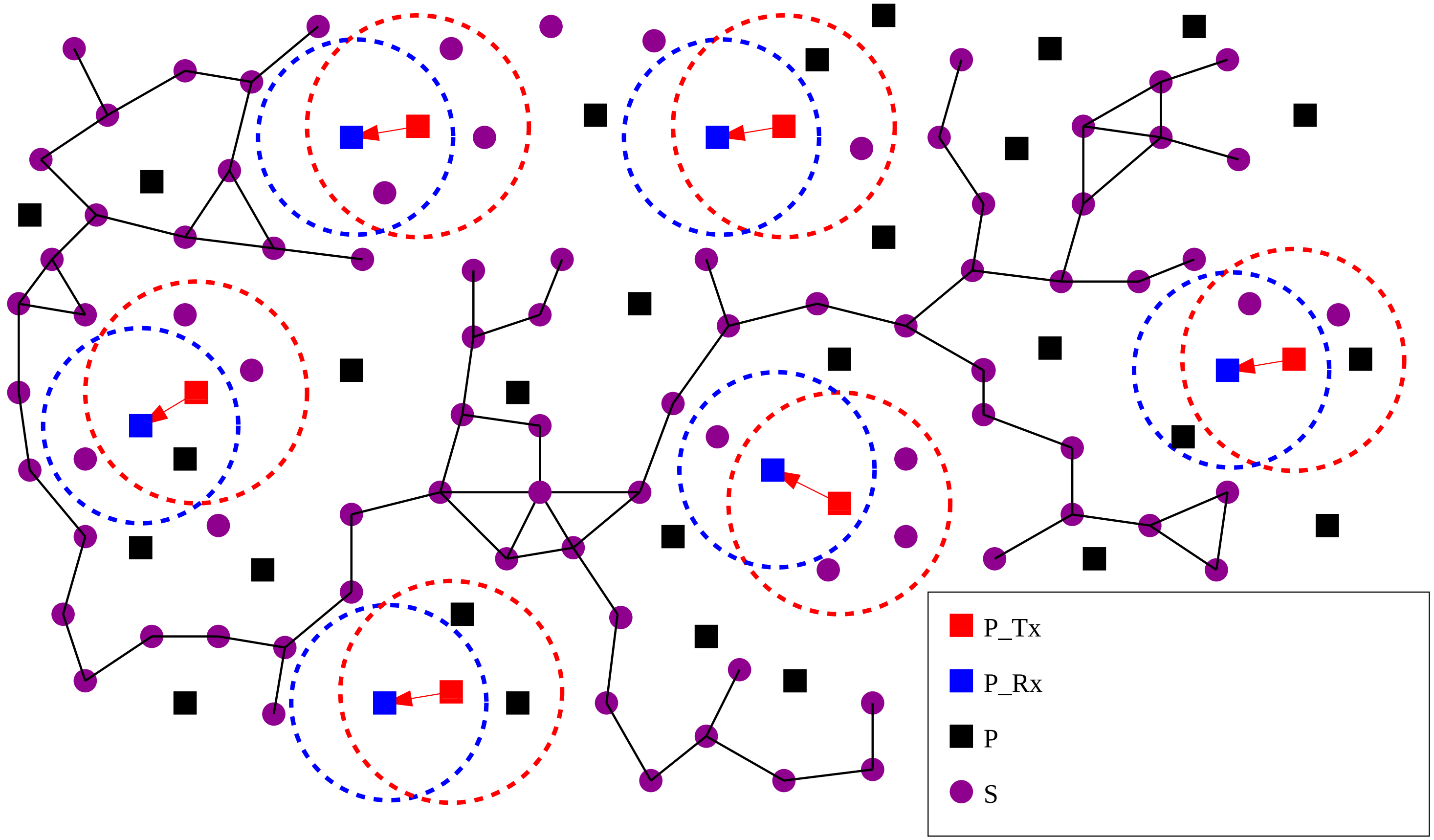


Topological Link vs. Communication Link

- A **communication link** is a **topological link** which sees a bidirectional opportunity.
- Random graph $\mathcal{G}_H(\lambda_S, \lambda_{PT}, t)$ formed by communication links



Connectivity

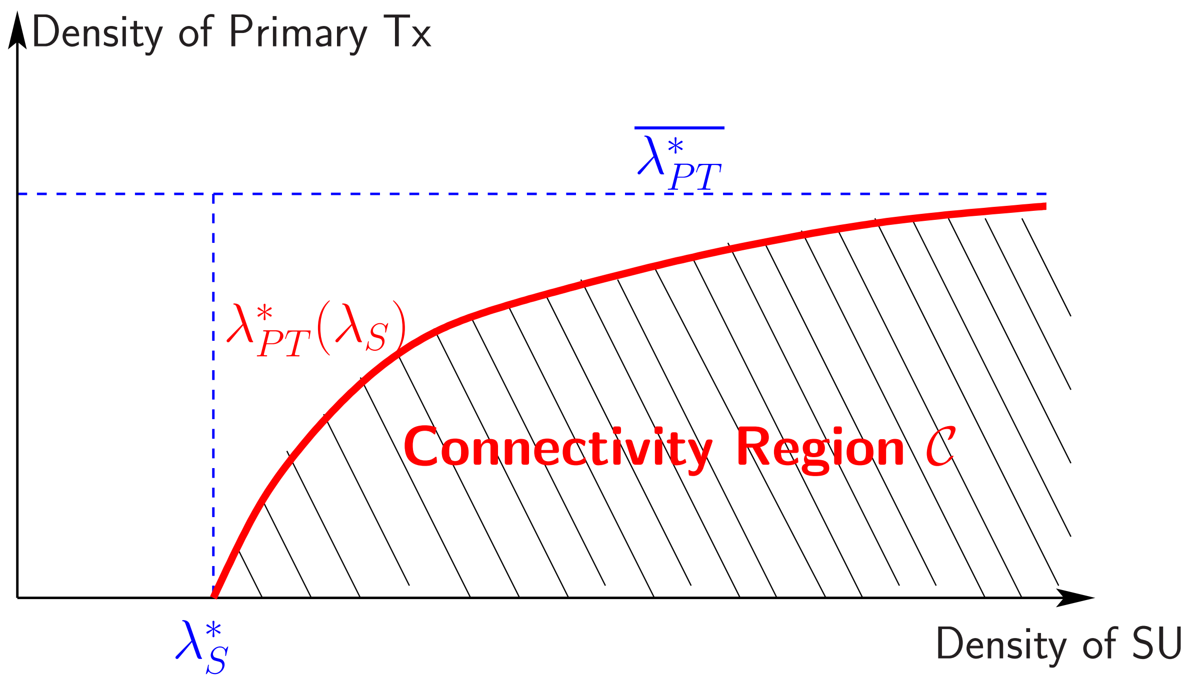


Connectivity: the existence of an infinite connected component almost surely.

Existence of A Link between Two Secondary Users:

- they are within Tx range;
- they see a bidirectional opportunity.

Connectivity Region



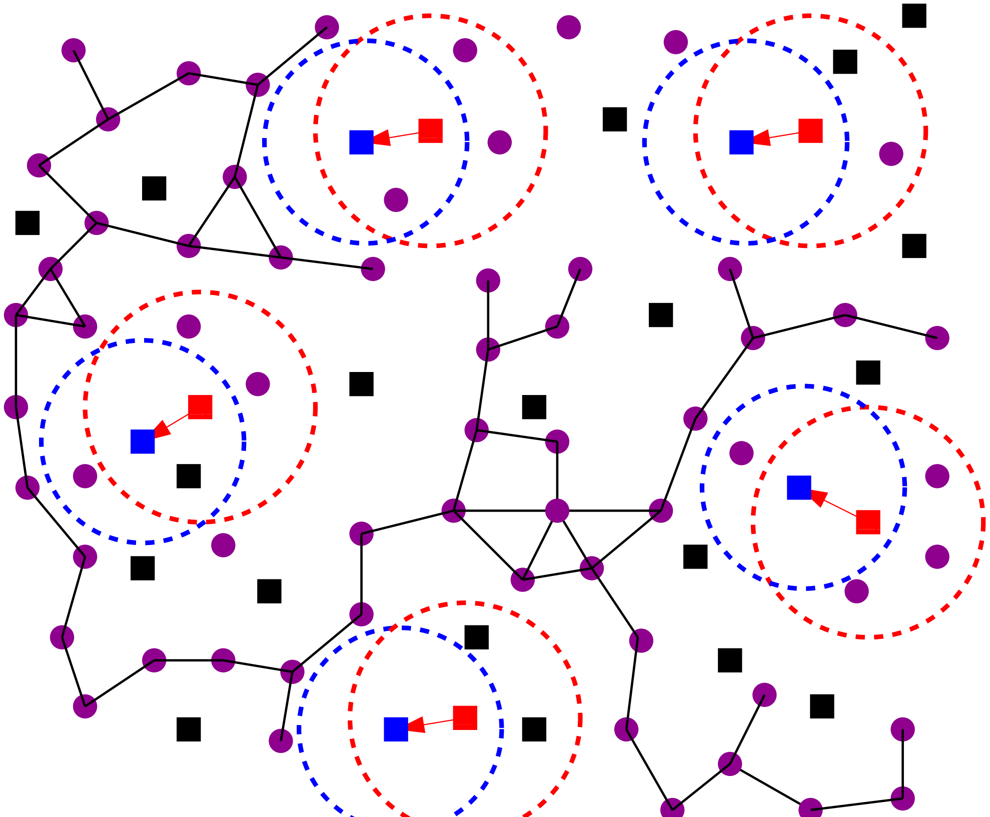
- $\forall(\lambda_S, \lambda_{PT}) \in \mathcal{C}$, there exists a *unique* infinite connected component.
- $\lambda^*_{PT}(\lambda_S)$ monotonically increases with λ_S.
- The critical density of secondary users: $\lambda^*_S = \lambda_c(r_{tx})$ (*CD of homogenous networks*).
- The critical density of primary Tx: $\overline{\lambda^*_{PT}} \leq \min\left\{\frac{1}{4\left(R_I^2 - r_p^2/4\right)}\lambda_c(1),\ \frac{1}{4\left(r_I^2 - r_p^2/4\right)}\lambda_c(1)\right\}$.

W. Ren, Q. Zhao, A. Swami, "Connectivity of Heterogeneous Wireless Networks," submitted to IEEE Trans. Information Theory.

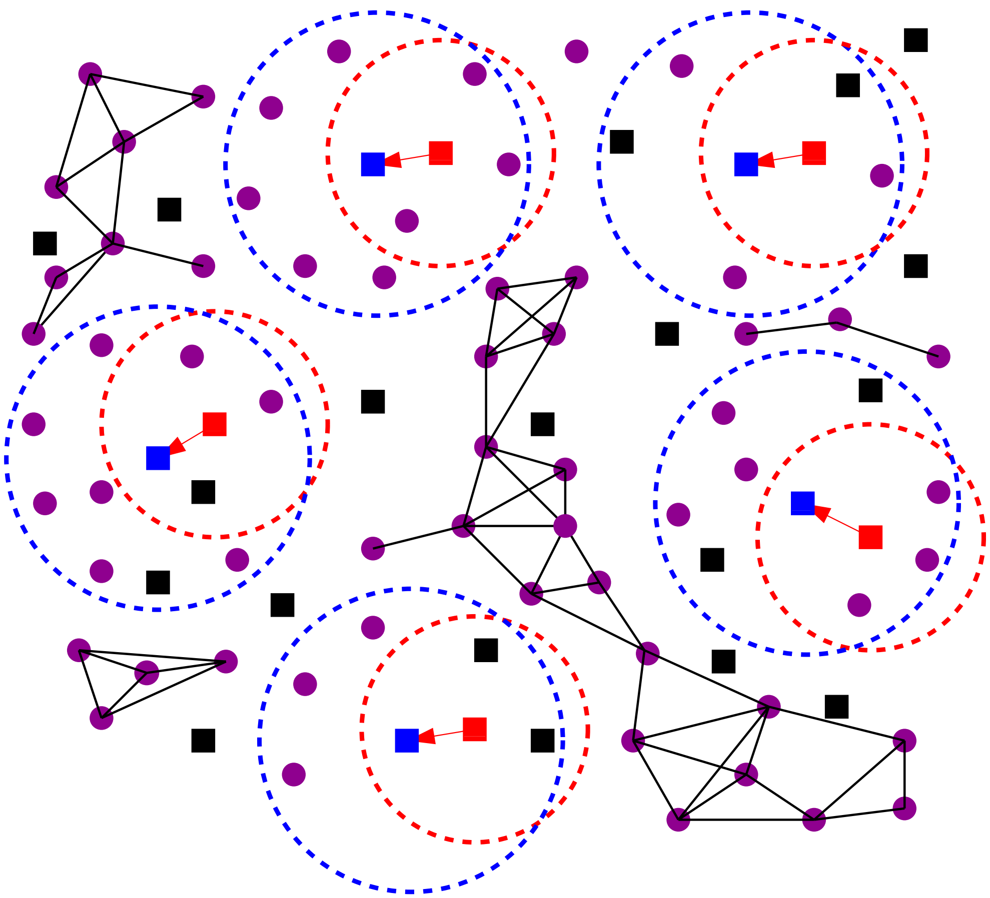
Proximity vs. Opportunity

Increasing P_S leads to more neighbors but fewer opportunities.

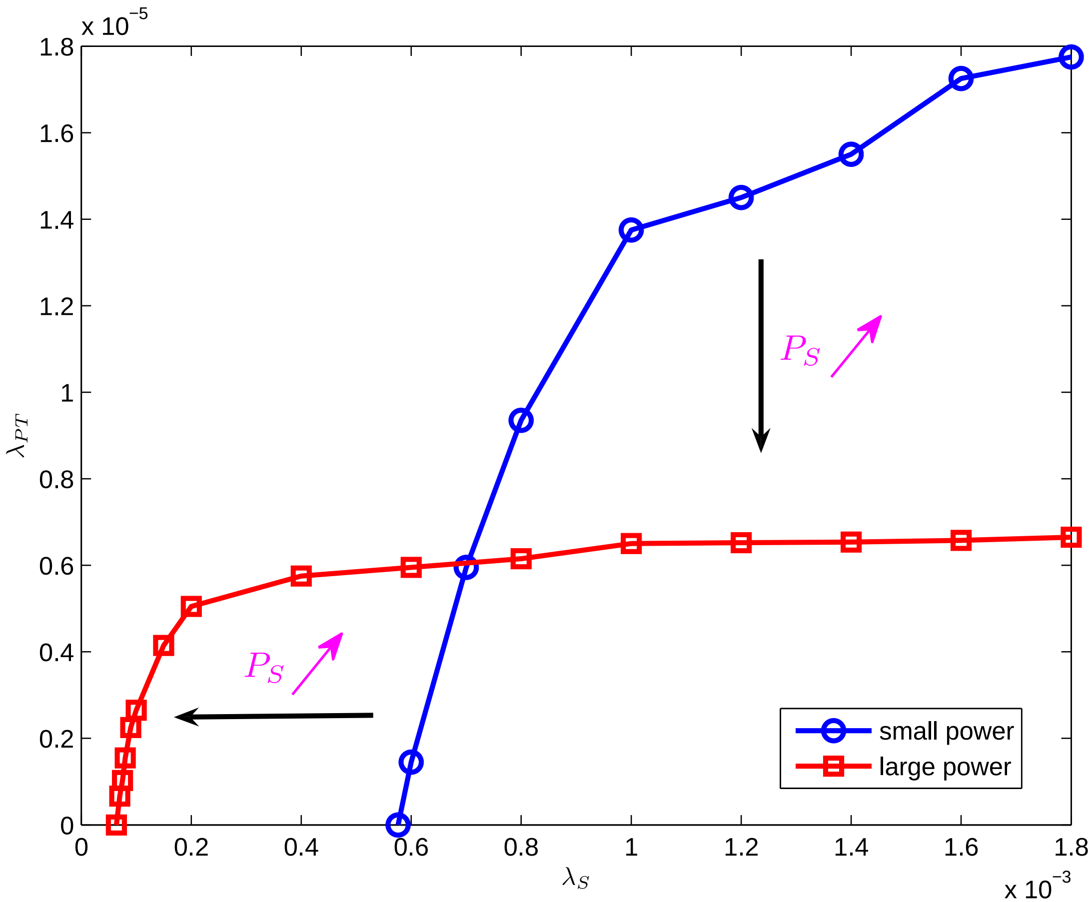
Small P_S



Large P_S



Proximity vs. Opportunity

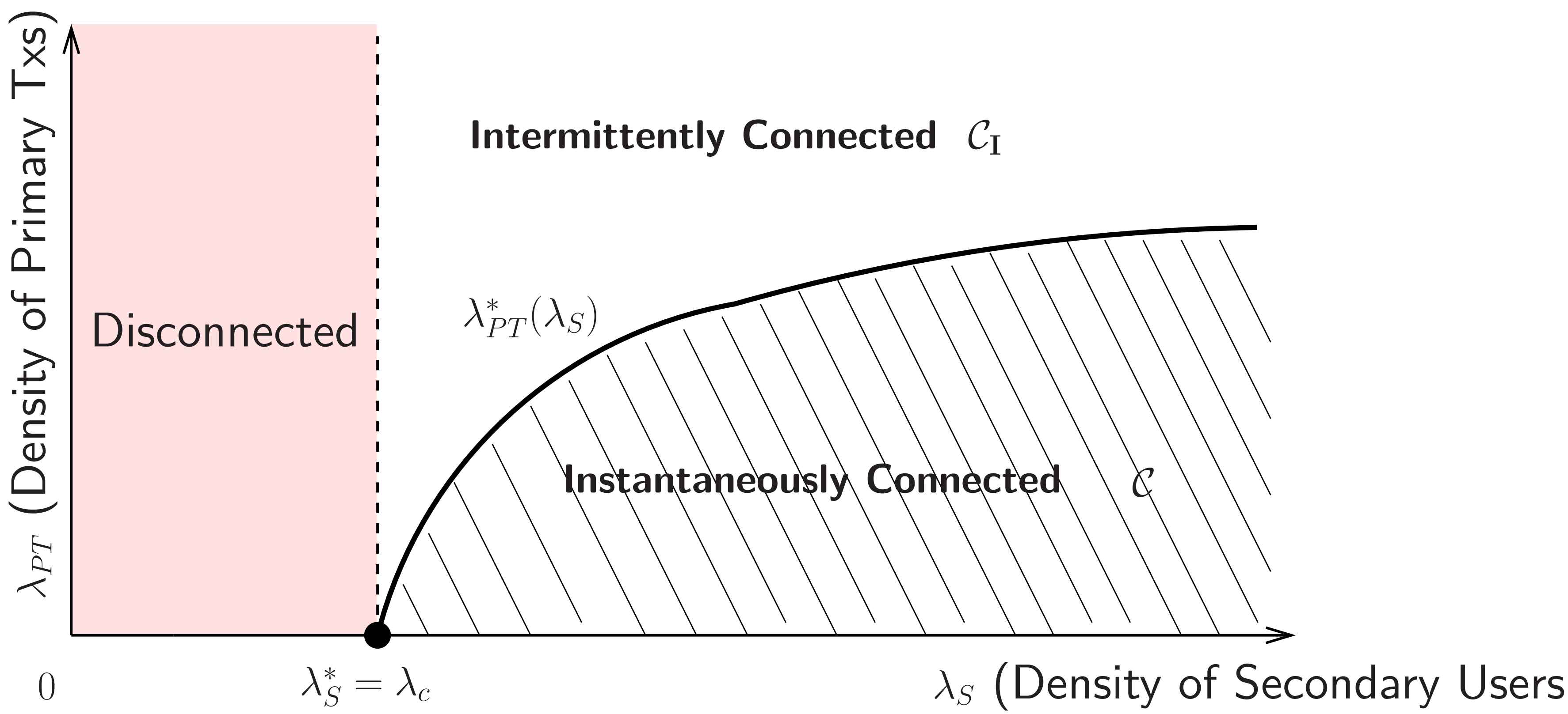


To coexist with heavy traffic load: Tx power matching between primary and secondary.

Relating Connectivity and Delay

- Connectivity of the secondary network $\triangleq$ finiteness of the minimum multihop delay (MMD) between two randomly chosen secondary users.

- When the temporal dynamics of the primary traffic are fficiently rich, connectivity of secondary network depends solely on its own density.



[7] W. Ren, Q. Zhao, and A. Swami, "On the connectivity and multihop delay of ad hoc cognitive radio networks", IEEE ICC, May 2010.

Main Results on Multihop Delay

- When the propagation delay is negligible,
  - the MMD is asymptotically independent of the source-destination distance if the secondary network is instantaneously connected;
  - the MMD scales linearly with the distance if the secondary network is only intermittently connected.

- When the propagation delay is nonnegligible,
  - the scaling order is linear;
  - the scaling rate for an instantaneously connected network can be orders of magnitude smaller than that for an intermittently connected network.

[7] W. Ren, Q. Zhao, and A. Swami, "On the connectivity and multihop delay of ad hoc cognitive radio networks", IEEE ICC, May 2010.

Characterization of Multi-Hop Delay

Connectivity and the Finiteness of MMD

When the temporal dynamics of the primary traffic is sufficiently rich, a necessary and sufficient condition for the connectivity of the secondary network, defined as the a.s. finiteness of the MMD, is the connectivity of $\mathcal{G}_S(\lambda_S)$ in the percolation sense.

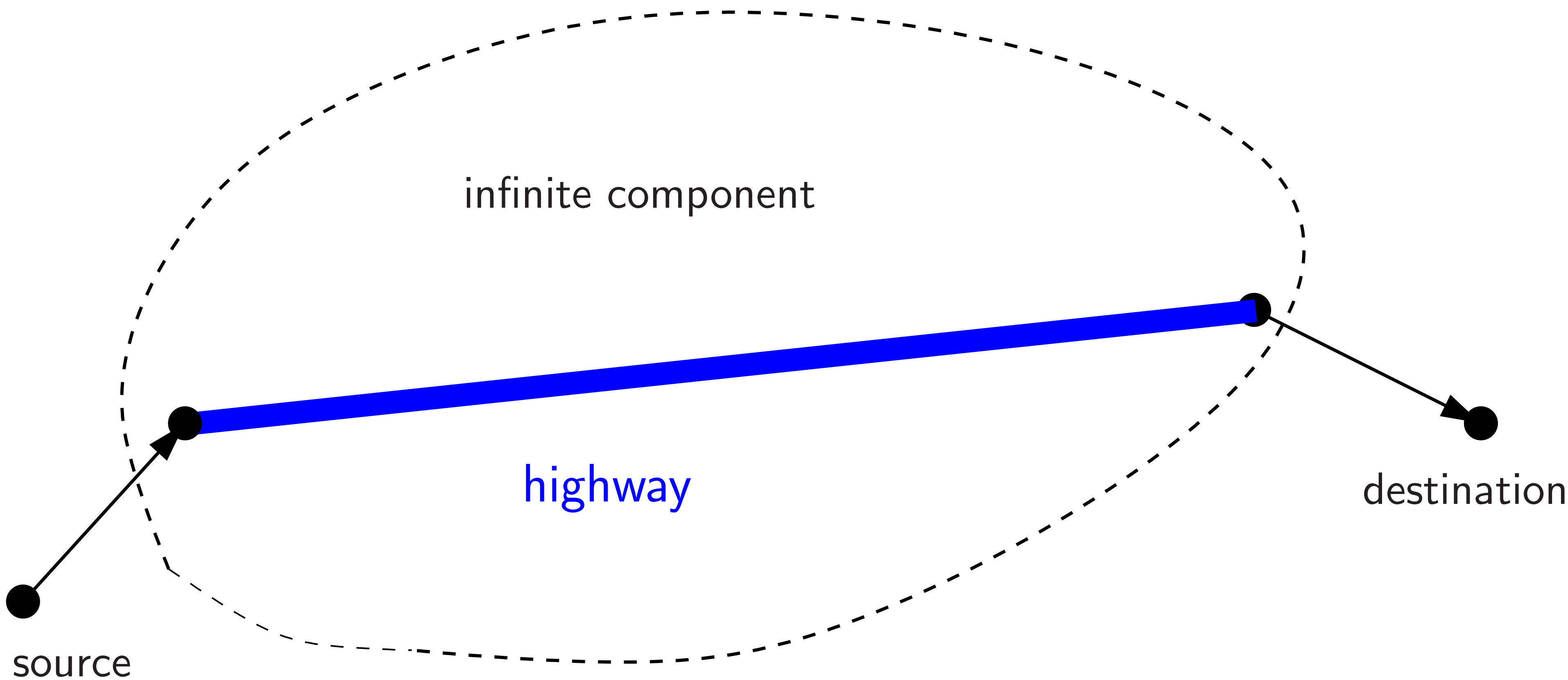
Scaling Law of Multihop Delay ($\tau = 0$)

When the propagation delay $\tau = 0$, the MMD is asymptotically independent of the source-destination distance for an instantaneously connected network, and the MMD scales linearly with the distance for an intermittently connected network.

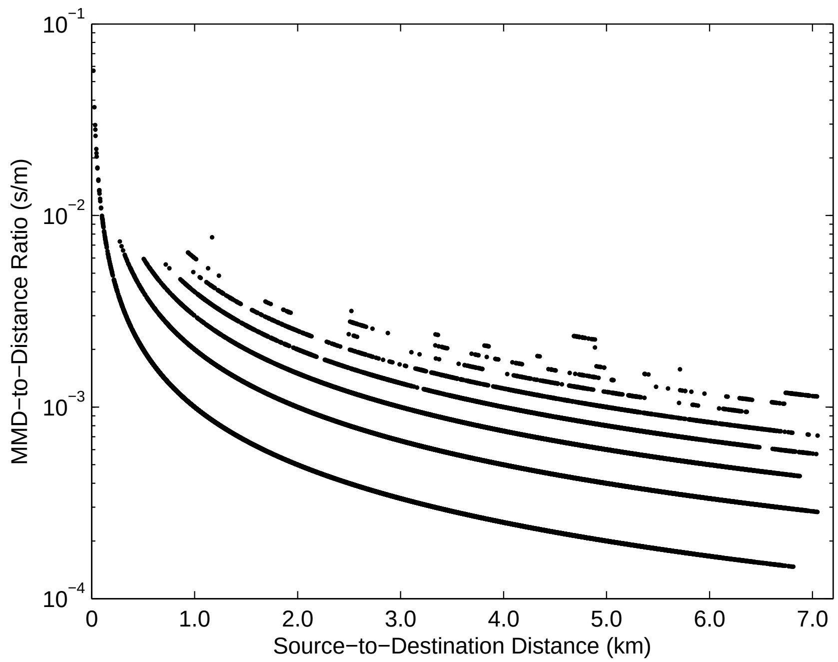
Scaling Law of Multihop Delay ($\tau > 0$)

When the propagation delay $\tau > 0$, the scaling order is always linear, but the scaling rate for an instantaneously connected network can be orders of magnitude smaller than that for an intermittently connected network.

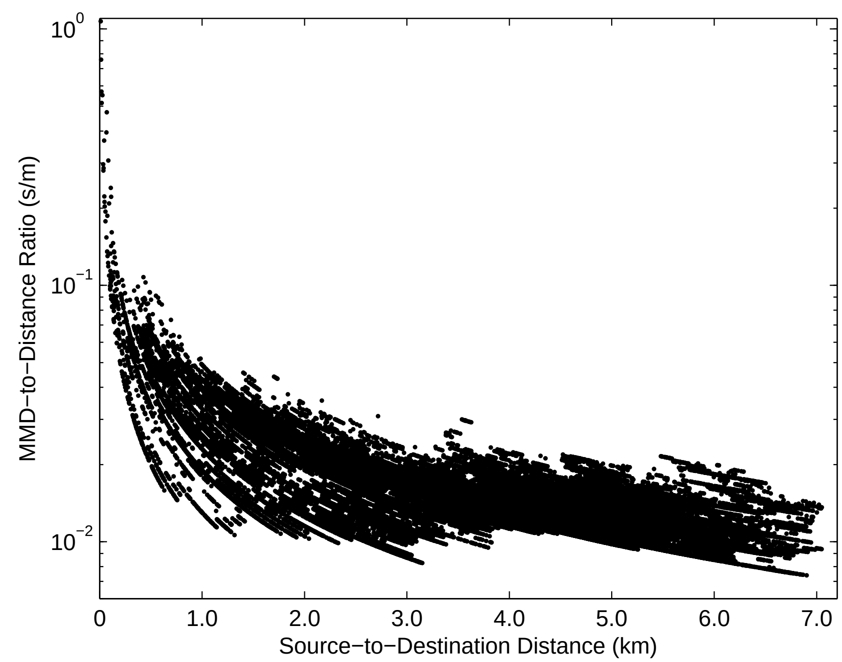
Analogy of Traveling when $\tau = 0$



Simulation Results ($\tau = 0$)



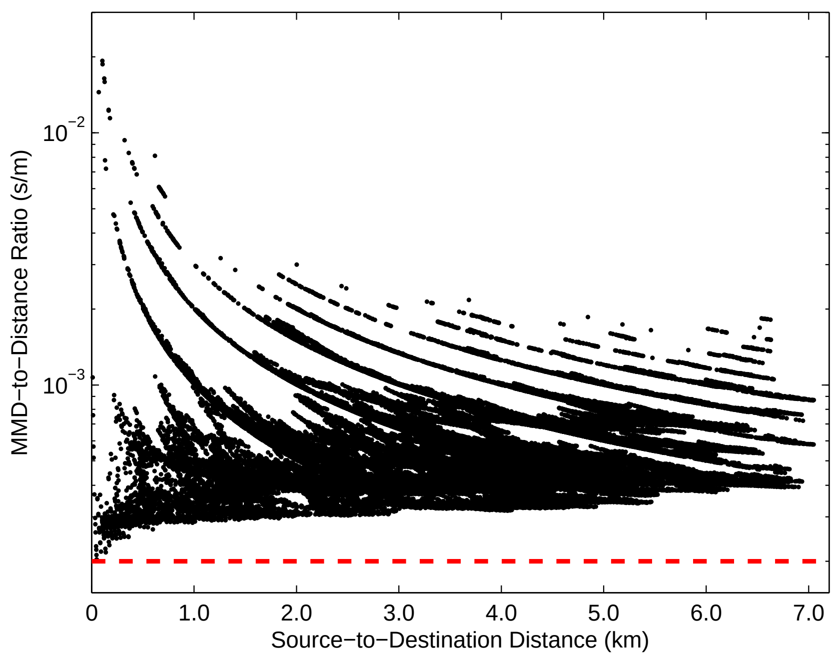
(a) instantaneously connected



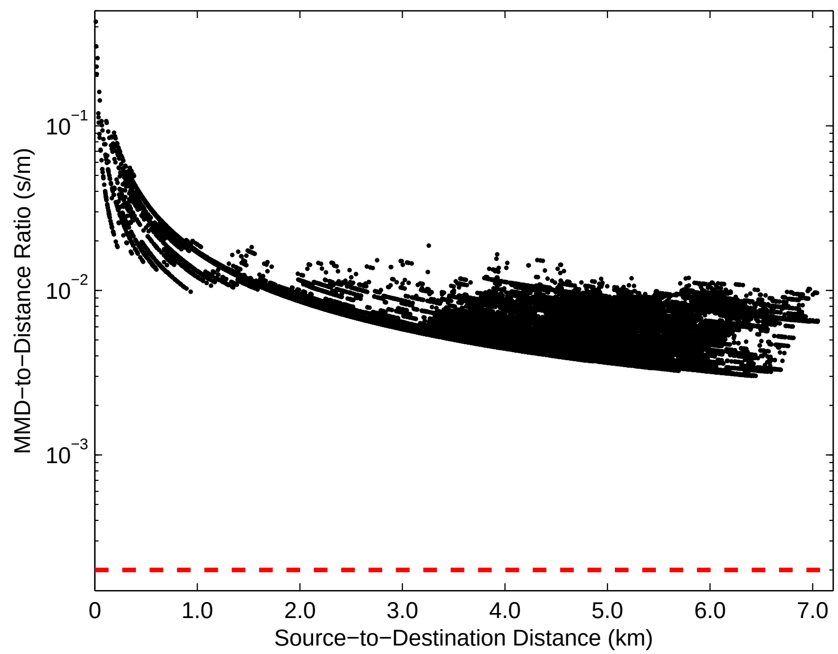
(b) intermittently connected

- One fixed source and other nodes as potential destinations.
- Flooding scheme.

Simulation Results ($\tau > 0$)



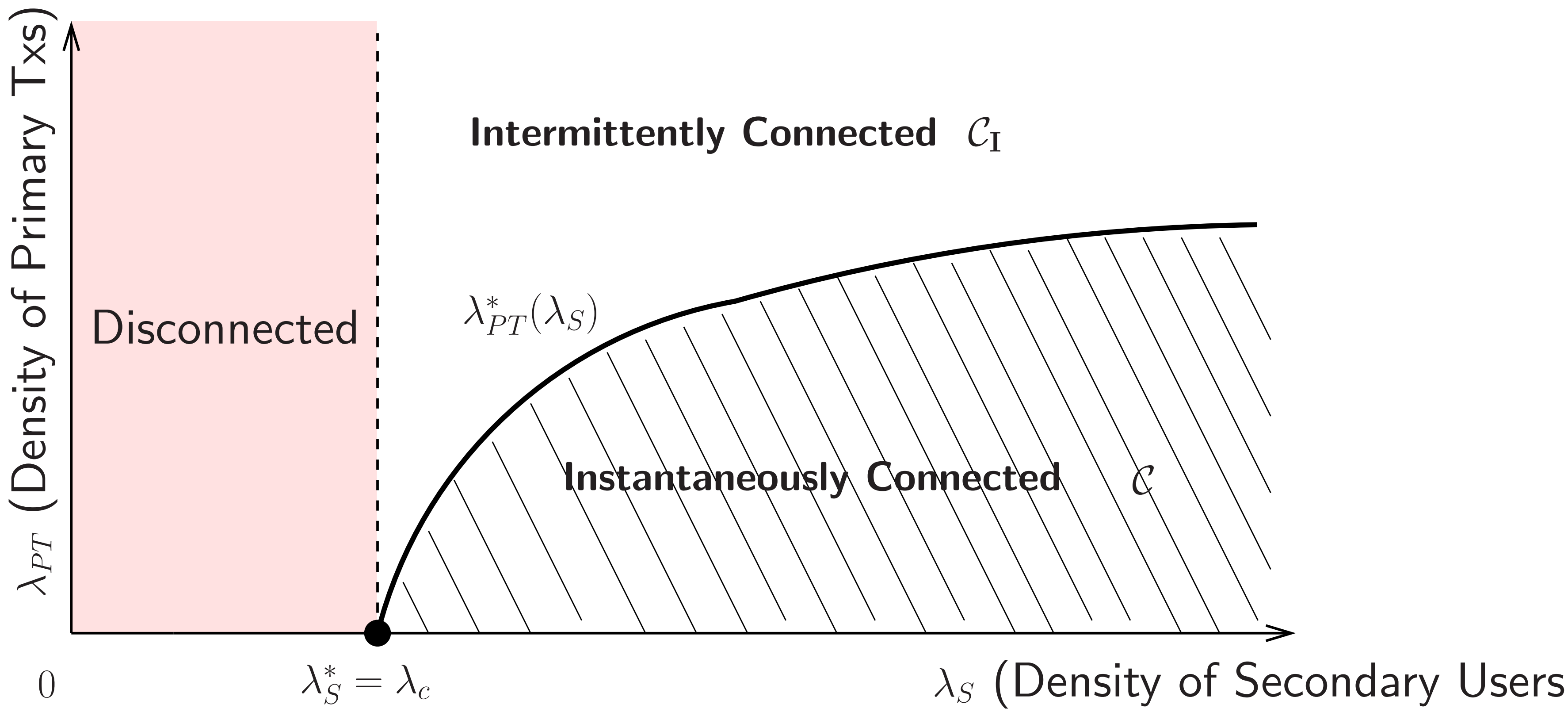
(a) instantaneously connected



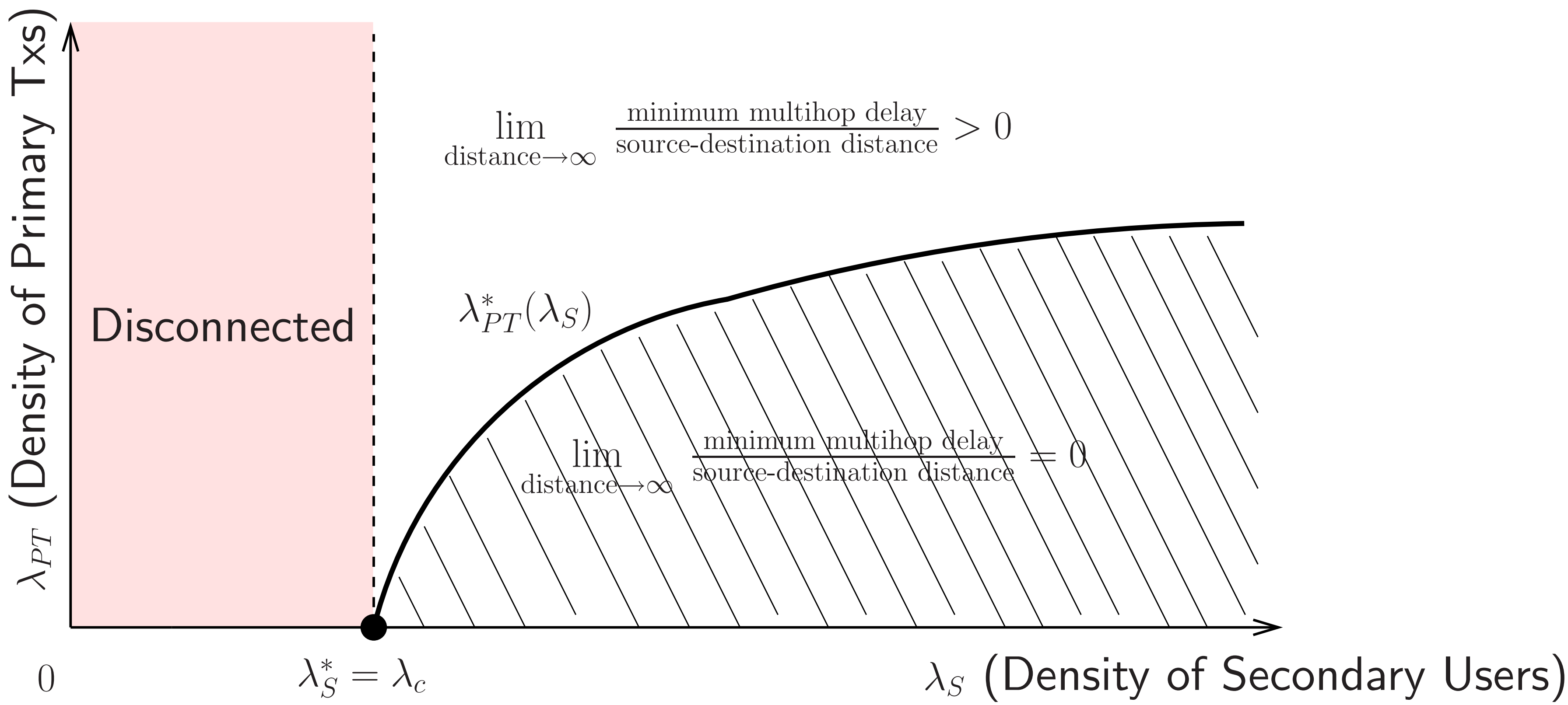
(b) intermittently connected

- One fixed source and other nodes as potential destinations.
- Flooding scheme.

Conclusion and Discussion



Conclusion and Discussion



- Extension to random connection model.
- Outage caused by aggregated interference.

Tutorial Outline

- Introduction
- Physical layer issues
- MAC layer issues
- Network layer issues
- ➢ Conclusion

Security Issues in DSA

Internal Threats

Byzantine:
- Falsifies local data
- Resources for detection vs. attack
  - game theoretic approaches
- Behavioral profiles
  - reputation based approaches

A. Rawat et al, Comsnets 10
A. Rawat et al, ICASSP'10

External Threats

PUE Attacks
- Emulates features of valid PU

R. Chen & J. Park, SDR 2006
R. Chen et al, IEEE Comm. Mag, April 08; JSAC'08

Software Threats

Changes to Policy
- blocking, spoofing

Vulnerabilities in the std (e.g., 802.22)

Mobile code protection

A. Sethi, T.Brown, Dyspan'08
Y. Tan et al, ICC'10

Channel Threats

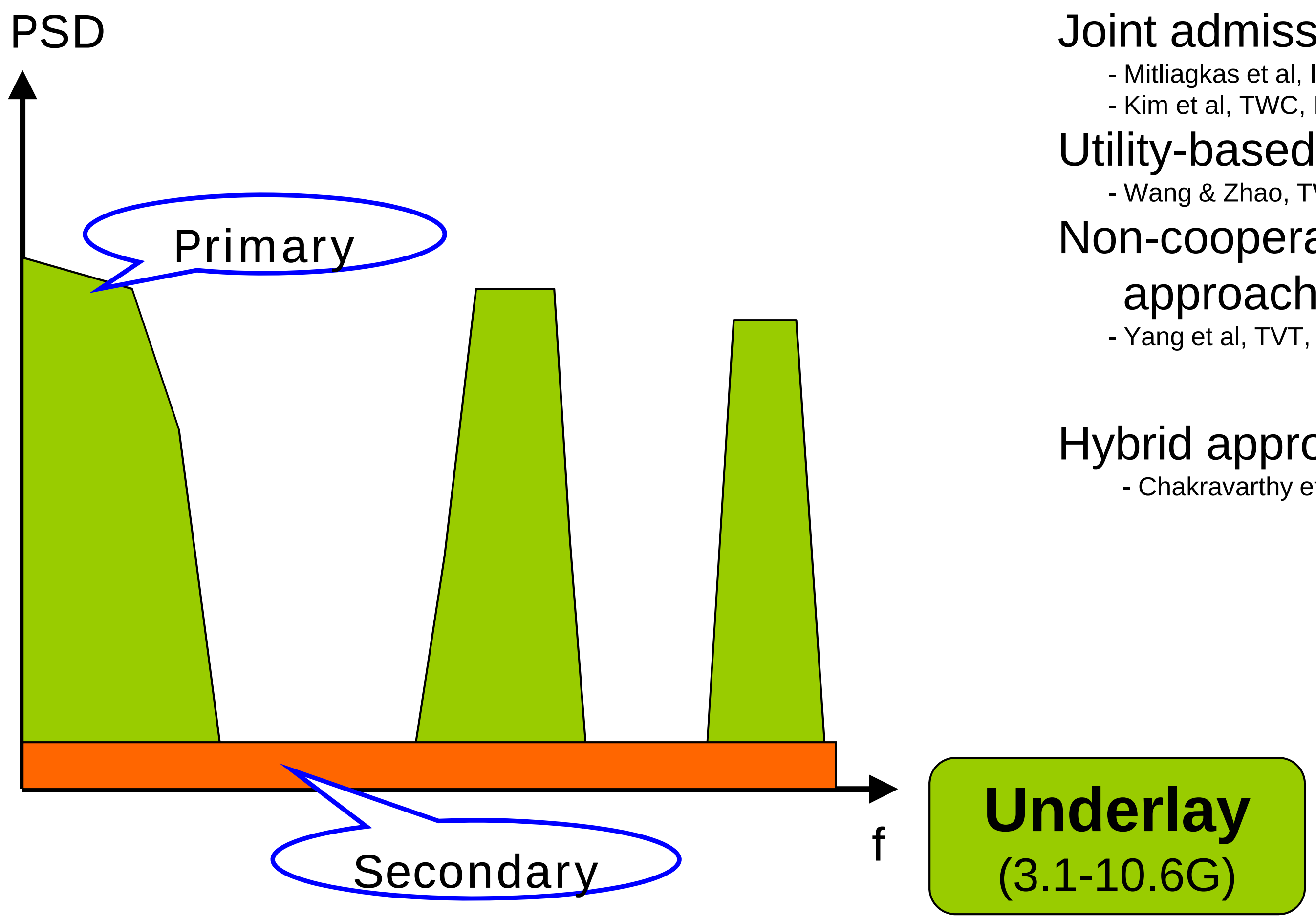
- Eavesdropping
- Jamming
- Location services
- Belief Manipulation

T. C. Clancy & N. Goergen, CrownCom'08
J. L. Burbank ,CrownCom'08
G. Safdar, M.O'Neill, VTC'09
Y. Wu et al, Globecom'09
T.C. Clancy & A.Khawar, CrownCom'09

C.N. Mathur & K.P. Subbalakshmi, Security issues in cognitive networks, in Cognitive Networks, Ed Q.H. Mahmoud

Spectrum Underlay

Spectrum Underlay (UWB)



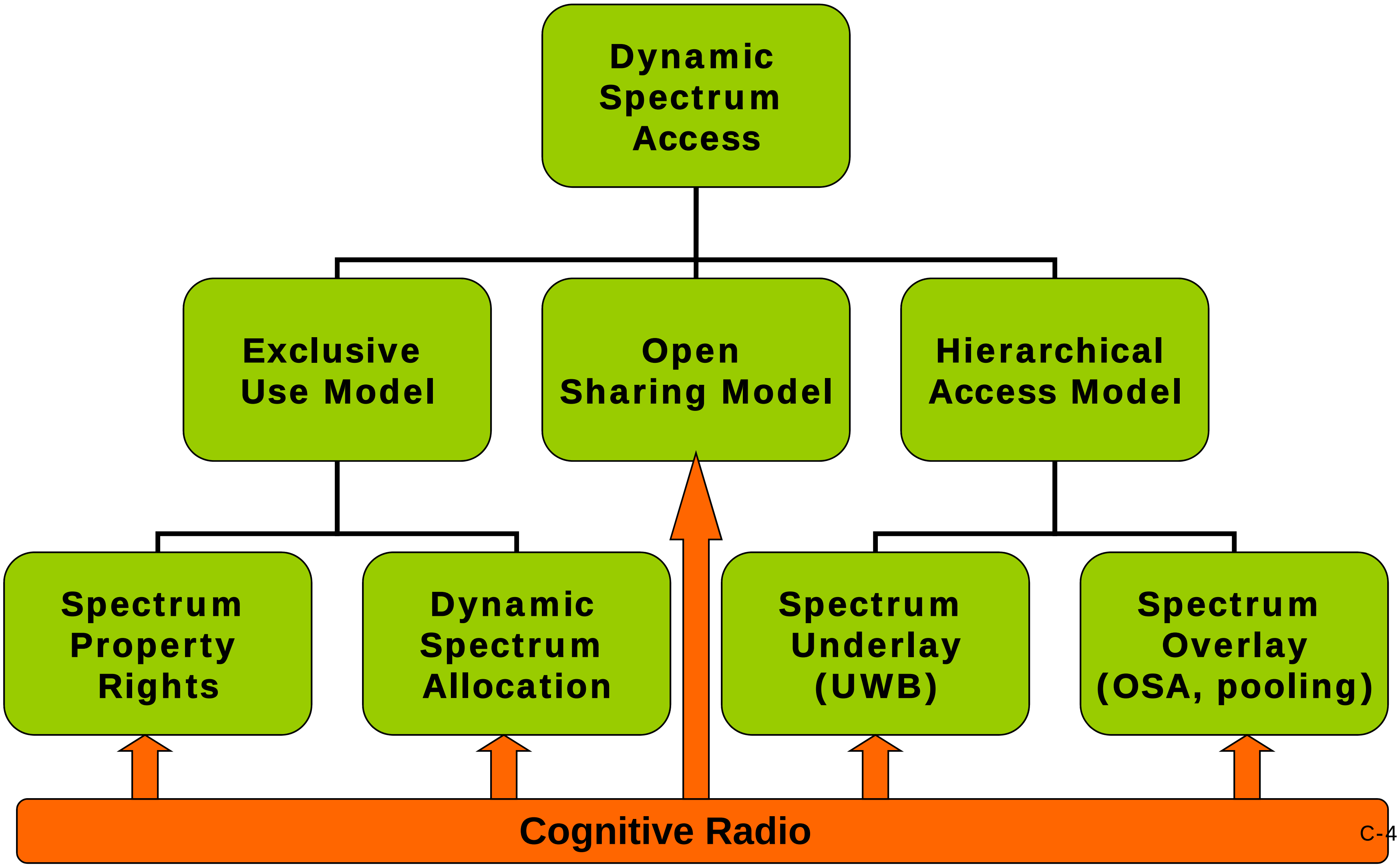
Joint admission & power control
- Mitliagkas et al, IWCMC'08, ICASSP'10
- Kim et al, TWC, Dec 2008

Utility-based scheduling
- Wang & Zhao, TWC Mar 2010

Non-cooperative game theoretic approaches:
- Yang et al, TVT, Sept 2009

Hybrid approaches
- Chakravarthy et al, Trans. Comm, Dec 2009

A Taxonomy of DSA



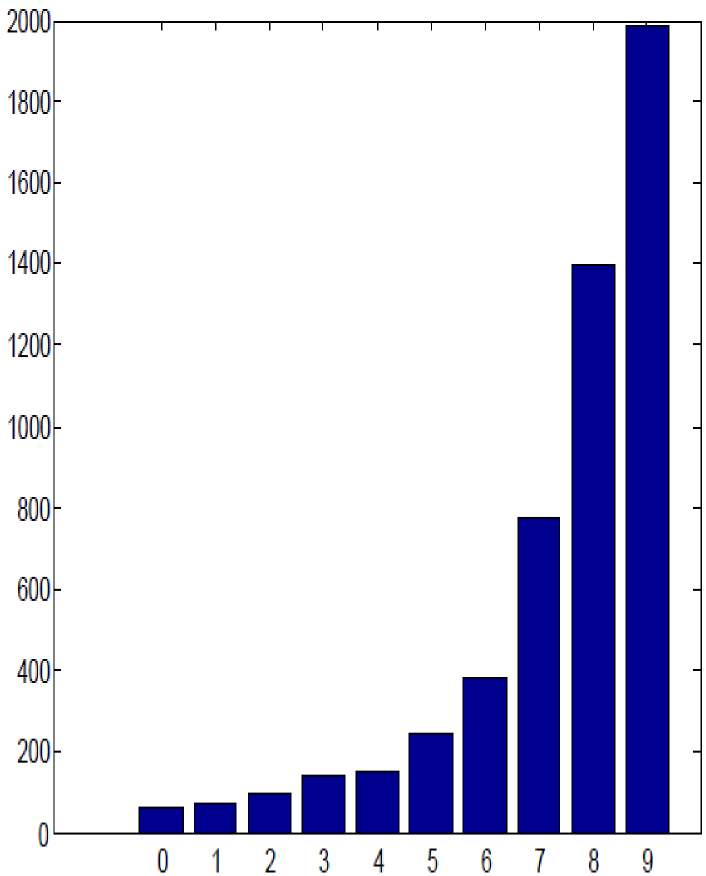
Conclusion: Spectrum Overlay

- Physical Layer
  - Opportunity sensing
  - Interference Aggregation

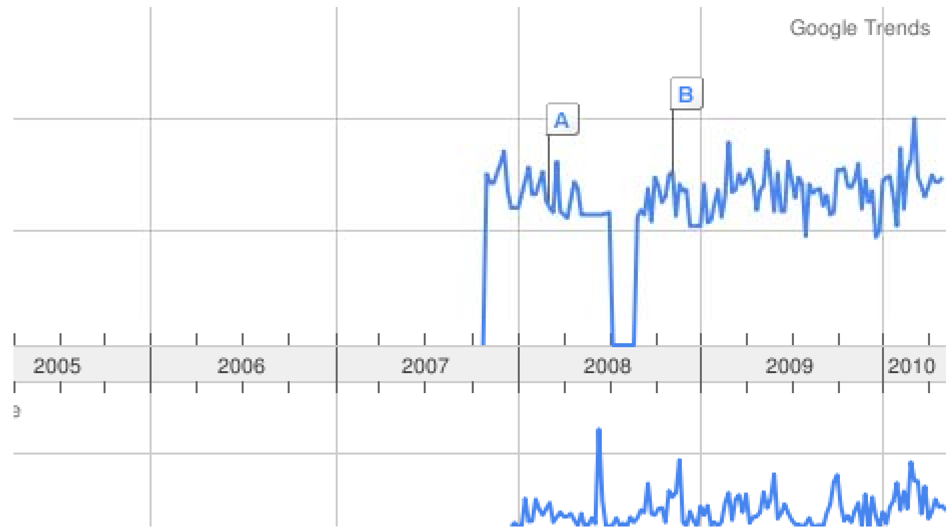
- MAC Layer
  - Opportunity tracking and learning
  - Opportunity exploitation with imperfect sensing
  - Opportunity sharing

- Network Layer
  - Power control and routing
  - Connectivity and delay

IEEE Explore



Google Trends



South Korea
Pakistan
Iran
Taiwan
India
Hong Kong
Singapore
Malaysia
Greece
Egypt

Teojon
Blacksburg
Kowloon
Seoul
Tehran
Bangalore
Wuhan
Nanjing
Singapore
Beijing

Korean
Chinese
Greek
English
Finnish

Some Open Issues

- Co-existence issues
- PHY – RF
- Security and privacy
- Models and measurements
- Increased cross-layer interactions
- Multicast …
- Policy translators
- All the usual radio issues with a twist – SWAP
- True MANET & co-existence still far away ?