

# Non-intrusive Dynamic Spectrum Access for Cognitive Radio Networks

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**Exit Seminar**

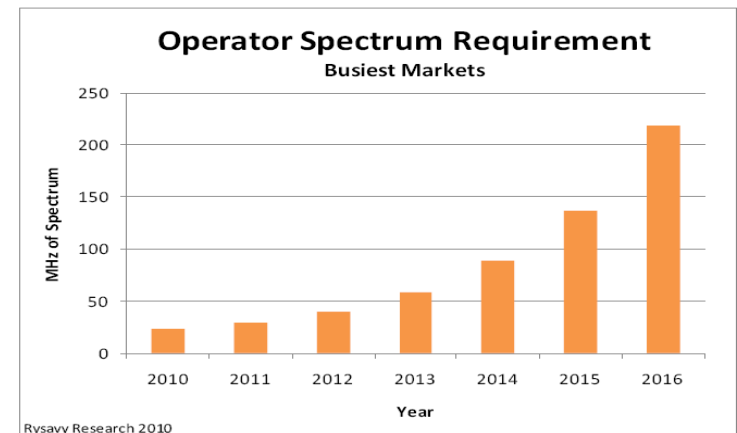
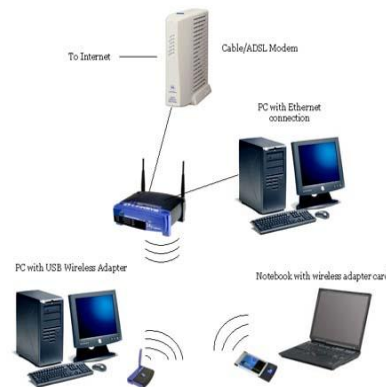
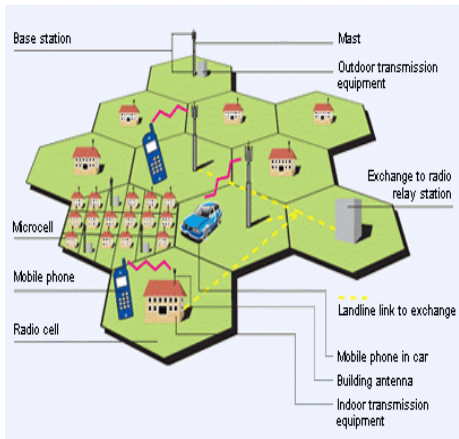
Electrical and Computer Engineering Department

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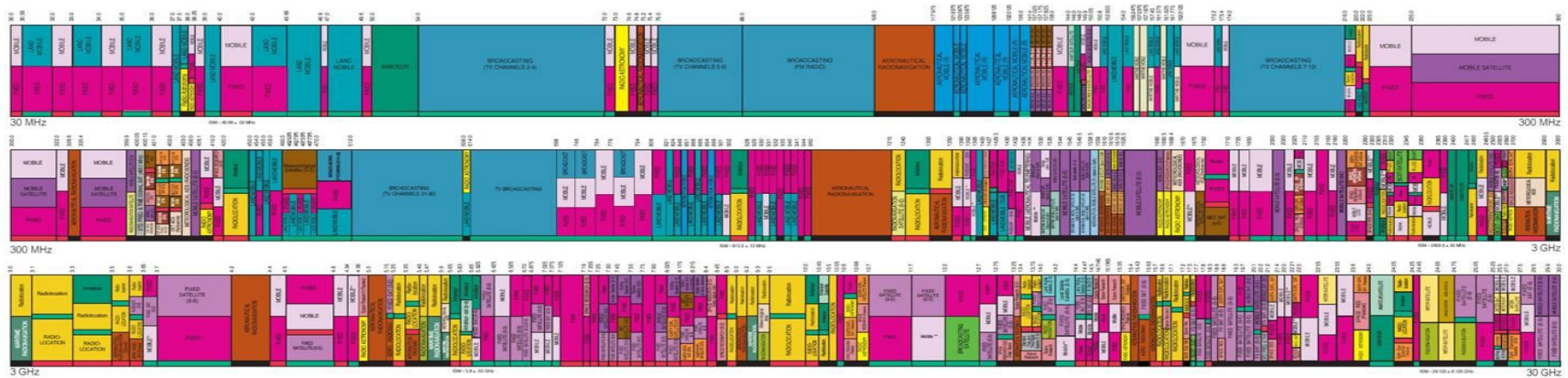
June 9, 2010

# Spectrum demand

- Proliferation of wireless technologies
  - Cellular, WiFi, Bluetooth, WSNs
    - 4 billion mobile subscribers by 2008 [ITU]
  - Fast growing wireless data users
    - Smart phones, mobile Facebook, ...
  - Spectrum requirement [ITU]: 1300 MHz in 2015



# Spectrum shortage



30 MHz – 30 GHz

- "I believe that the biggest threat to the future of mobile in America is the looming spectrum crisis," J. Genachowski (FCC chairman) 2009

# Heavy regulatory control

- Exclusive license
  - Command-and-control
  - Static, long-term licensing
  - Takes a long time to retrofit existing licenses
  - Expensive
    - US FCC TV band auction: ~20 billion dollars 52 MHz
- Unlicensed bands
  - No regulatory barrier
  - Encourage Innovations
  - Over crowded

# On the news: “How AT&T made Steve Jobs look bad...again”

“....., CEO Steve Jobs had an embarrassing onstage moment .... The download failed and his demo crashed on the new iPhone 4 because he couldn't maintain **a solid Wi-Fi connection.**”

CNET June 8, 2010

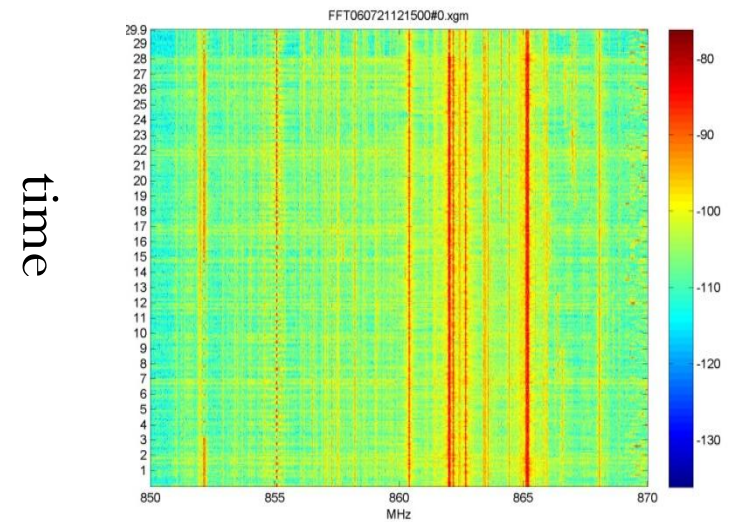
- **>570 WiFi mini stations**
- **5000 people**

# Wasteful spectrum usage

5.2%

30 MHz – 3 GHz

Source: Shared Spectrum Company



A snapshot of spectrum usage  
on public safety band  
Source: JHU/APL

# We need more flexible and efficient spectrum access!

- To support sustainable growth of wireless services
- To encourage innovation
- To reduce spectrum access cost

# Cognitive radios

- Radios adapt transmission to its operating environment
  - WiFi: sensing, channel selection
  - Cellular: AMC, power control, channel allocation
  - Unlicensed 5 GHz: dynamic frequency selection
- Increasing reconfigurability
  - Advance in computing technologies
- Development of software-defined radio
  - GNU Radio, Microsoft Soft-WiFi, Rice WARP

# More intelligent spectrum access with CR

- Unlicensed devices transmitted in rural areas
  - TV white space
- Secondary spectrum market
  - Leasing, active negotiation
- More intensive use by licensees within their own networks
  - IMT-advanced carrier aggregation, femto-cell
- Spectrum users sharing spectrum access on a negotiated or an opportunistic basis
- ....

# Current activities

- DARPA XG program
  - Allow cognitive radios to transmit on idle bands
  - Successful field trials in 2006
  - Test criteria
    - To “cause no harm”
    - To “work”
    - To “add value”
- IEEE 802.22 standardization effort
  - TV white space device
  - FCC “proof of concept” test in 2008: satisfying

# Dissertation focus:

## Non-intrusive dynamic spectrum access

- Key ideas
  - Exploit spectrum opportunities by secondary users
  - Respect the access priority of legacy users
- Non-intrusiveness
  - Cause insignificant interruption to the PUs
  - Do not require cooperation from the PUs
    - Reduce cost of infrastructure update
    - Quick deployment



# Challenges of non-intrusive DSA

- PU protection: **vital**
  - Interruption: controllable, minimal
  - Compensation mechanism
- Decision making under uncertainty
  - Exploration versus exploitation
  - Observation errors (e.g., sensing errors)
- Limited coordination among multiple SUs
  - Ad hoc deployment

## Key Contribution: Non-intrusive DSA

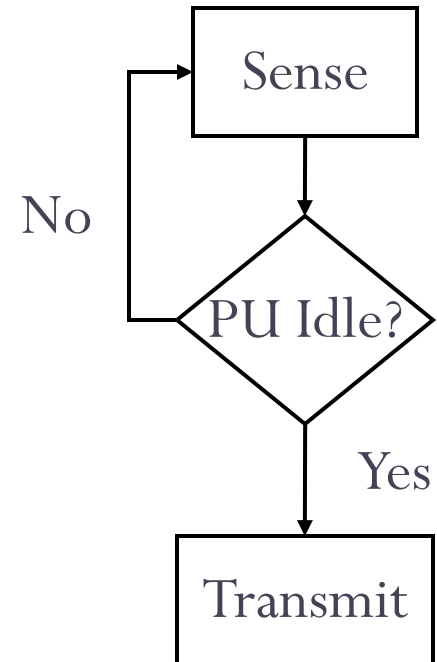
- Optimization on Listen-before-talk schemes with general PU traffic pattern
- Overlay spectrum sharing based on PU feedback
  - Distributed SU power control algorithm without message passing

# Outline

- Introduction
- Dissertation overview
- **Optimization on listen-before-talk DSA**
- Cognitive access framework based on PU feedback
- Conclusions

# Listen-before-talk DSA

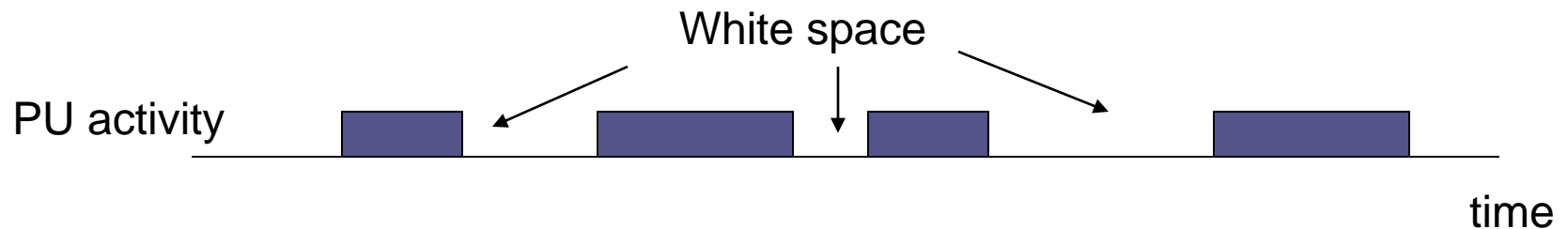
- Exploit the spectrum opportunities in **time** domain
- Early approach to protect PU QoS
- Passive sensing to detect spectrum white space
- Little infrastructure and planning



# Related works

- [Zhao et al. '05, Chen et al. '08, Liu et al.'10] POMDP approach for access decision and channel selection
- [Geirhofer et al. '08] optimizes (fixed) transmission probability after detecting PU idle
- [Liang et al. '08] optimizes the (fixed) sensing-data frame structure
- [Chang et al. '07] multi-channel probing, access decisions under uncertainty

# System model: primary user



- PU traffic dynamics: semi-Markov process
  - **General** idle/busy time distribution
  - Random # of packets in a busy period
  - Percentage of idle time:  $\alpha$

# Performance metrics

- SU throughput: percentage of time that white space is successfully used

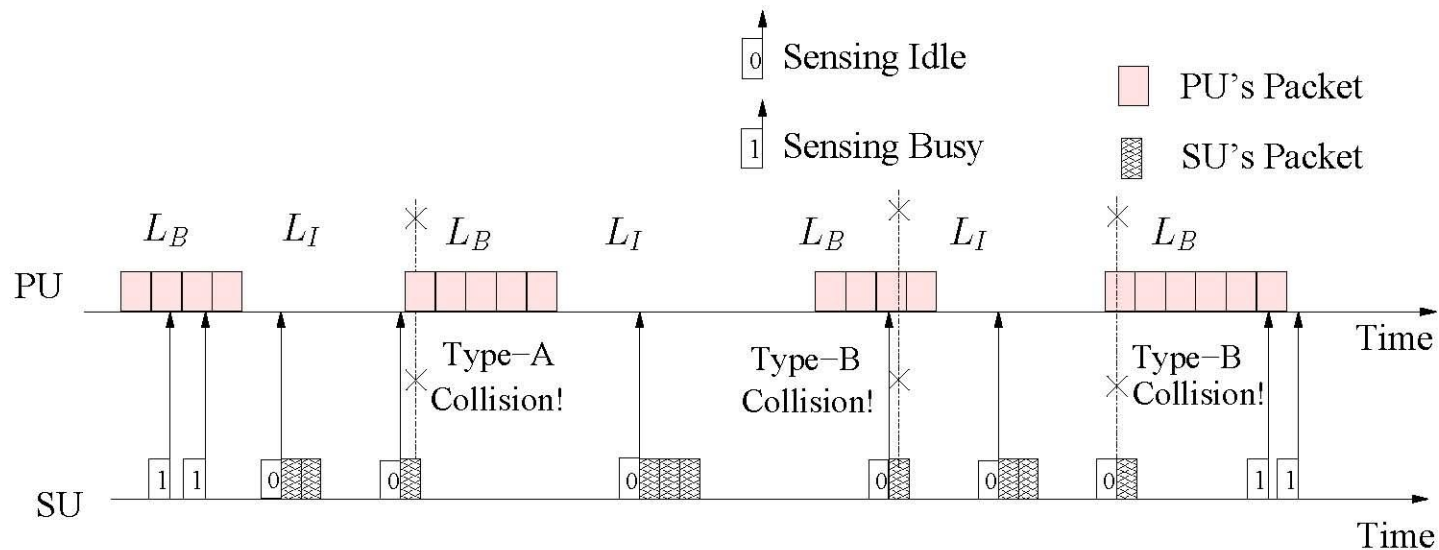
$$\Gamma_s = \frac{\text{Successful SU Transmission Time}}{\text{Total Time}}$$

- PU protection: collision rate

$$p_c = \frac{\# \text{ collided PU packets}}{\text{Total transmitted PU packets}}$$

# Collisions perceived by the PU

- Un-slotted PU traffic
  - Type-A: exists even with perfect sensing
  - Type-B: miss detection



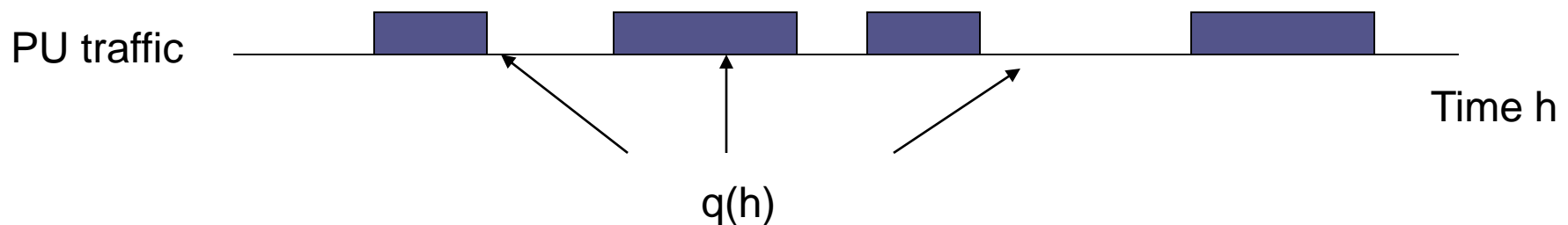
# Constrained optimization problem

$$\begin{array}{ll} \text{maximize}_{\pi} & \Gamma_s \\ \text{subject to} & p_c \leq \eta \end{array}$$

SU throughput

PU collision prob. constraint

- Policy space:
  - SU Transmission prob.  $q(h)$ ,  $h = 0, \dots, \infty$
  - Stationary policy only



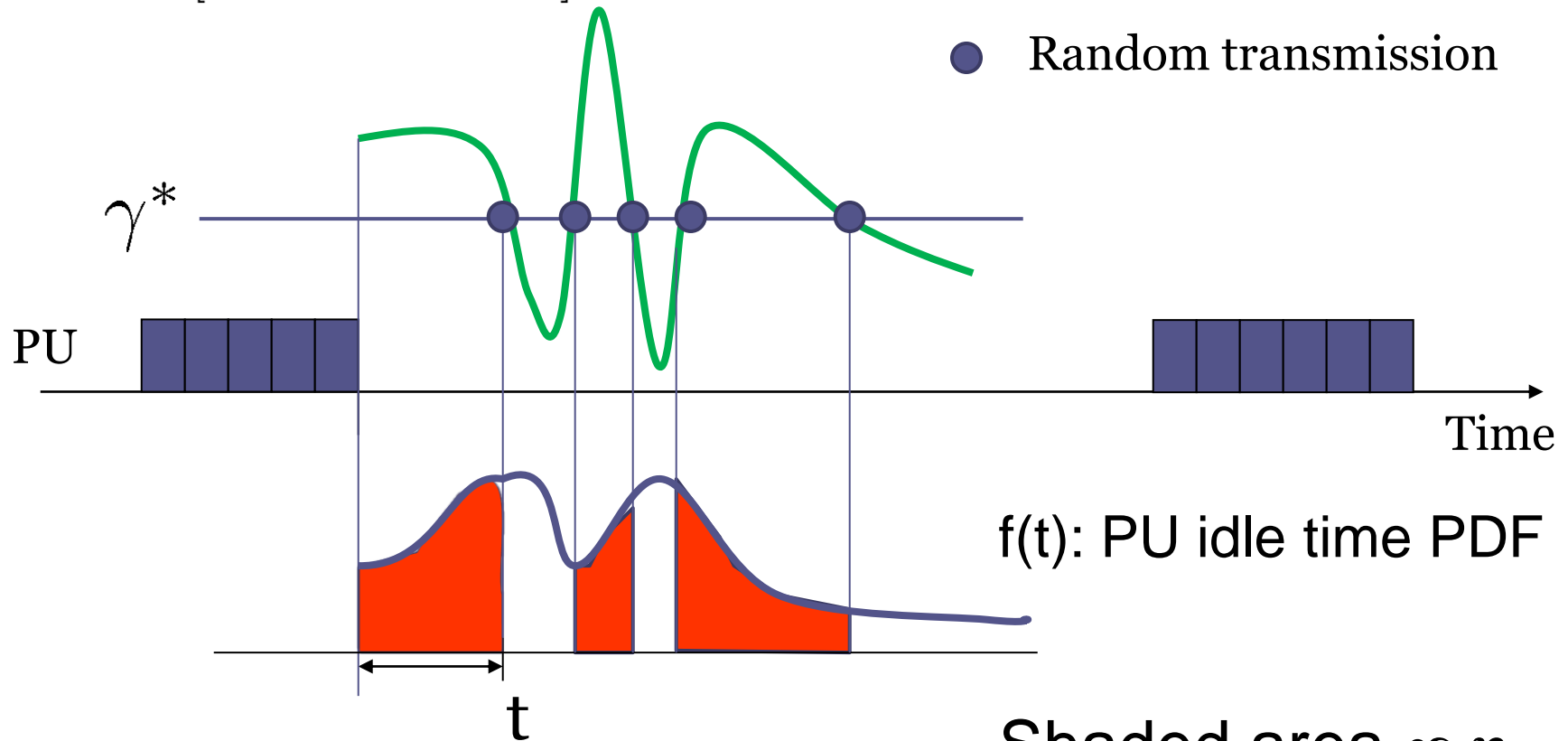
# Theoretical results

- More assumptions
  - Perfect collision detection
  - No captured effect at receivers
  - Perfect sensing: zero sensing time and error
    - Only type-A collision
  - SU knows the beginning of the idle period
- Upper bound on throughput:  $\alpha$

# Optimal spectrum access policy

$$g(t) = \frac{\Pr[\text{PU idle time} \geq t + l_s]}{\Pr[\text{PU idle time} \geq t]}$$

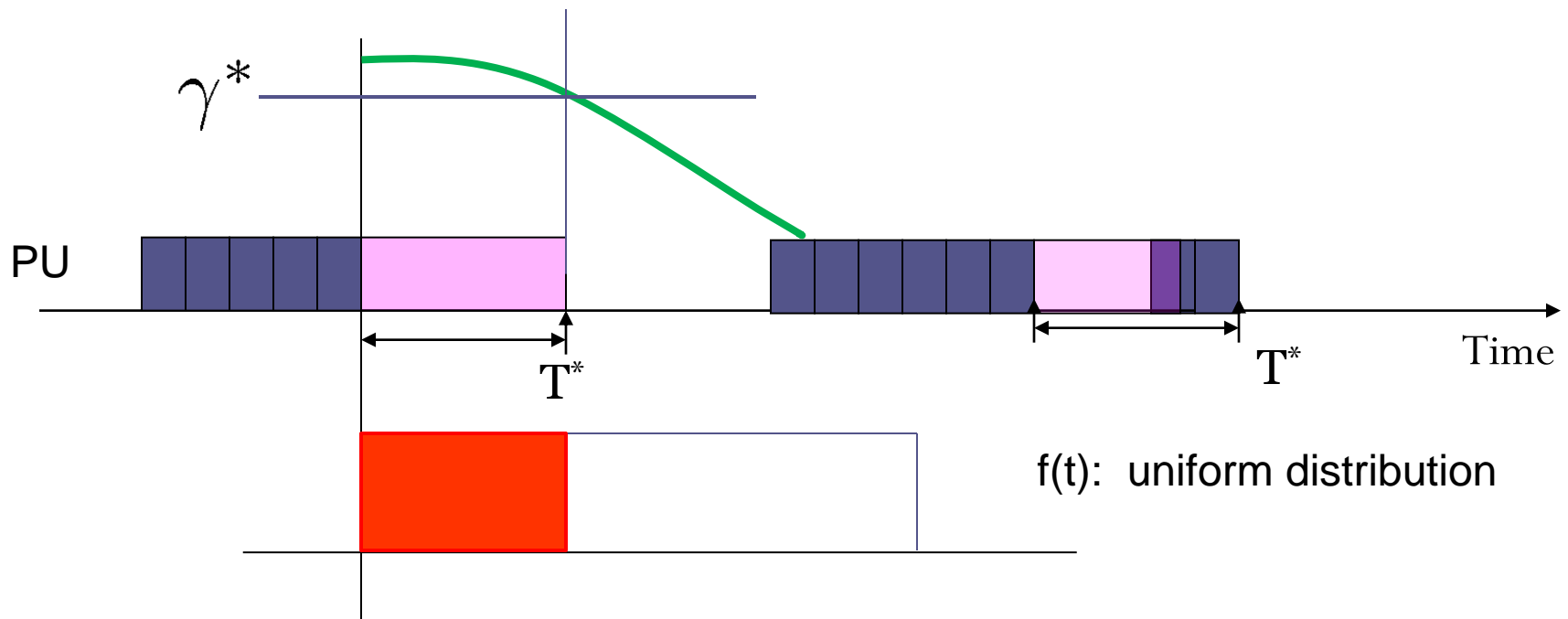
● Random transmission



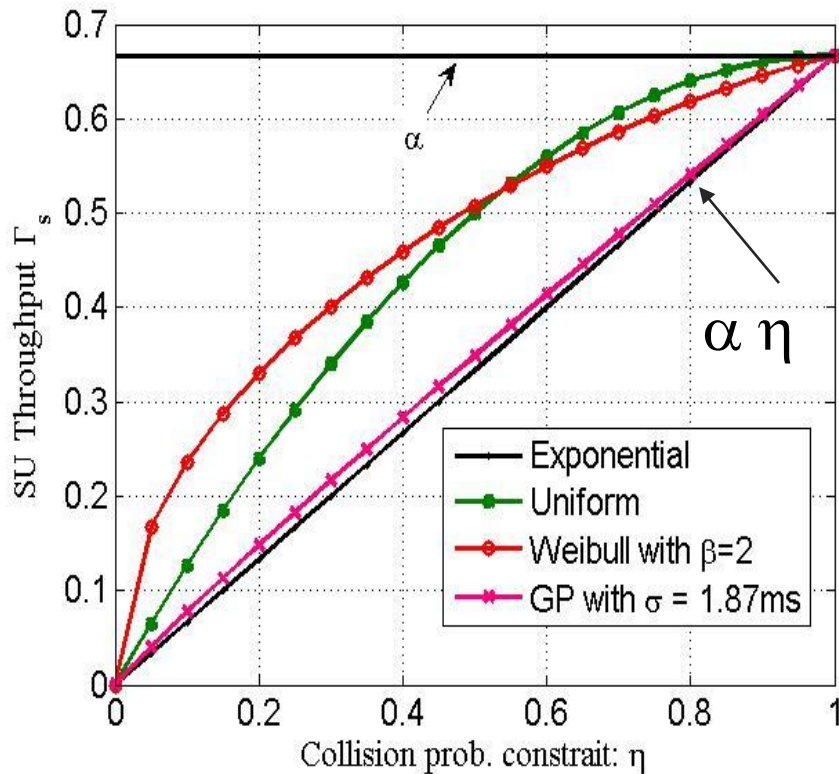
Similarity to Neyman–Pearson Lemma

# Time-threshold based policy

- Monotonically decreasing  $g(t)$



# Performance bounds

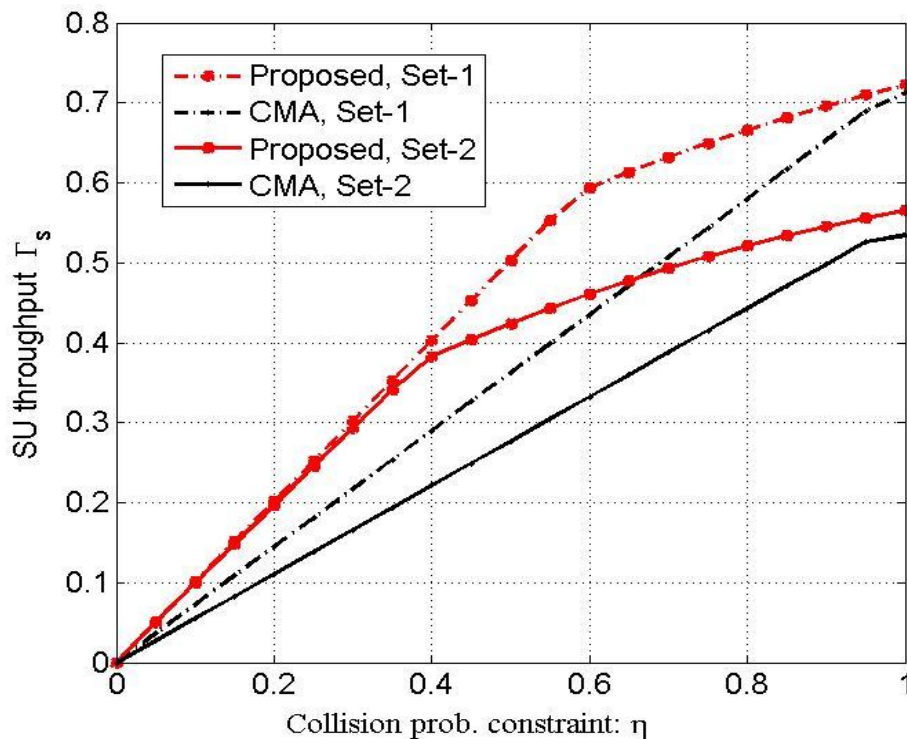


$$\alpha = 2/3, n_p = 1$$

- Important factors
  - Idle time percentage
  - Packet collision prob. constraint
  - Idle time distribution
  - Average busy time length

# Comparison with random access

- Optimal for exponential idle time dist.
- Without knowledge of PU idle time dist.



SU slot length: 100 us  
 PU traffic pattern: WLAN data  
 mixed uniform and general  
 Pareto dist.

CMA: a random access scheme  
 proposed by [Geirhofer et al.  
 2008]

# Direct extensions

- A modified threshold-based transmission strategy for imperfect sensing
  - Closed to optimum performance
  - Guarantee PU outage probability constraint
- An adaptive and distributed access scheme
  - Without information about PU idle time distribution
  - Interference from multiple SUs accumulates
  - Monotone  $g(t)$

# Multi-SU: An Adaptive Access Scheme

- Time-threshold based policy

- Step 0: initialize  $T_0$

- Step 1: estimate collision probability in a window  $W$

$$\tilde{\eta}^m(i) = \frac{\sum_{k=(i-1)W+1}^{kW} N_c^m(k)}{W n_p}$$

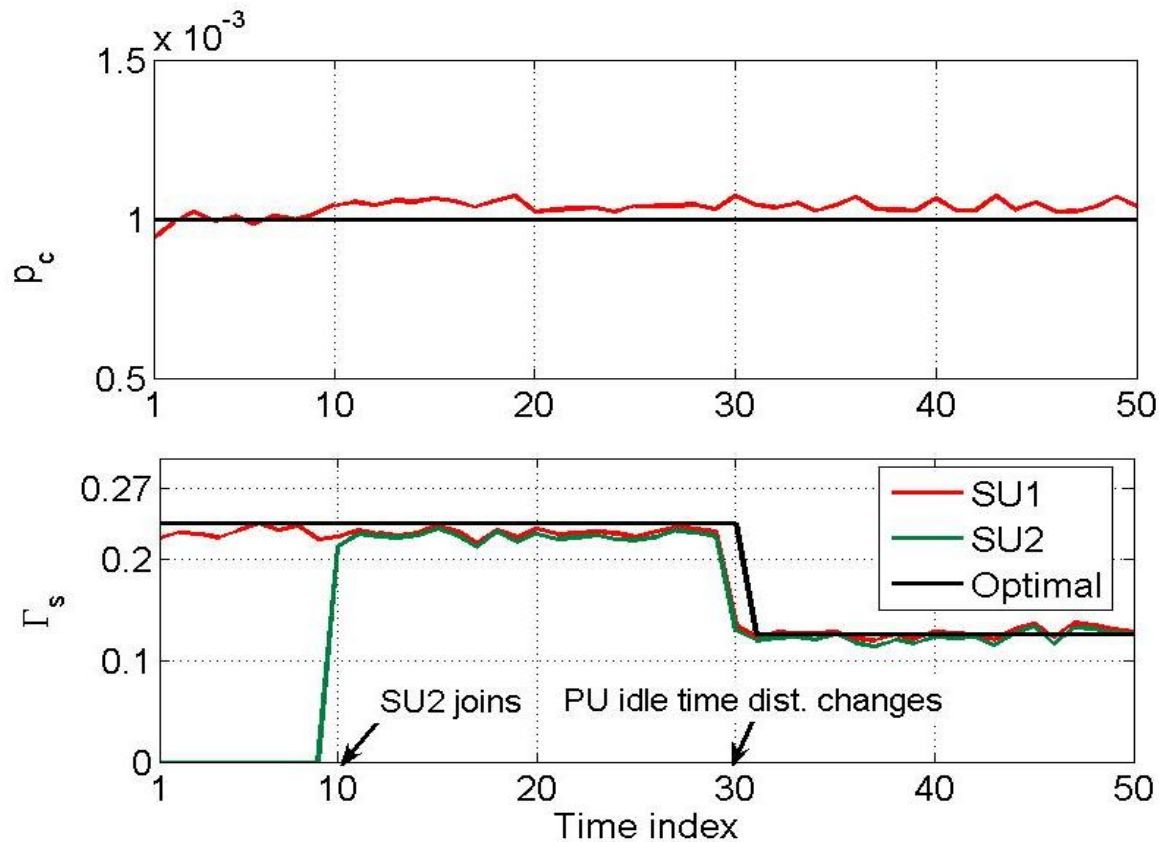
# of collisions in k-th  
idle-busy period

- Step 2: update  $T$

$$T^m(i+1) = T^m(i) + \xi(i)T^m(0) \frac{\eta - \tilde{\eta}^m(i)}{\eta}$$

- Step 3: follow  $T^*$  policy using the updated  $T$  in the next  $W$  idle-busy periods. Go back Step 1.

# Simulation



SU-1:

$P_f$ : 0.67

$P_m$ :  $1.3203 \times 10^{-8}$

SU-2:

$P_f$ : 0.2

$P_m$ :  $1.3203 \times 10^{-6}$

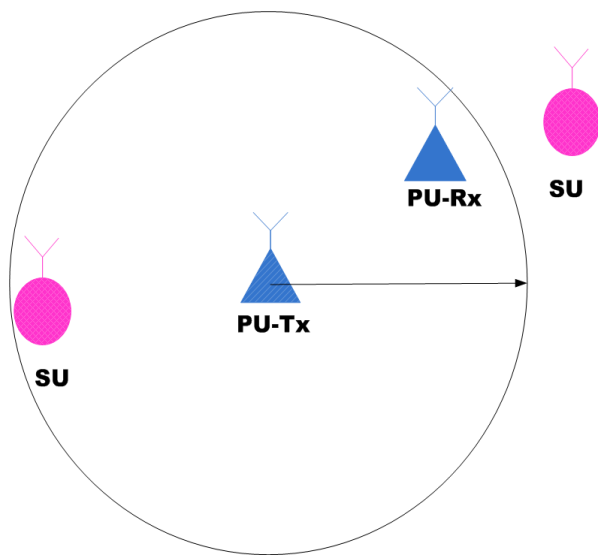
# Summary and extensions

- What we have learned
  - Distinguish between good and bad opportunities
  - Transmit when opportunity is **good**
  - Use knowledge about the PU if available
- Extensions
  - Imperfect collision detection
  - Exploitation of SU ACK/NACK information
  - Optimal sensing/transmission structure

# Outline

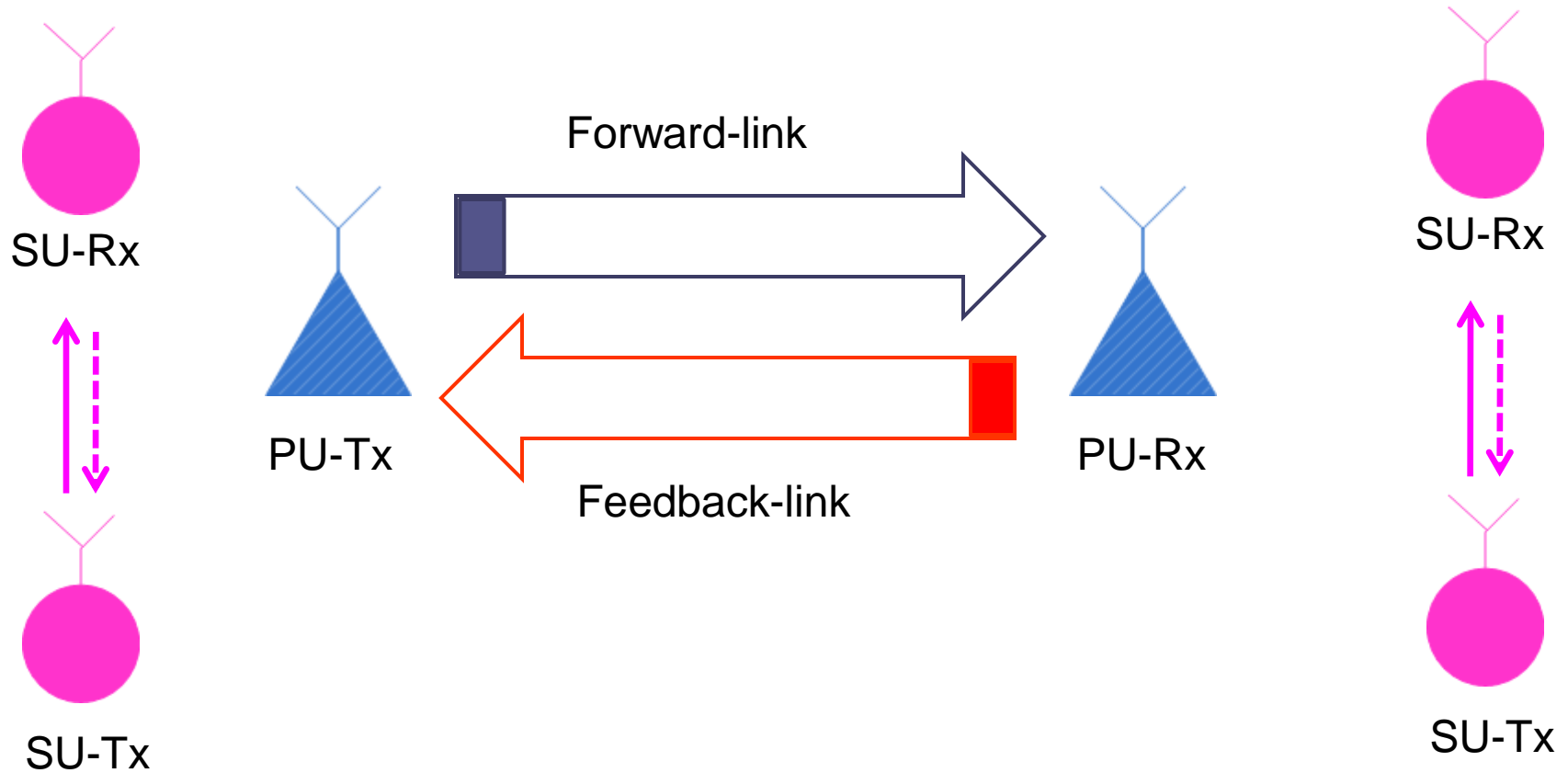
- Introduction
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- **Distributed SU power control based on PU feedback**
- Conclusions

# Limitations of LBT DSA



- Focus on PU transmitter
  - Hidden node
  - Exposed node
- Ultra conservative to provide PU protection
  - Worst case fading
  - Multiple SUs
  - Not counting for interference-resistant systems

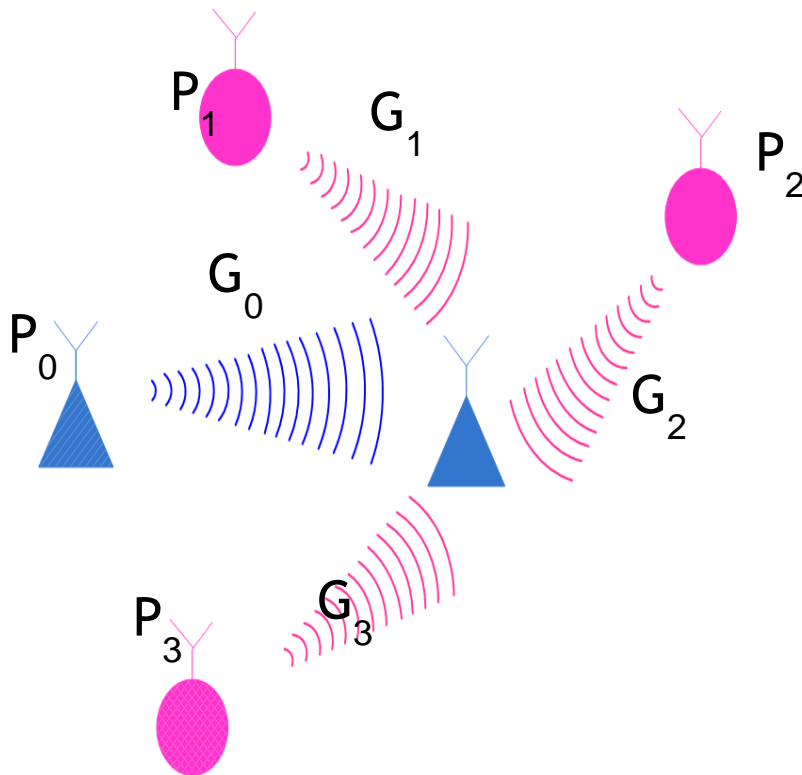
# Cognitive access based on PU feedback



# Implementation requirements

- Primary systems use two-way communications
- PUs **allow** SUs to overhear the physical link control feedback information
  - Same interest groups
  - Contract
- SUs are able to decode the primary link control feedback

# Distributed power control problem



System model

- Rayleigh fading
- SINR at the PU-Rx

$$\gamma = \frac{P_0 G_0 F_0}{N_0 + \sum_{i=1}^M P_i G_i F_i}$$

- PU Outage:

$$\gamma < \gamma_{th}$$

- Without SUs, PU outage

$$\eta_0 = 1 - \exp\left(-\frac{N_0 \gamma_{th}}{P_0 G_0}\right)$$

- SU-i knows only  $G_i$
- PU 1-bit outage feedback

# Distributed power control problem

- Problem formulation

$$\underset{\mathbf{P}}{\text{maximize}} \quad \sum_{i=1}^M \log(1 + h_i P_i)$$

Total SU utility

$$\text{subject to} \quad f(\mathbf{P}) \leq \eta,$$

PU outage prob. constraint

$$\mathbf{P} \preceq P_{max}.$$

SU max. power constraint

- Relative interference margin

$$\mu = \frac{1 - \eta_0}{1 - \eta} \geq 1$$

# Transformation to convex opt.

- Utility approximation:  $\log(1 + h_i P_i) \rightarrow \log(h_i P_i)$
- Variable transformation:  $x_i = \log(P_i)$
- Effective interference channel gain:

$$b_i = \frac{G_i \gamma_{th}}{P_0 G_0}$$

- Convex optimization problem

$$\begin{aligned} & \underset{\mathbf{x}}{\text{minimize}} && - \sum_{i=1}^M x_i \\ & \text{subject to} && \sum_i \log(1 + b_i e^{x_i}) \leq \log \mu, \\ & && \mathbf{x} \preceq \bar{x} \mathbf{1}. \end{aligned}$$

# Sufficient optimality conditions

- Small maximum power: trivial

$$\lambda^o = 0, x_i^o = \bar{x}.$$

- Large maximum power:

$$\sum_{i=1}^M \log(1 + b_i e^{x_i^o}) = \log \mu$$

$$x_i^o = \begin{cases} \min\{-\log((\lambda^o - 1)b_i), \bar{x}\}, & \text{if } \lambda^o > 1, \\ \bar{x}, & \text{if } \lambda^o = 0. \end{cases}$$



$$\log(\eta) = \log(f(\mathbf{x}^o))$$



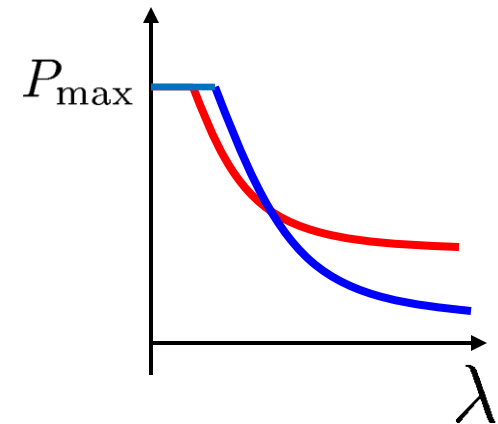
$$\eta = f(\mathbf{x}^o)$$

# Ideal synchronized DPC

- Iterations

$$\lambda(k+1) = \max\{\lambda(k) + a(k)g(\lambda(k)), 0\},$$

$$P_i(k+1) = \begin{cases} \min\left\{\frac{1}{(\lambda(k+1)-1)b_i}, P_{\max}\right\}, & \text{if } \lambda(k+1) > 1; \\ P_{\max}, & \text{if } 0 \leq \lambda(k+1) \leq 1. \end{cases}$$



- Update direction functions:

$$g(\lambda) = \log(f(\mathbf{P})) - \log(\eta) \quad \text{😊}$$

$$g(\lambda) = \log(1 - \eta) - \log(1 - f(\mathbf{P}))$$

$$g(\lambda) = f(\mathbf{P}) - \eta$$

# Practical concerns

- Noisy estimate of outage probability (T slots)

$$\hat{f}_d(k) = \begin{cases} 1/T, & \text{if } N_k = 0, \\ N_k/T, & \text{otherwise.} \end{cases}$$

- No message passing among SUs
  - Different initial values
  - Asynchronous step sizes

~~$$\lambda_1(k) = \lambda_2(k) = \dots = \lambda_M(k) = \lambda(k)$$~~

- If we stick to the ideal DPC update, ...
  - Total SU utility: not maximized

# Discounted distributed power control

$$\lambda_i(k+1) = \max\{\beta_i(k)\lambda_i(k) + a_i(k)g(\lambda_1(k), \dots, \lambda_M(k)), 0\},$$

Discount factor  $\beta_i(k) = 1 - ca_i(k)$ ,  $c > 0$

$$a_i(k) \rightarrow 0, \beta_i(k) \rightarrow 1$$

- Key ideas:
  - Discount factors to diminish update inconsistency
  - Effective update function:
 
$$g(\lambda_1(k), \dots, \lambda_M(k)) - c\lambda_i(k)$$
  - Use PU outage feedback to estimate outage prob.

# Convergence results for DDPC

- Synchronized noisy update

- Global clock:  $a_1(k) = a_2(k) = \dots = a_M(k)$

- Step size rule:

$$\lim_{n \rightarrow \infty} \sum_{k=0}^n a(k) = \infty \quad \text{and} \quad \lim_{n \rightarrow \infty} \sum_{k=0}^n a^2(k) < \infty.$$

- Moderate condition on the maximum power constraint

- Result:

- With prob. 1,  $\lambda_i(k) \rightarrow \lambda_*$

- Biased from  $\lambda^o$  due to the estimate error and concavity of  $\log()$  function

# Convergence results for DDPC

- Asynchronous noisy update

- Two SUs

- Unbiased bounded noise

$$g_s(\lambda_1(k), \lambda_2(k)) = \tilde{g}(\lambda_1(k), \lambda_2(k)) + w(k)$$

$$\tilde{g}(\Lambda) = \log(f(\mathbf{P})) - \log(\eta).$$

- Large enough power constraint

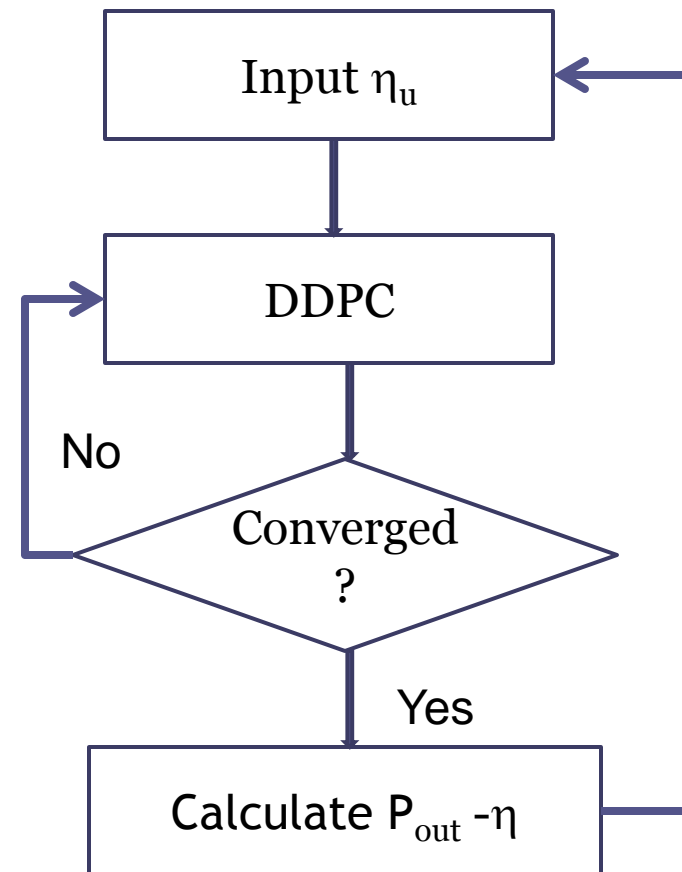
- More conditions on step size

- Result

- With moderate conditions,  $\lim_{k \rightarrow \infty} \lambda_i(k) = \lambda_s$  in prob.

# Adjust target outage prob.

- Convergent point is biased from  $\lambda^0$
- Adopts a different target outage prob. for DDPC



# Interference temperature

- Approximate the outage prob. constraint

$$\gamma_{ce} = \frac{P_0 G_0}{N_0 + \sum_{i=1}^M P_i G_i}, \quad \text{CEM} = \frac{\gamma_{ce}}{\gamma_{th}}$$

$$1 - (1 - \eta_0) \left(1 + \frac{1}{\text{CEM}} - \frac{\gamma_{th} N_0}{P_0 G_0}\right)^{-1} \leq f(\mathbf{P}) \leq 1 - \exp\left(-\frac{1}{\text{CEM}}\right)$$

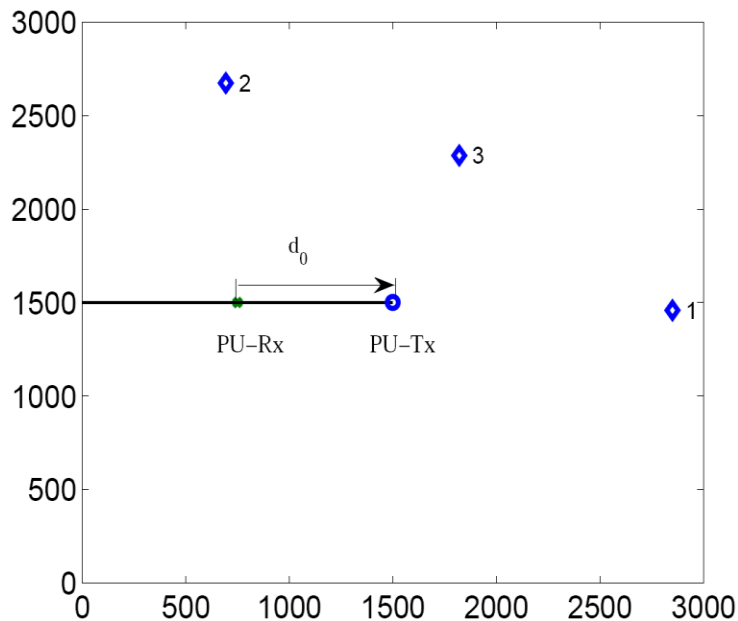
Lower bound

Upper bound

$$\sum_{i=1}^M P_i G_i \leq \frac{-P_0 G_0 \log(1 - \eta)}{\gamma_{th}} - N_0$$

$$\sum_{i=1}^M P_i G_i \leq \frac{\eta - \eta_0}{1 - \eta} \frac{P_0 G_0}{\gamma_{th}}$$

# Simulation setups



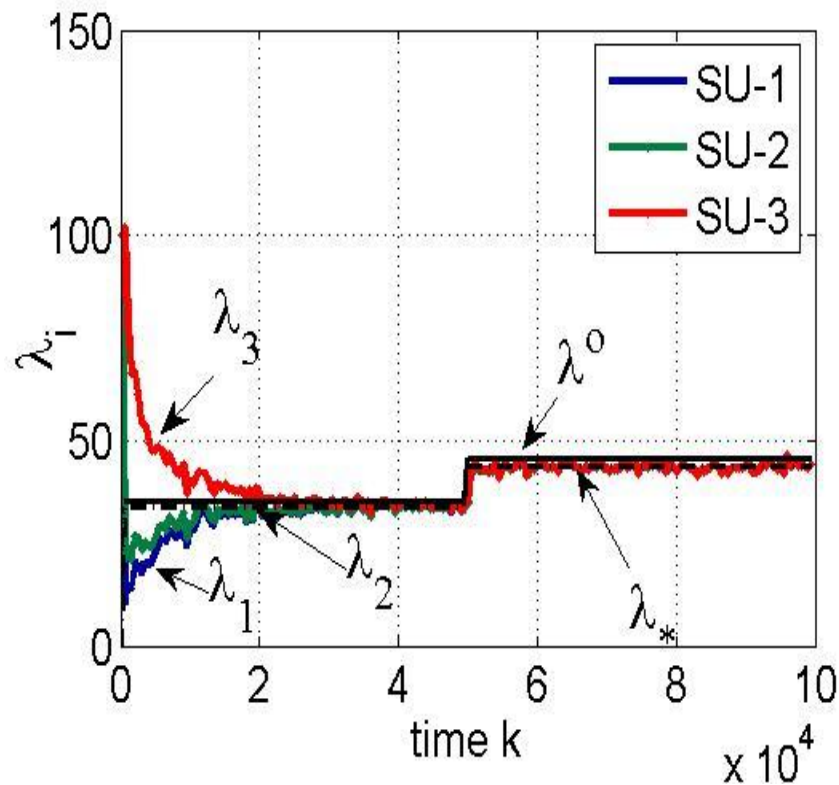
Locations of users

- Max. SU power: 33dBm
- 3 SU pairs
- Time to join  $k_i$ : [0 100 200]
- Observation window size  $T$ : 200
- PU-Rx location changes from 500 meters to 600 meters
- $\eta_o$  changes from 1.9% to 3.8%
- Outage prob. Constraint: 10%
- Step size rule

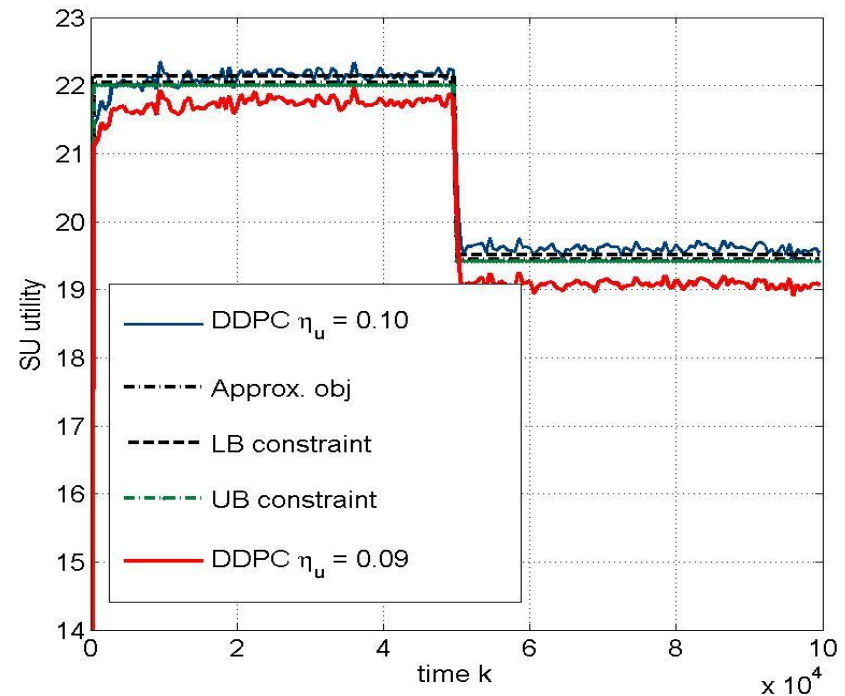
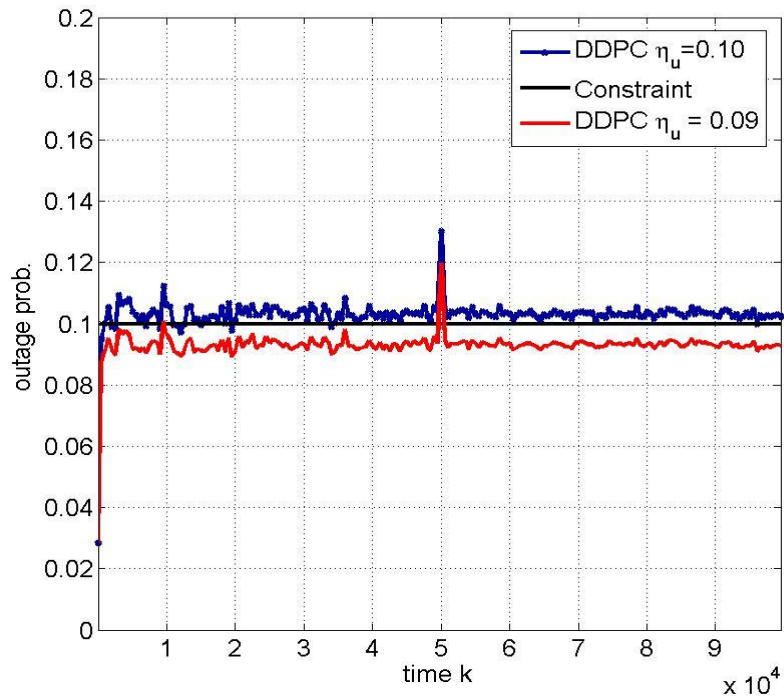
$$a_i(k) = 50(k + k_i)^{-0.4}$$

- $c = 1.0e-4$

# Simulation results



- Observations
  - Convergence
  - Adaptiveness to the system dynamics
  - Distance from the optimal Lagrange multiplier



- Satisfy outage prob. constraint most of the time
- Closed-to optimum SU utility performance
- Utility approximation works well

# Summary

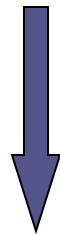
- Use of primary feedback control information
  - Guarantee protection on the primary receiver
  - Achieve higher spectrum efficiency than LBT
  - **Coordinate** (implicitly) distributed SU control

# Conclusions

- Artificial spectrum shortage problem
- Non-intrusive dynamic spectrum access
  - Improve spectrum efficiency
  - Generate small interference to the PU
  - Fast and easy to deploy

Optimization on Listen-before-talk

More information  
&  
Processing power



Smarter  
&  
Better performance

Optimization based on PU feedback info.

Thank you very much!