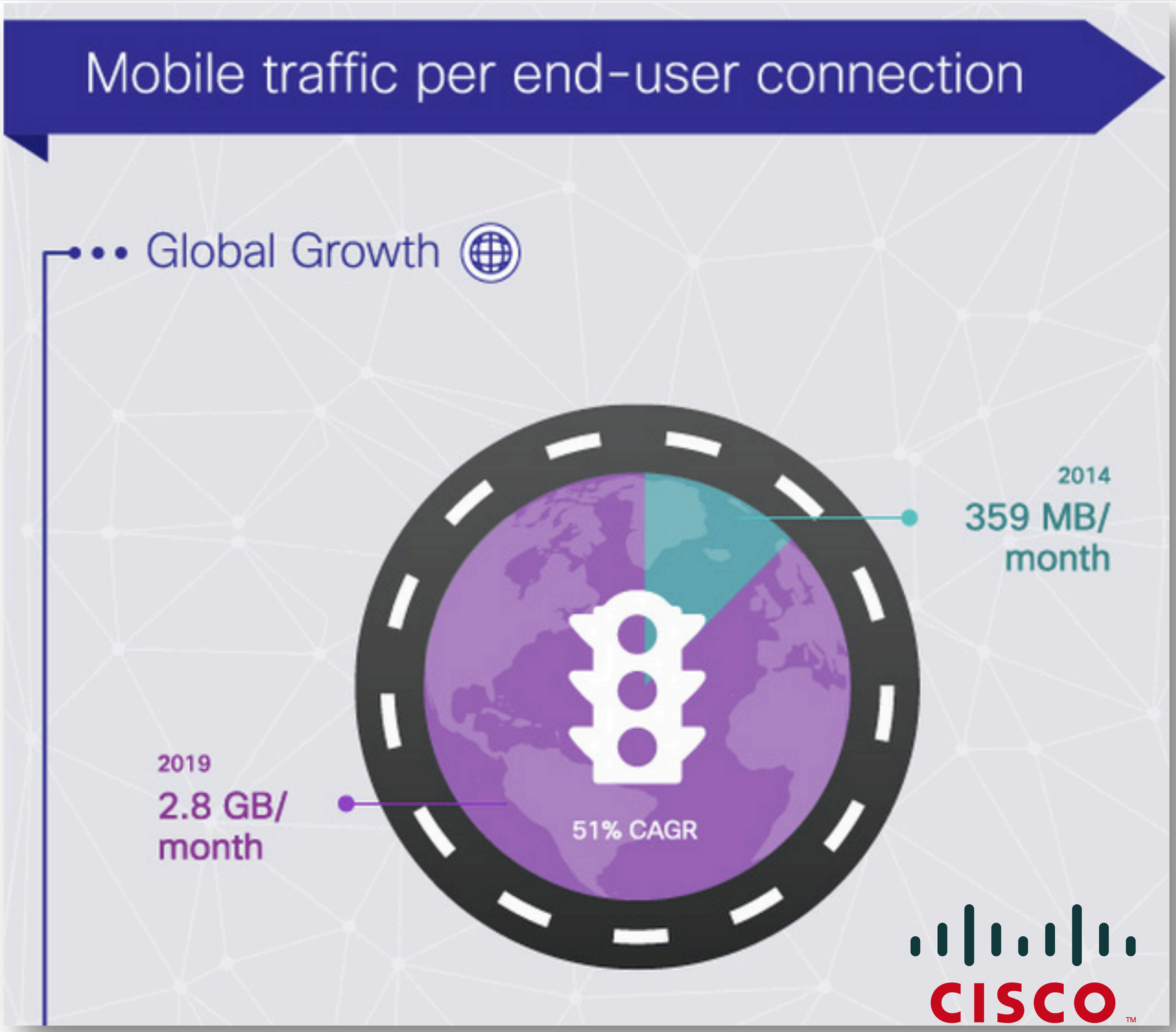
Universidad Politécnica de Cartagena

Coexistence Policies in Cognitive Radio

Mario López Martínez
Directed by: Juan José Alcaraz Espín


Mobile traffic per end-user connection
Global Growth
2014
359 MB/
month
2019
2.8 GB/
month
51% CAGR
CISCO

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- GOVERNMENT EXCLUSIVE
- GOVERNMENT/NON-GOVERNMENT SHARED
- NON-GOVERNMENT EXCLUSIVE

ALLOCATION USAGE DESIGNATION

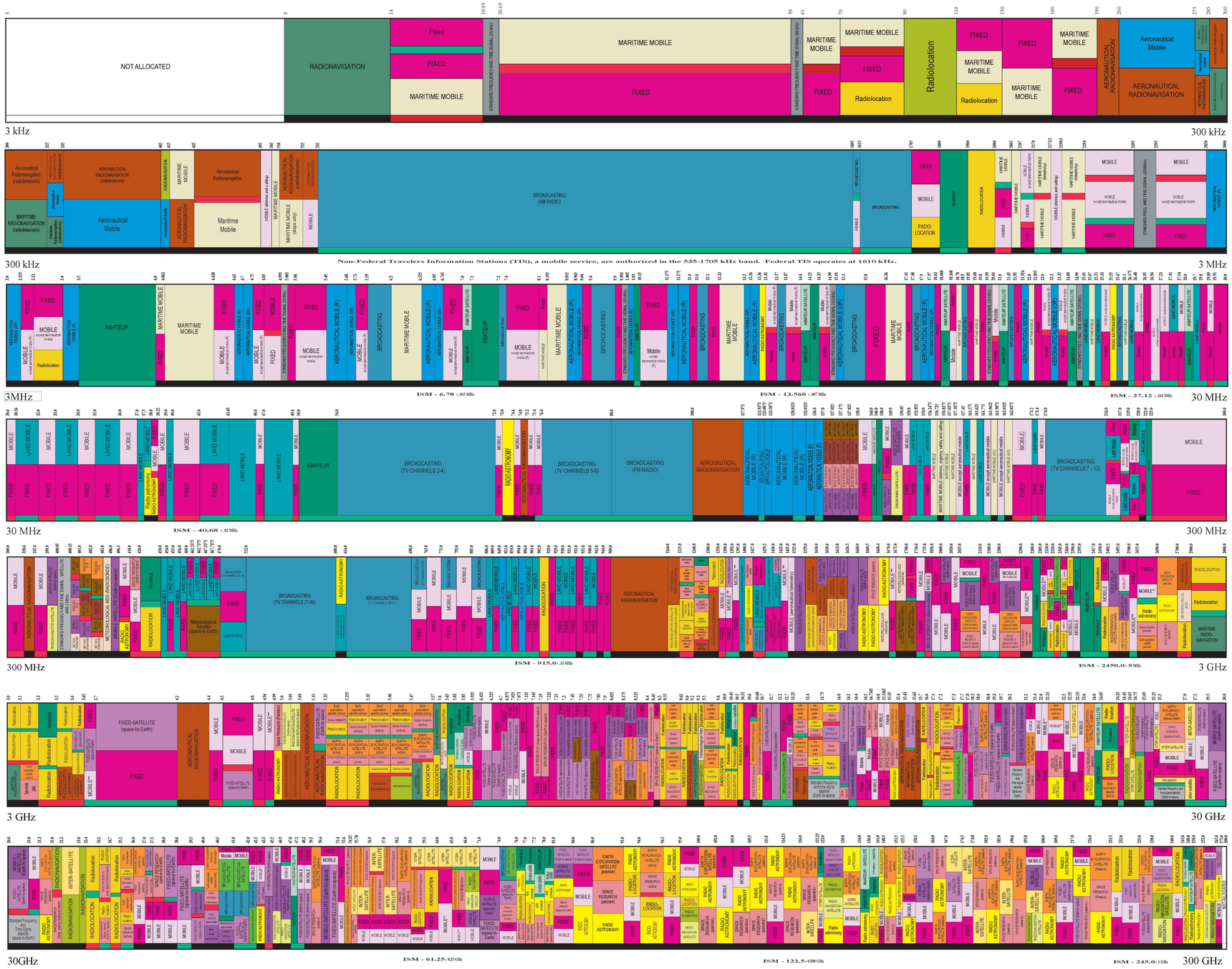
SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it does not completely reflect all aspects, i.e. footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

August 2011

For sale by the Superintendent of Documents, U.S. Government Printing Office
Internet: bookstore.gpo.gov Phone toll free (866) 512-1800; Washington, DC area (202) 512-1800
Facsimile: (202) 512-2250 Mail: Stop SSOP, Washington, DC 20402-0001

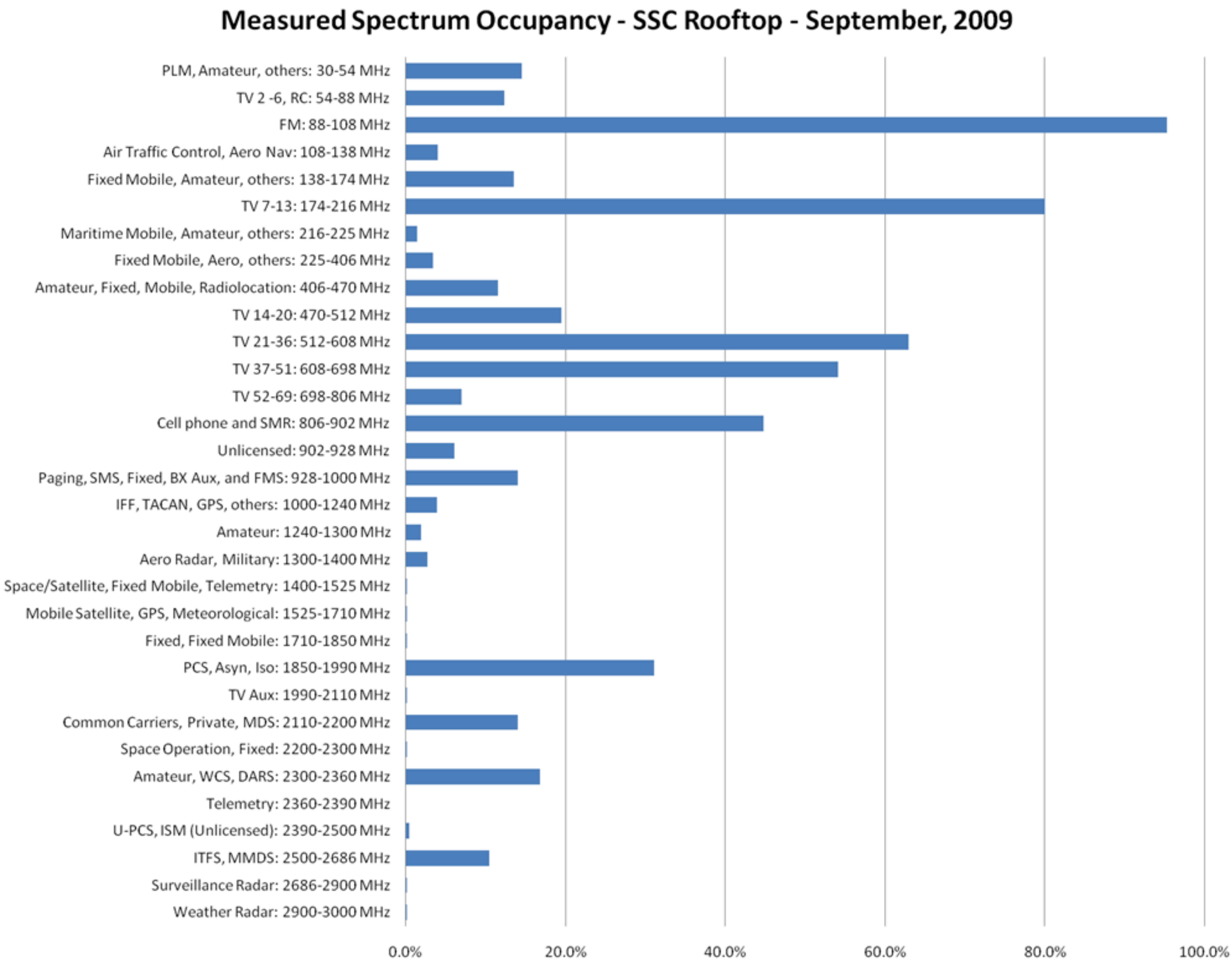


* EXCEPT AERONAUTICAL MOBILE (R)

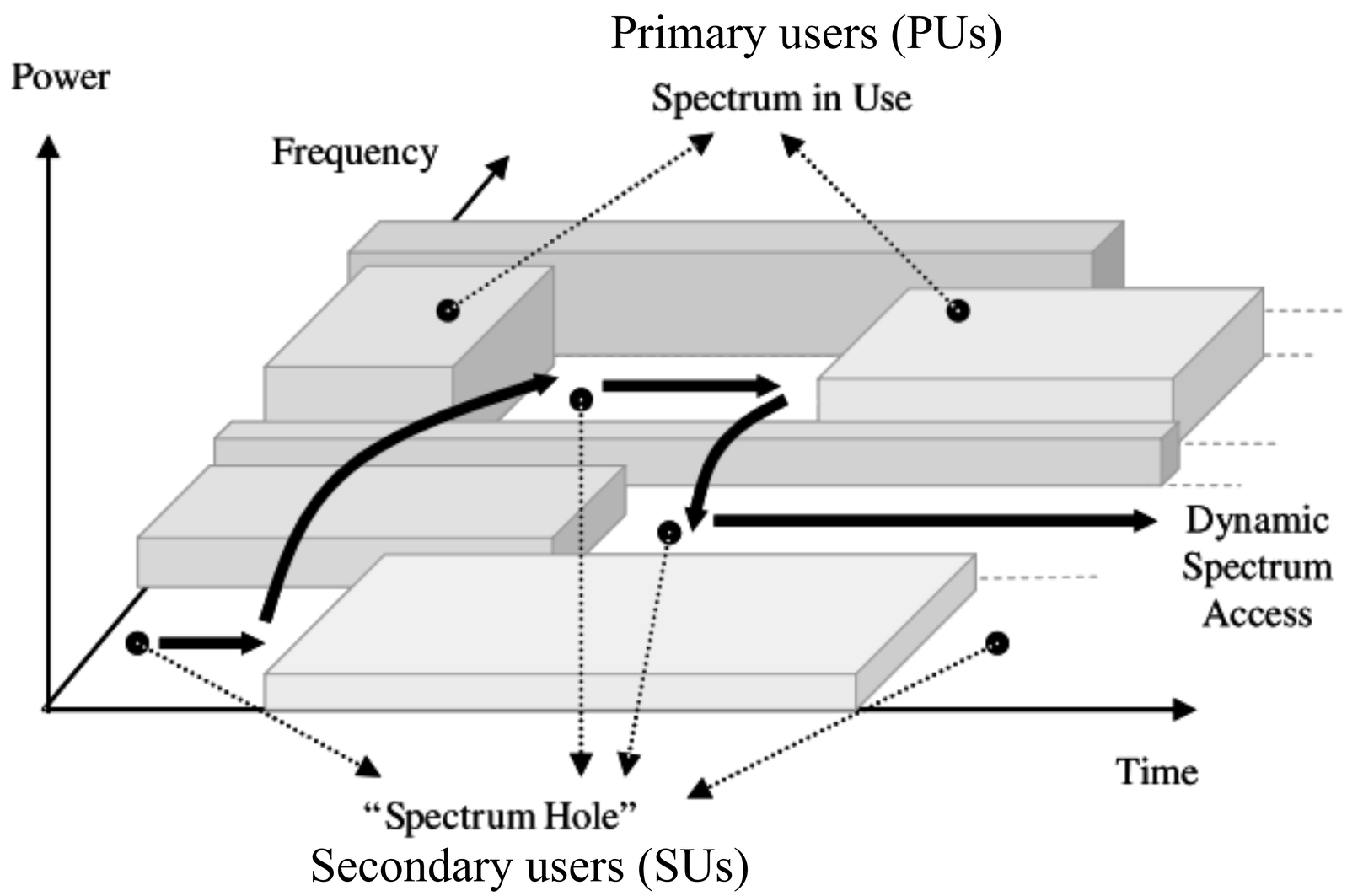
** EXCEPT AERONAUTICAL MOBILE

PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM OCCUPIED.

Almost all assigned. BUT...

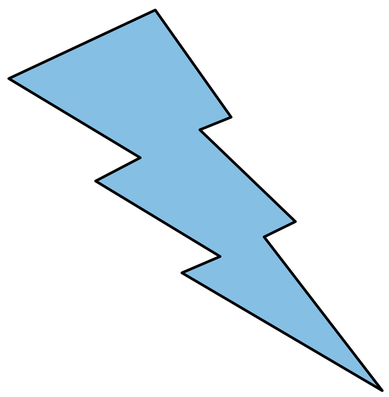

Measured Spectrum Occupancy - SSC Rooftop - September, 2009
PLM, Amateur, others: 30-54 MHz
TV 2 -6, RC: 54-88 MHz
FM: 88-108 MHz
Air Traffic Control, Aero Nav: 108-138 MHz
Fixed Mobile, Amateur, others: 138-174 MHz
TV 7-13: 174-216 MHz
Maritime Mobile, Amateur, others: 216-225 MHz
Fixed Mobile, Aero, others: 225-406 MHz
Amateur, Fixed, Mobile, Radiolocation: 406-470 MHz
TV 14-20: 470-512 MHz
TV 21-36: 512-608 MHz
TV 37-51: 608-698 MHz
TV 52-69: 698-806 MHz
Cell phone and SMR: 806-902 MHz
Unlicensed: 902-928 MHz
Paging, SMS, Fixed, BX Aux, and FMS: 928-1000 MHz
IFF, TACAN, GPS, others: 1000-1240 MHz
Amateur: 1240-1300 MHz
Aero Radar, Military: 1300-1400 MHz
Space/Satellite, Fixed Mobile, Telemetry: 1400-1525 MHz
Mobile Satellite, GPS, Meteorological: 1525-1710 MHz
Fixed, Fixed Mobile: 1710-1850 MHz
PCS, Asyn, Iso: 1850-1990 MHz
TV Aux: 1990-2110 MHz
Common Carriers, Private, MDS: 2110-2200 MHz
Space Operation, Fixed: 2200-2300 MHz
Amateur, WCS, DARS: 2300-2360 MHz
Telemetry: 2360-2390 MHz
U-PCS, ISM (Unlicensed): 2390-2500 MHz
ITFS, MMDS: 2500-2686 MHz
Surveillance Radar: 2686-2900 MHz
Weather Radar: 2900-3000 MHz
0.0%
20.0%
40.0%
60.0%
80.0%
100.0%

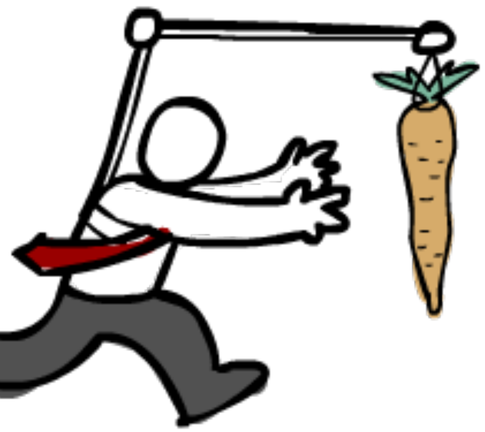
Dynamic Spectrum Access (DSA)



Motivation of the thesis

Wireless industry's concerns about DSA:





We develop DSA mechanisms focusing on the protection and creation of incentives to the licensed users

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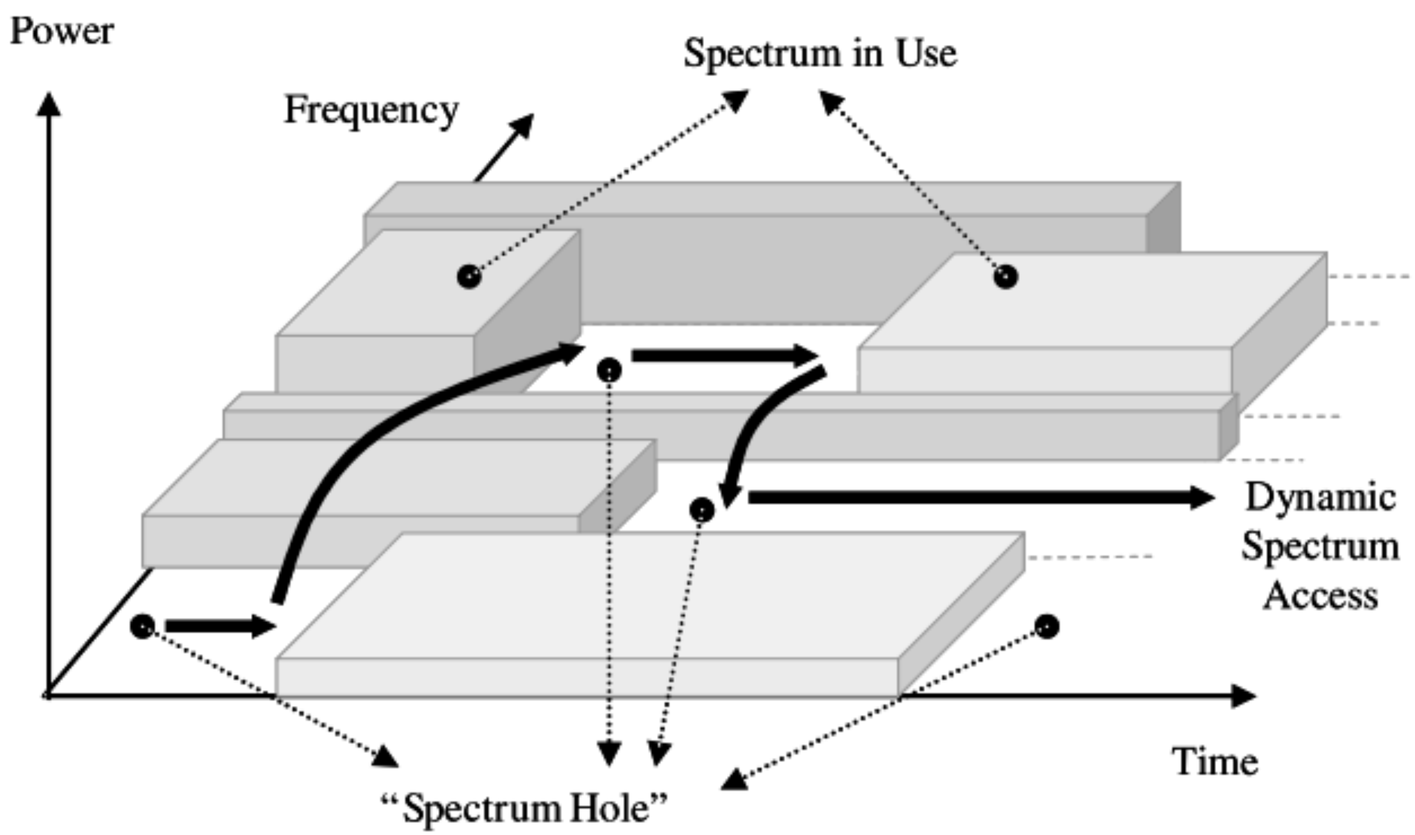
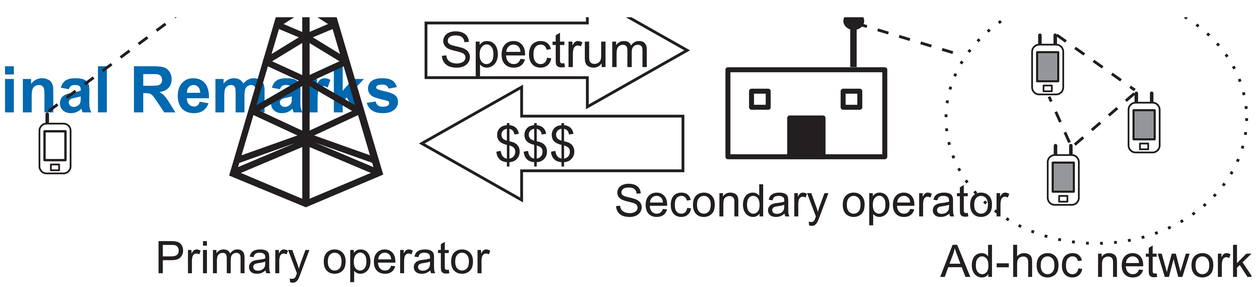
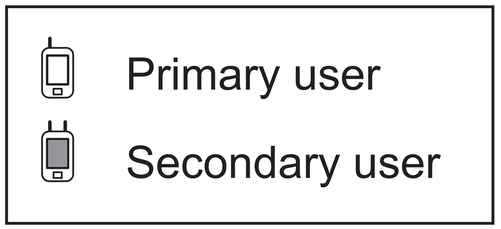
I. Opportunistic Spectrum Access



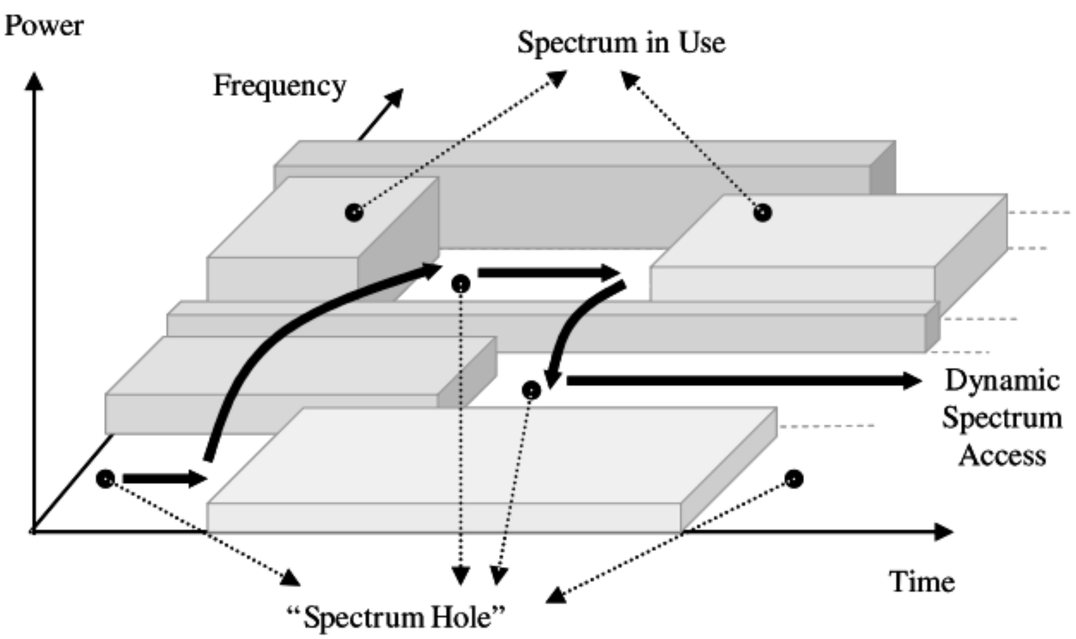
II. rative

Final Remarks

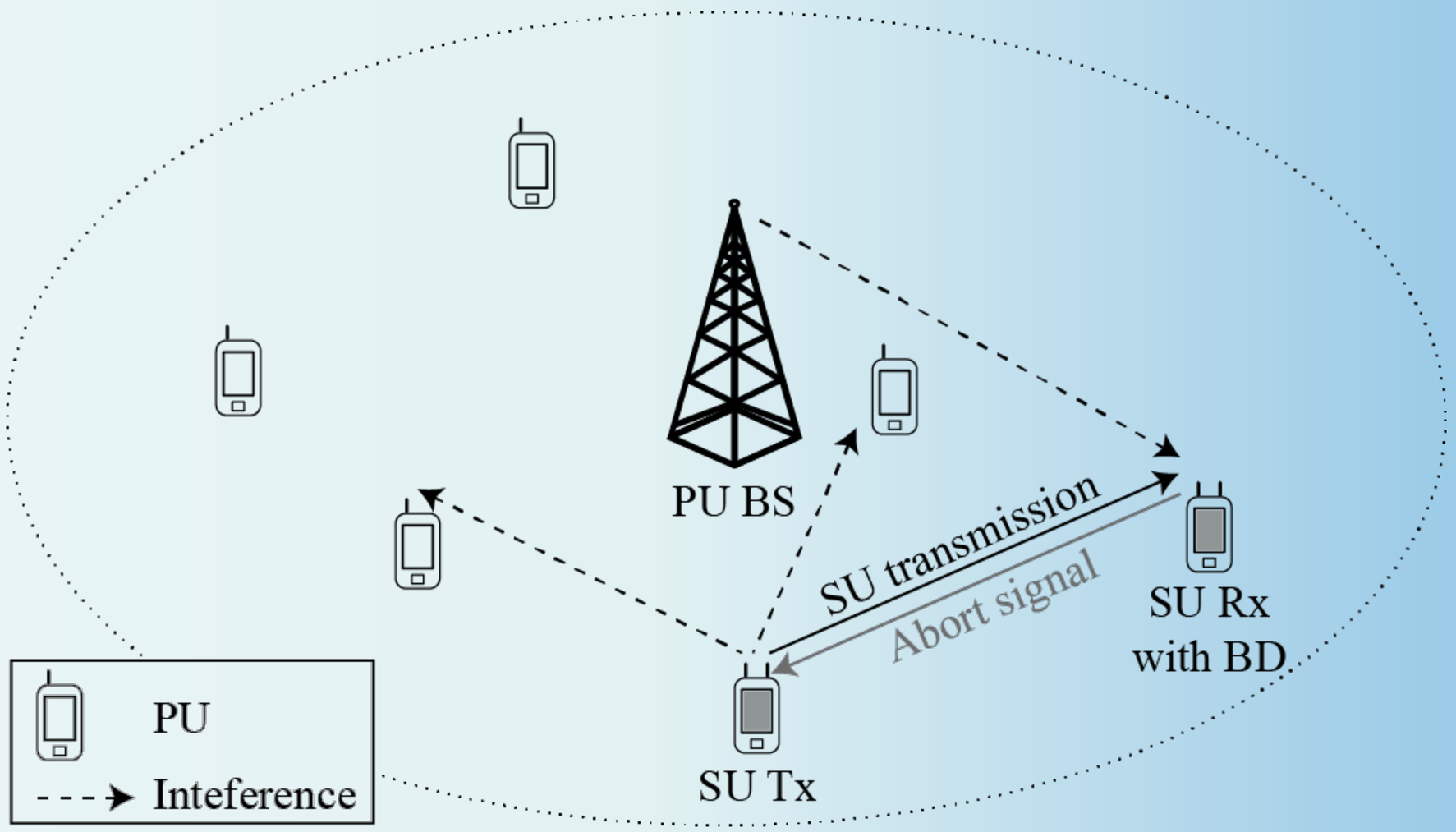




Opportunistic Spectrum Access



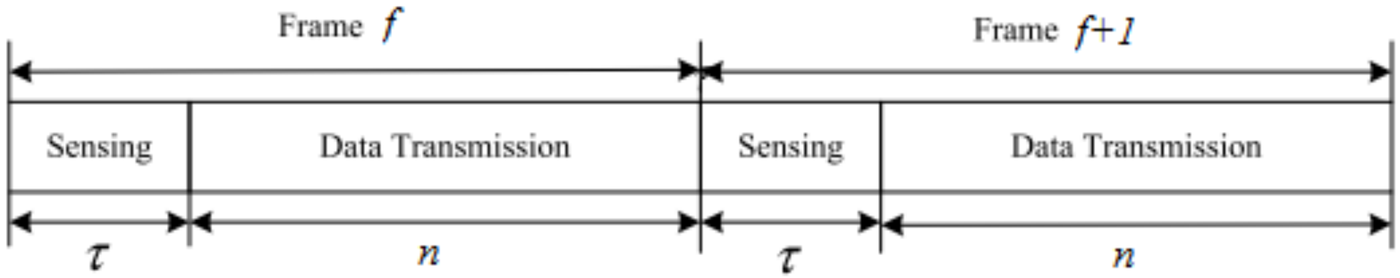
- Background Detection of Primary User Activity
- Bandwidth Reservation as a Coexistence Strategy
- Uncertainty-Aware OSA in Coexistence-Friendly Systems



Background Detection of Primary User Activity

Motivation

Baseline approach: optimized OSA



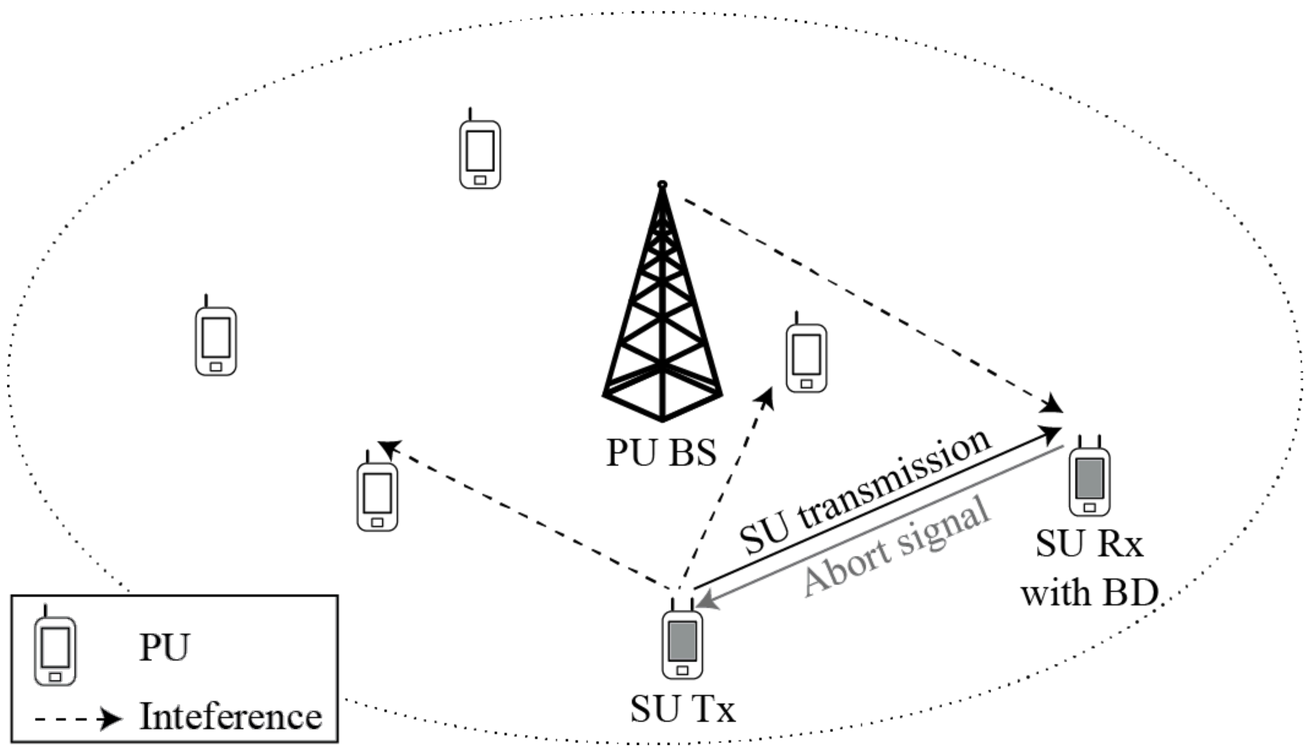
$$\arg\max_{n} T(n) \text{ subject to } P_c(n) \leq \alpha, \quad 0 \leq n \leq n_{max}$$

What if a PU arrives while an SU is on “data transmission”?

Contribution

Optimized OSA + **“Background Detection (BD)”**

- Operates at the SU Rx, during ongoing SU transmission
- Decides, by a MAP, if there has been overlap with a PU



Maximum a posteriori rule

$$\arg\max_{\theta} \mathbf{P}(\Theta = \theta | P = p_r, E = e)$$

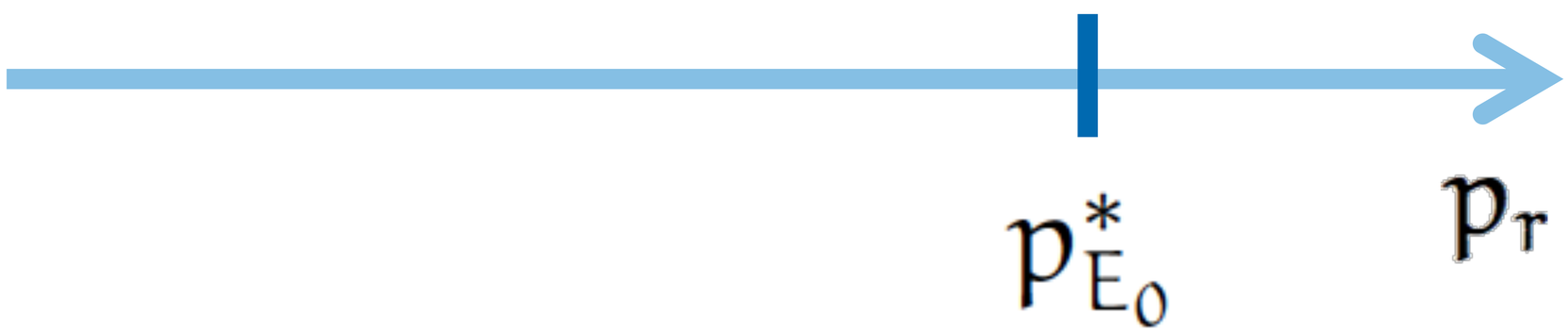
PU presence event

Received power

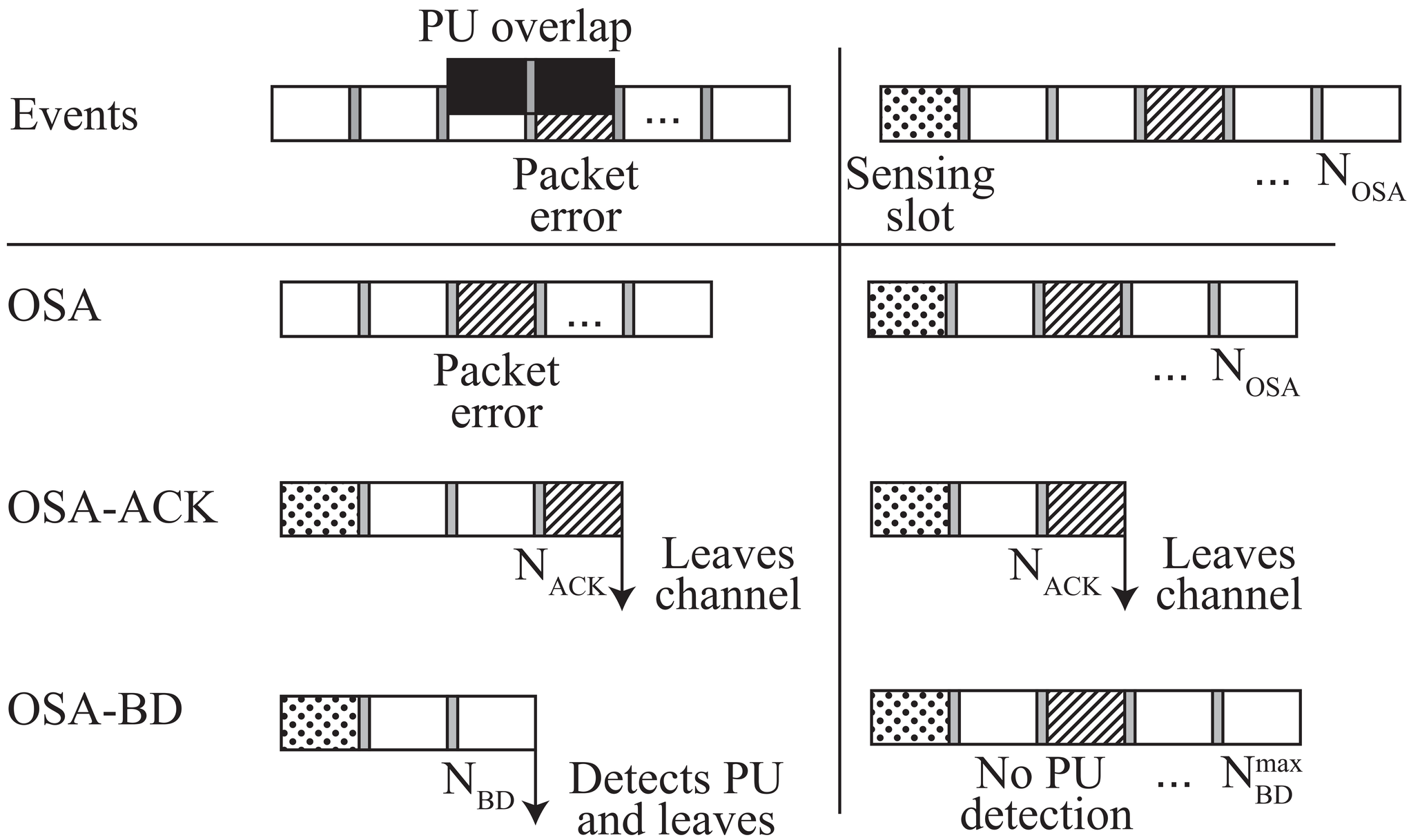
Packet error event

SU infers:
"PU is not present"

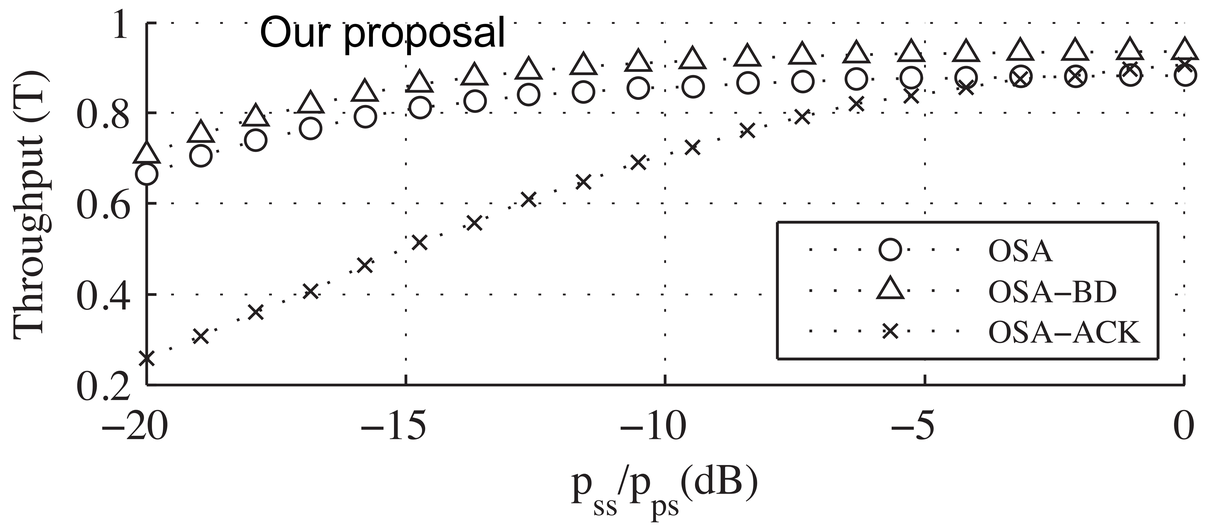
SU infers:
"PU is present"

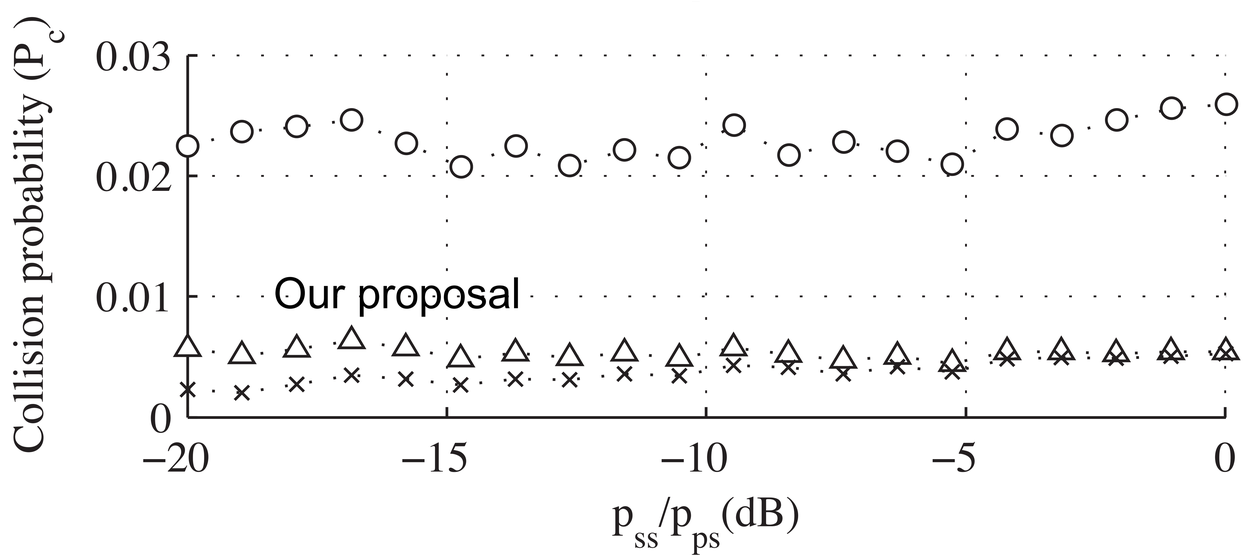


Benchmarks of our proposal: OSA & OSA-ACK

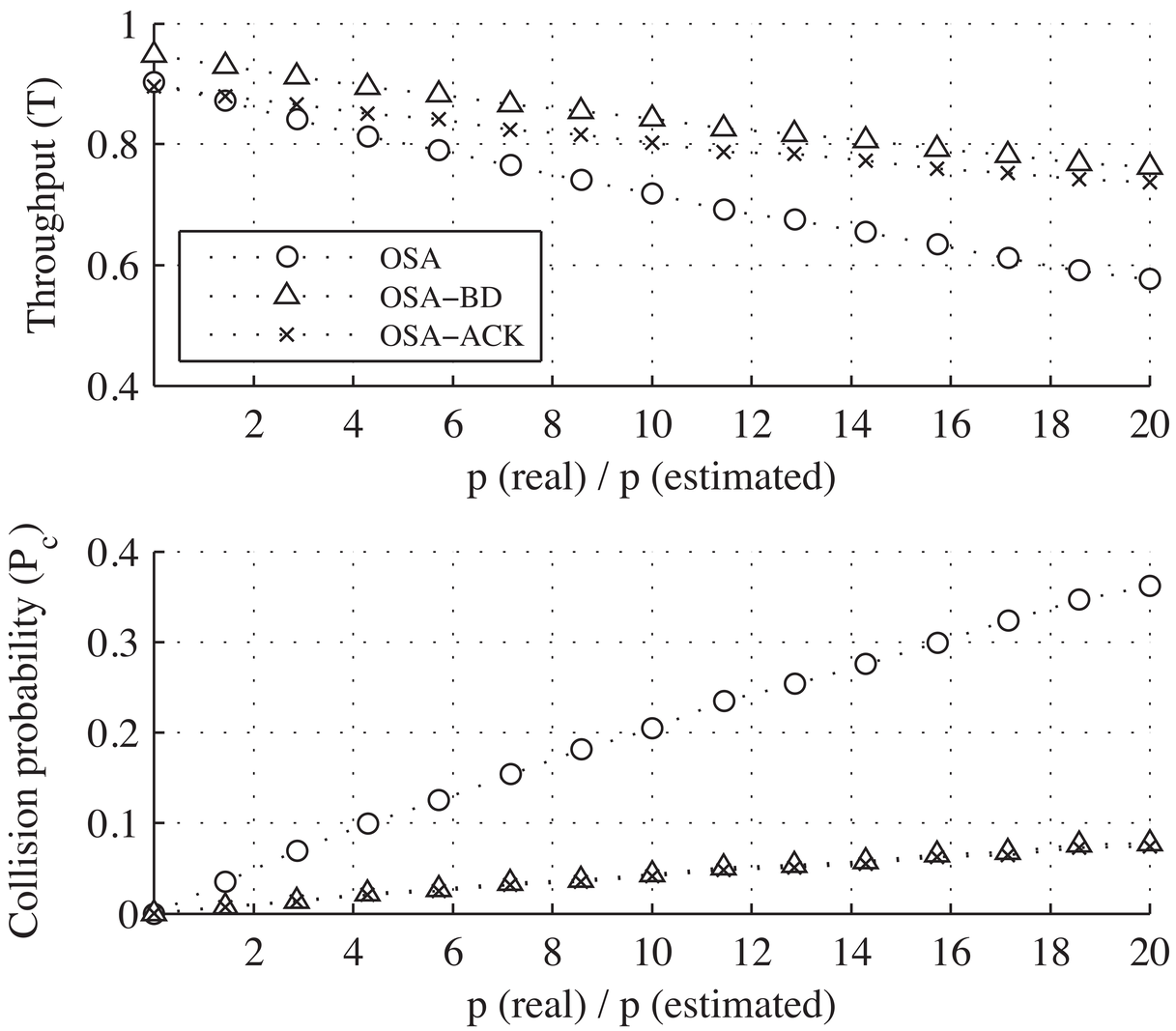


Results: more SU throughput for the same collision probability



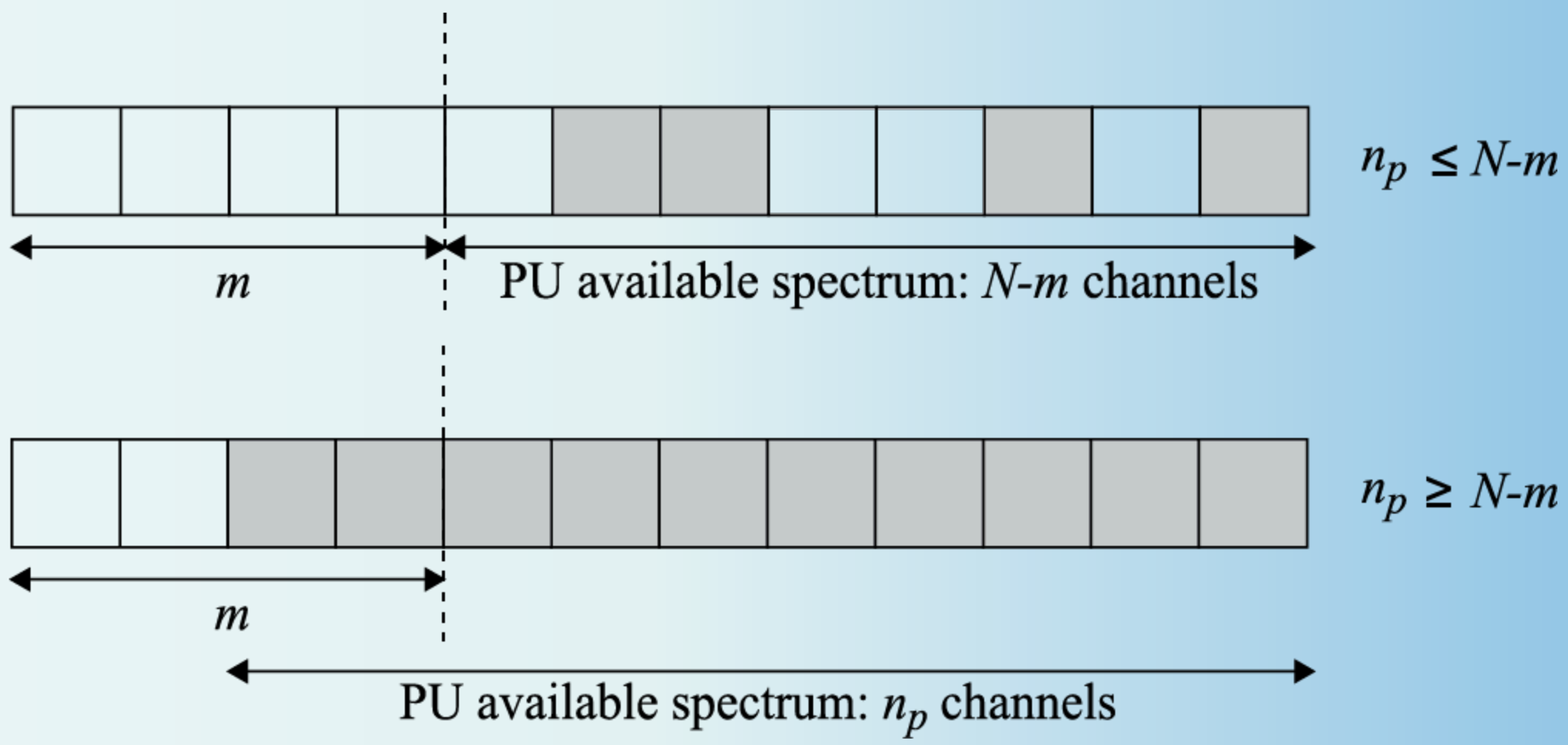


Results (II): BD is robust against parameter misestimations



Novelty of the work

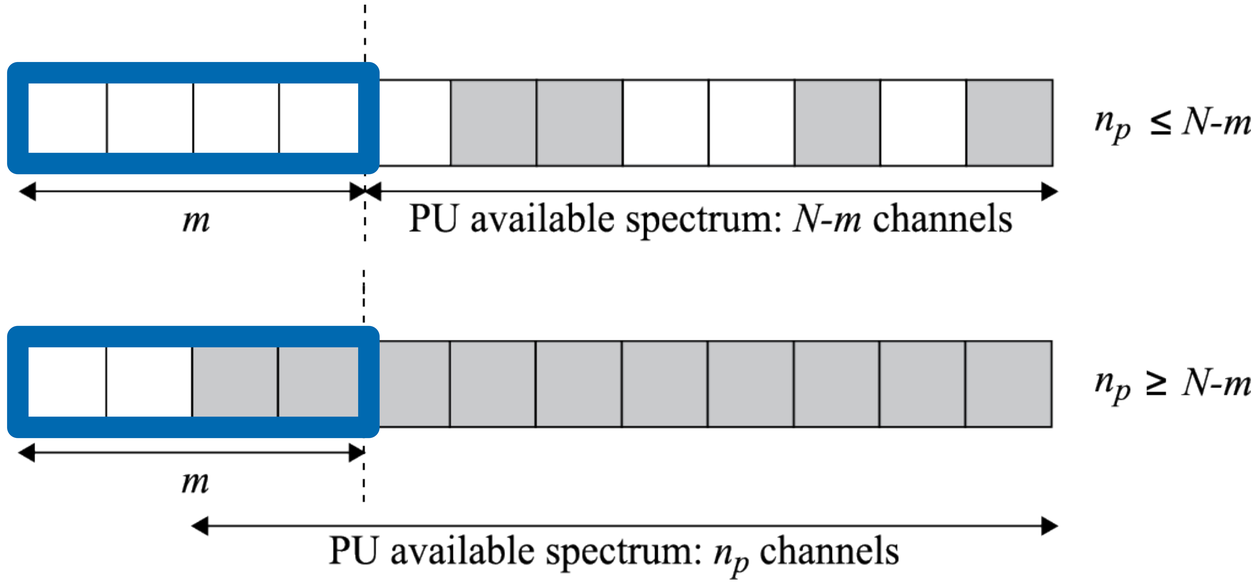
- Previous works focus on detection on the TX side
- Previous works on receiver-side detectors:
  - a theoretical study
  - SU TX always correctly decoded



Bandwidth Reservation as a Coexistence Strategy

Motivation

In case of forced OSA, is it worth for a primary operator to reserve spectrum for SU access?



Less interference from SUs

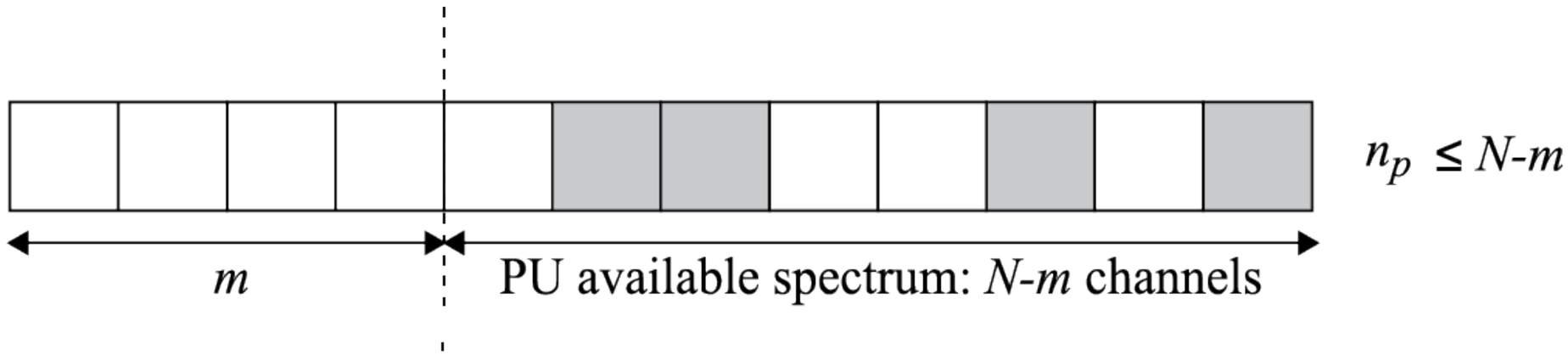
Fewer options for PU channel allocation

Contribution

Impact evaluation of the BR on PU and SU performance:

- Expected capacity, interference power and collision probablities.
- Markov Reward Model.
- Considering propagation issues, and random locations.

Problem definition



- PUs: Poisson(λ_p, μ_p), full CSI
- Channel gains ~ Rayleigh
- SUs: coordinated access (p_s, q_s)

  imperfect sensing with MAP estimator

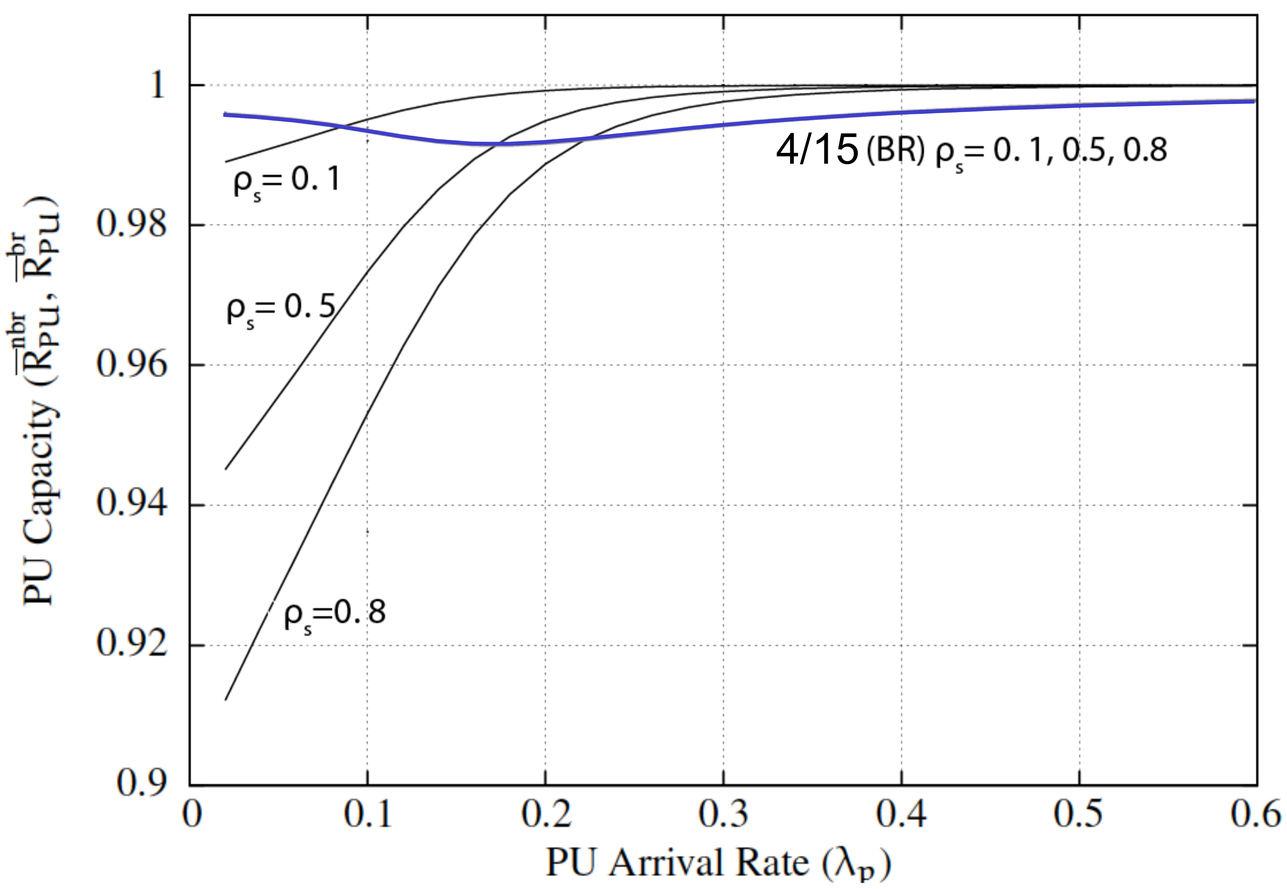
$$\bar{R} = \sum_{n_p=0}^{N} \sum_{n_s=0}^{m-k} R(n_s, n_p)\, P(n_s, n_p)$$

Results

In case of forced OSA, is it worth for a primary operator to reserve spectrum for SU access?

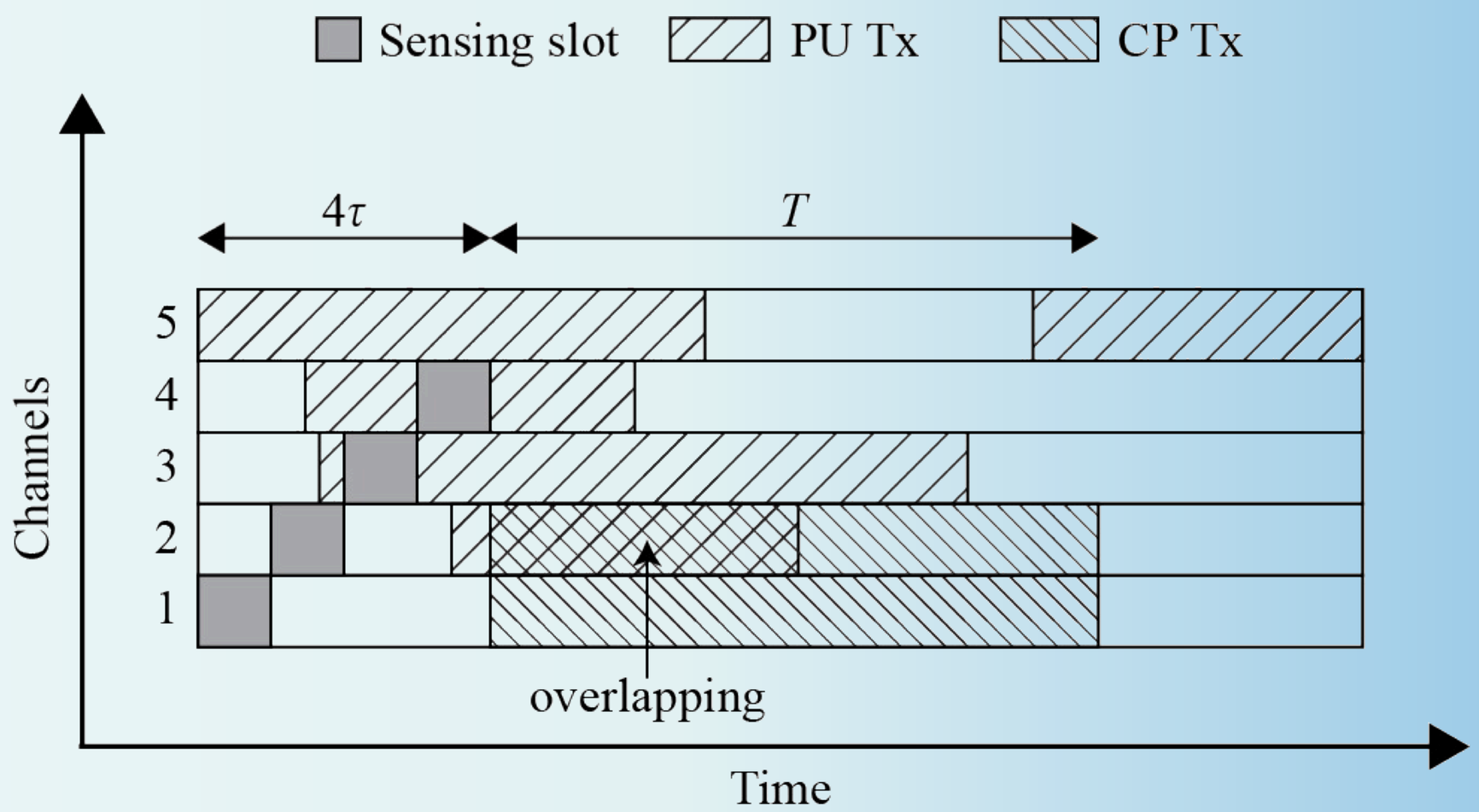
Yes:

- For low PU traffic, PU capacity improves
- Worst case: 1% PU capacity reduction



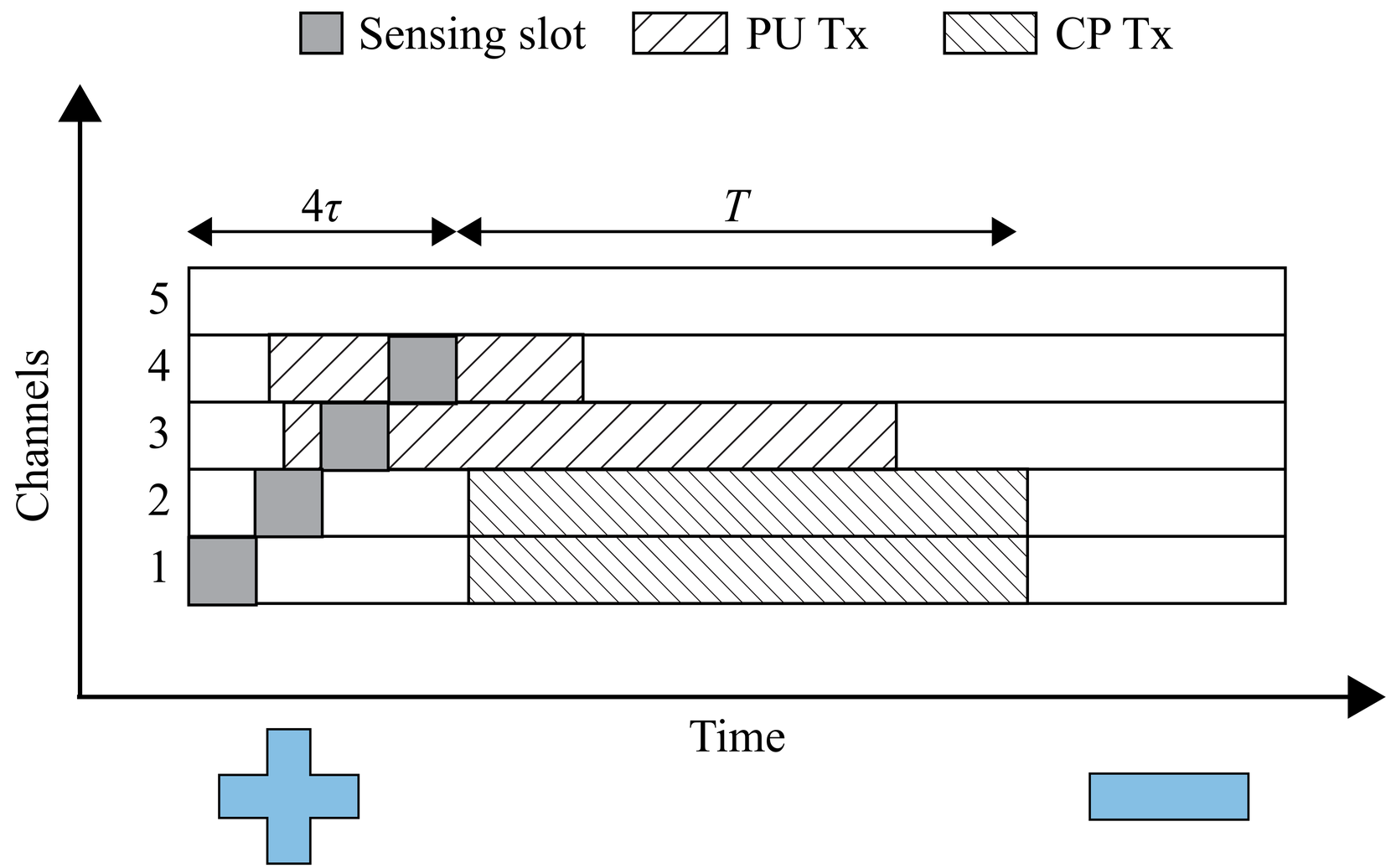
Related Work

- PU Bandwidth reservation assuming no impact on PU performance.
- Bandwidth reservation for handover calls.
- Bandwidth reservation for spectrum trading.



Uncertainty-Aware OSA in Coexistence-Friendly Systems

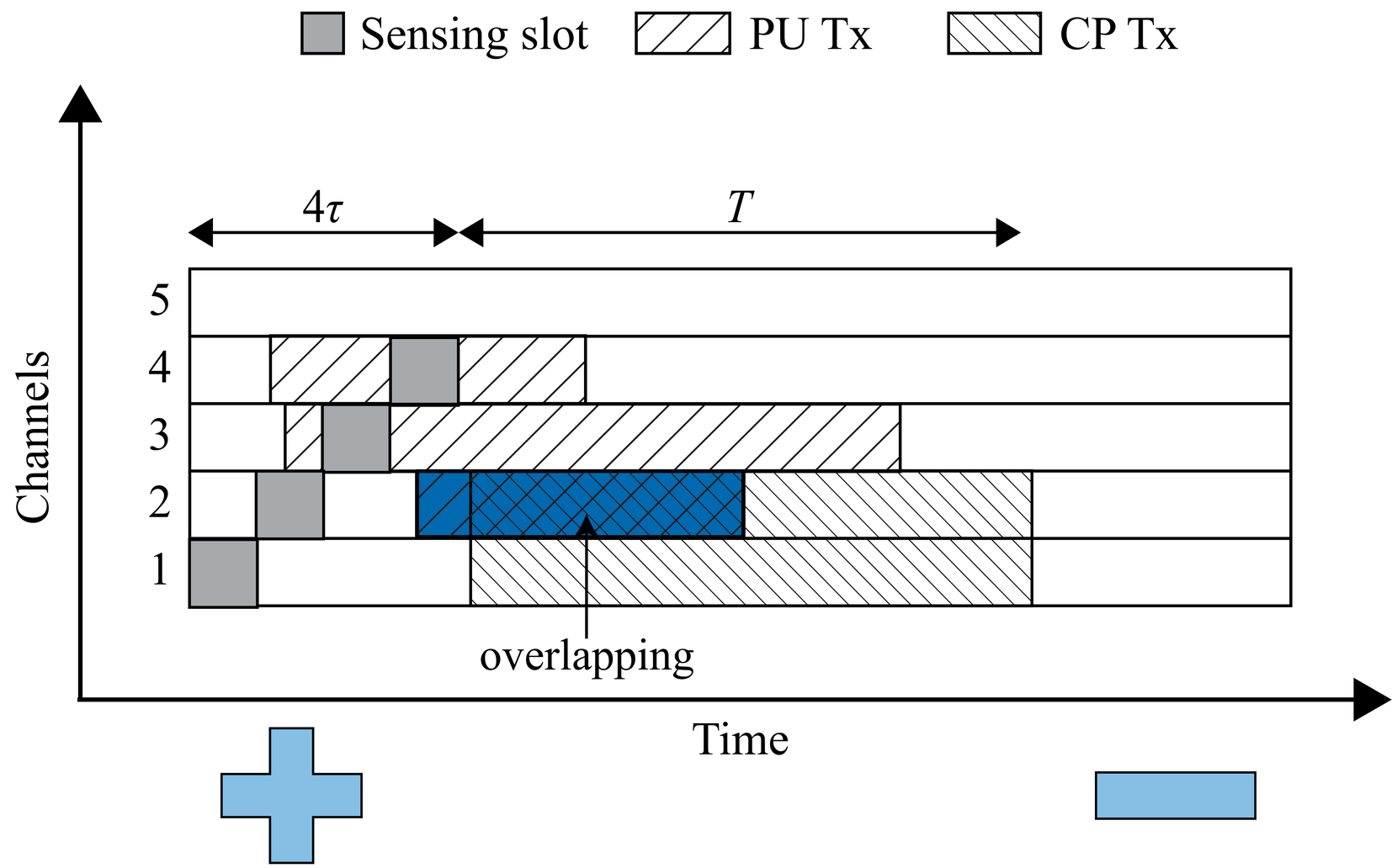
The sensing-throughput trade-off problem



(Potentially)
more free channels

Less TX time

Motivation



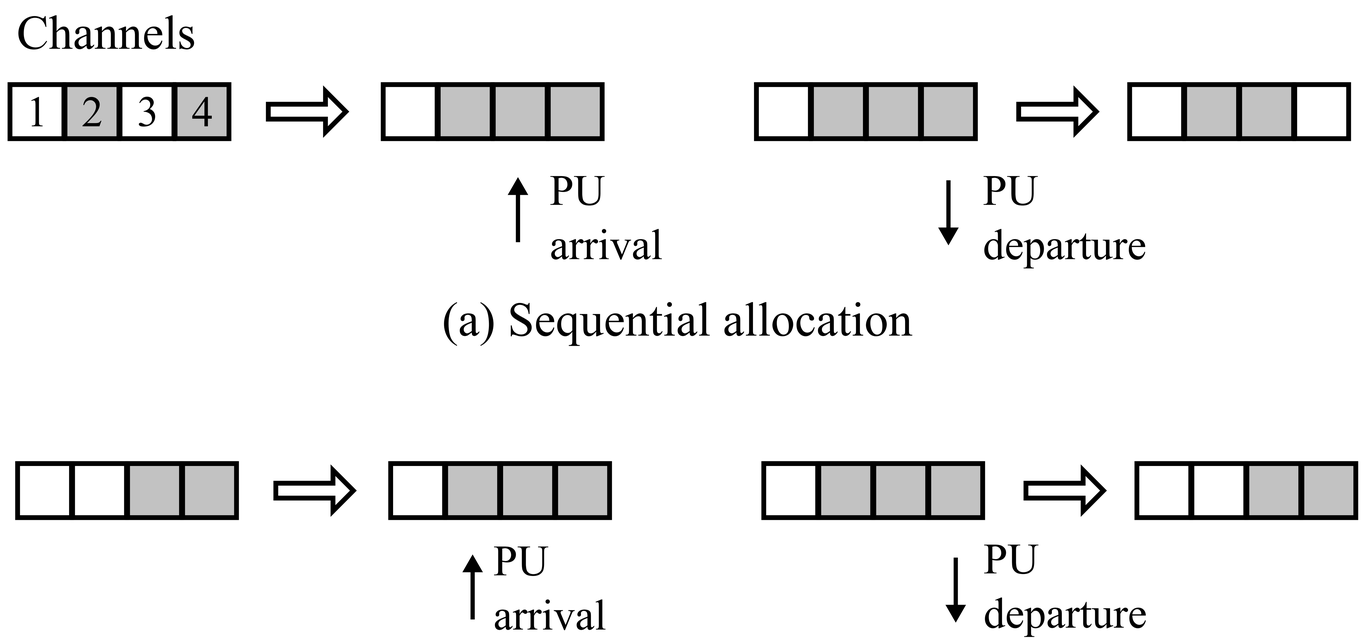
(Potentially)
more free channels

Less TX time
AND more uncertainty

Obtain an optimal access strategy

Motivation (II)

What is the impact of these channel allocation schemes for PUs?



(a) Sequential allocation

(b) Sequential allocation and aggregation (merged spectrum)

Contribution

Optimal SU access strategy

- Under increasing uncertainty
- For random, sequential and merged allocation
- POMDP
- Objective: SU throughput & average overlapping time

Problem formulation

POMDP

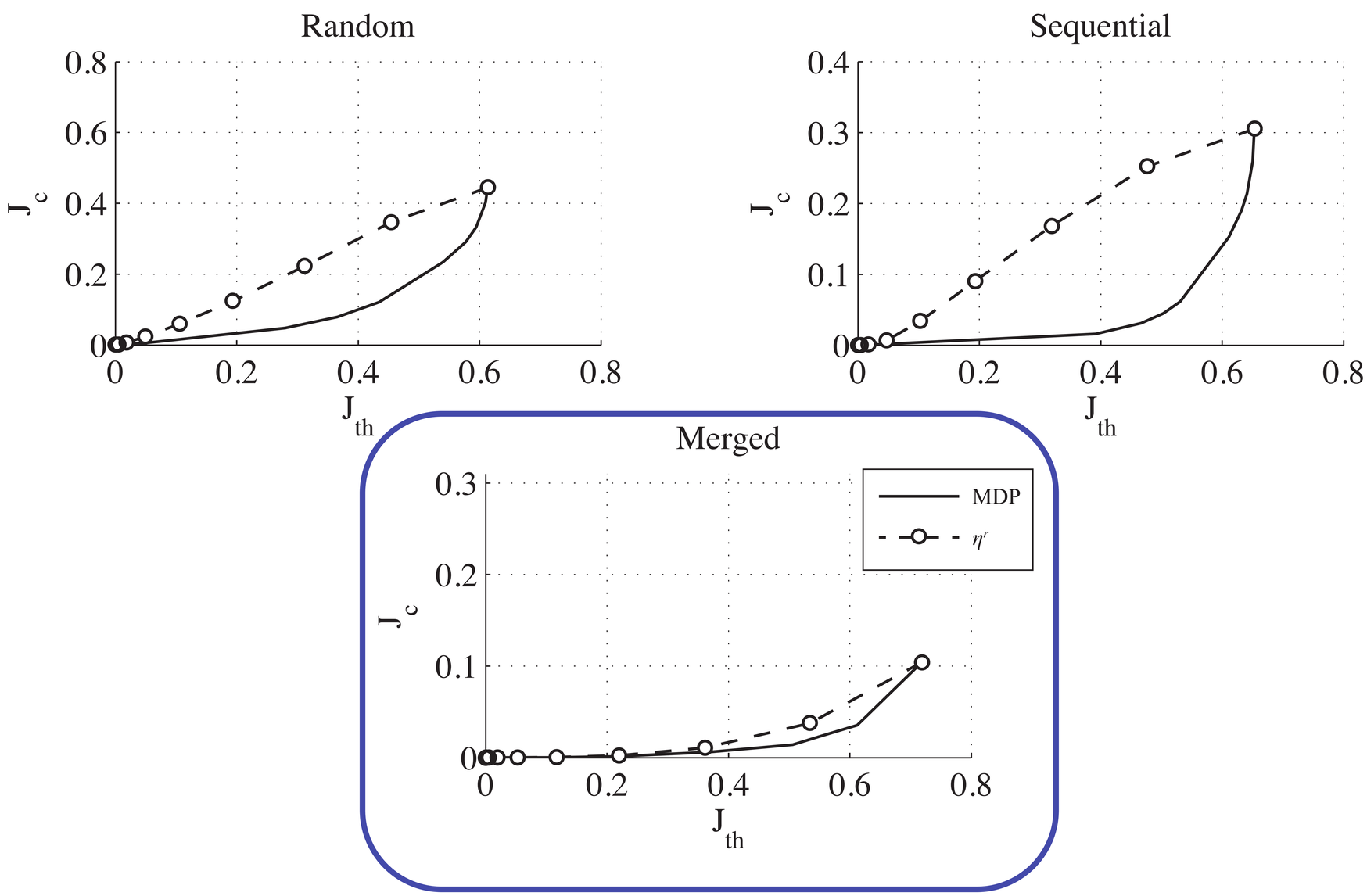
- Action $d_k = (u_k, m_k)$ (sense, TX)
- Cost $= \tilde{g}_k(x_k, d_k) = \left[\alpha \frac{c_k(x_k, m_k)}{c_{max}} + (\alpha - 1)\frac{b_k(m_k)}{b_{max}}\right]$ (overlap, throughput)
- PU channel occupancy: CTMC
- State x_k: channels sensed free
- Objective. For k=0...N-1:

$$J_k^*(x_k) = \min_{d \in \mathcal{D}_k(x_k)} \left\{ g_k(x_k, d) + \sum_{j \in \mathcal{X}_k^*} p_k(j|x_k, d)\, J_{k+1}^*(j) \right\}$$

Results: great impact of the "merged" allocation

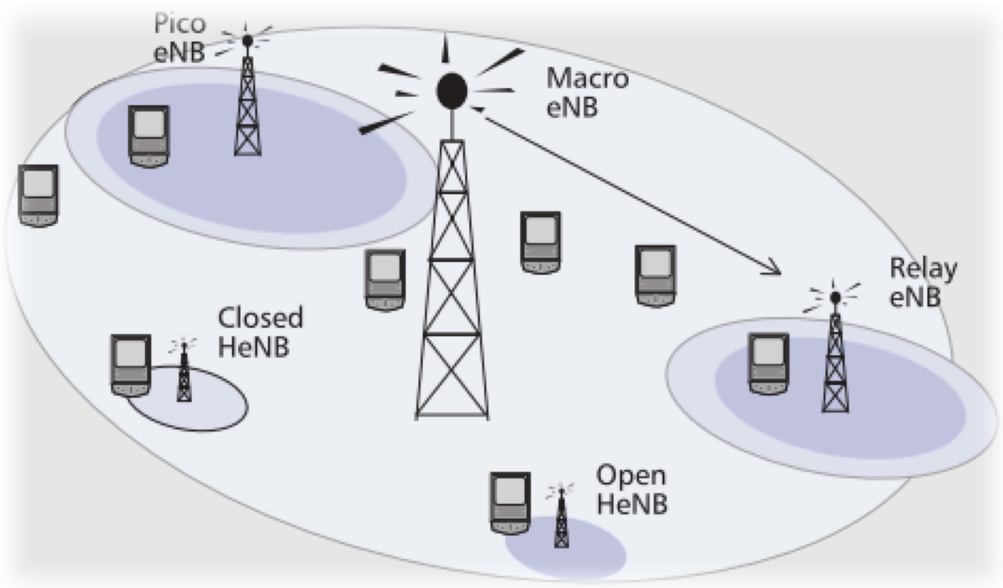
5 ⟵ 3 2

- Benchmark η^r : transmit when free ch. = max_ch + margin



Novelty: uncertainty in sequential decision

- Previous works: uncertainty across different episodes
- Related: channel assignment strategies in HetNets



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- Background Detection of Primary User Activity
- Bandwidth Reservation as a Coexistence Strategy
- Uncertainty-Aware OSA in Coexistence-Friendly Systems

II. Automated Spectrum Trading

- The Big Picture
- A Superprocess with Upper Confidence Bounds for Cooperative Spectrum Sharing

Final Remarks

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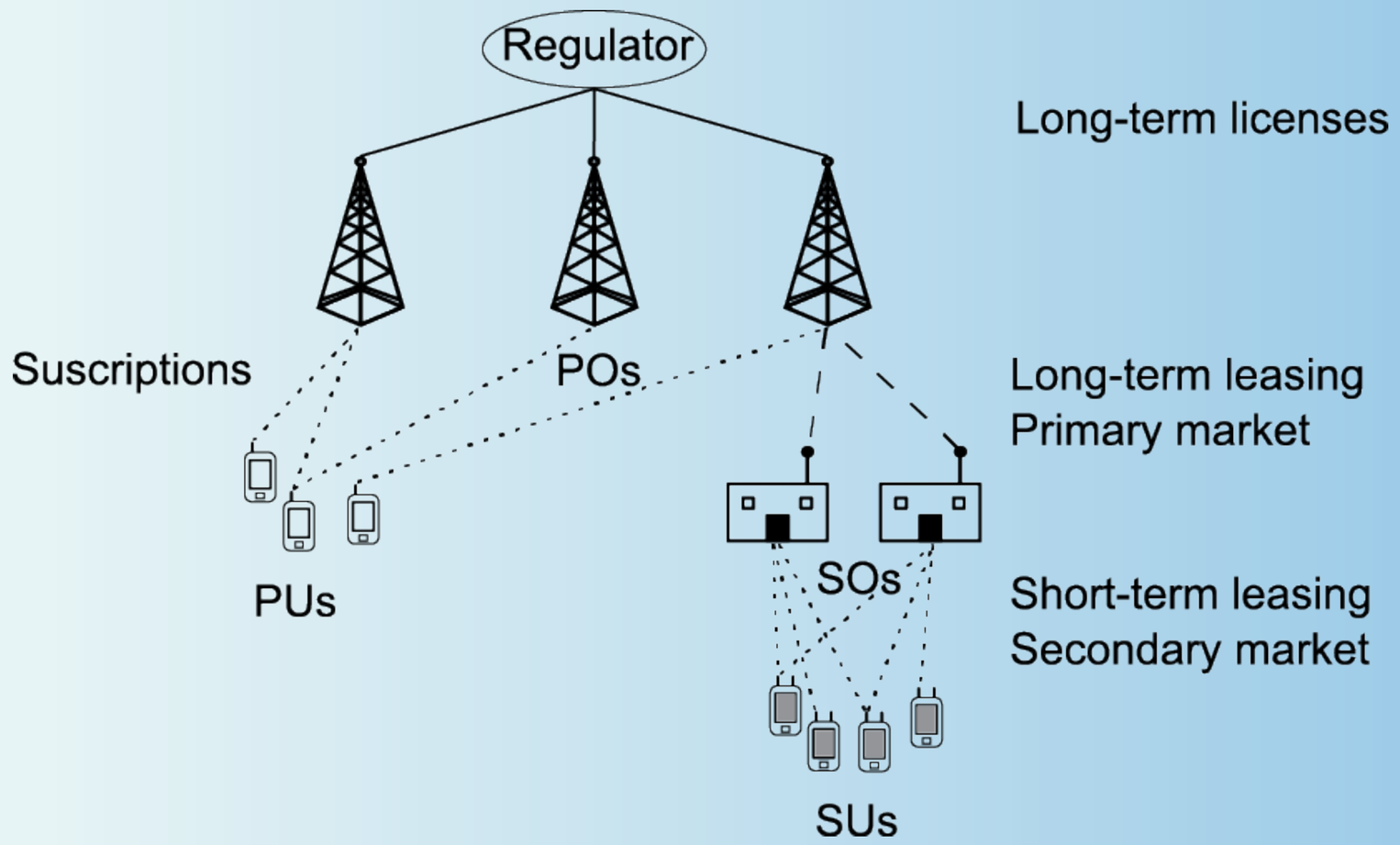
II

Automated Spectrum Trading

- The Big Picture
- A Superprocess with Upper Confidence Bounds for Cooperative Spectrum Sharing



Automated Spectrum Trading Mechanisms: Understanding the Big Picture

Contribution

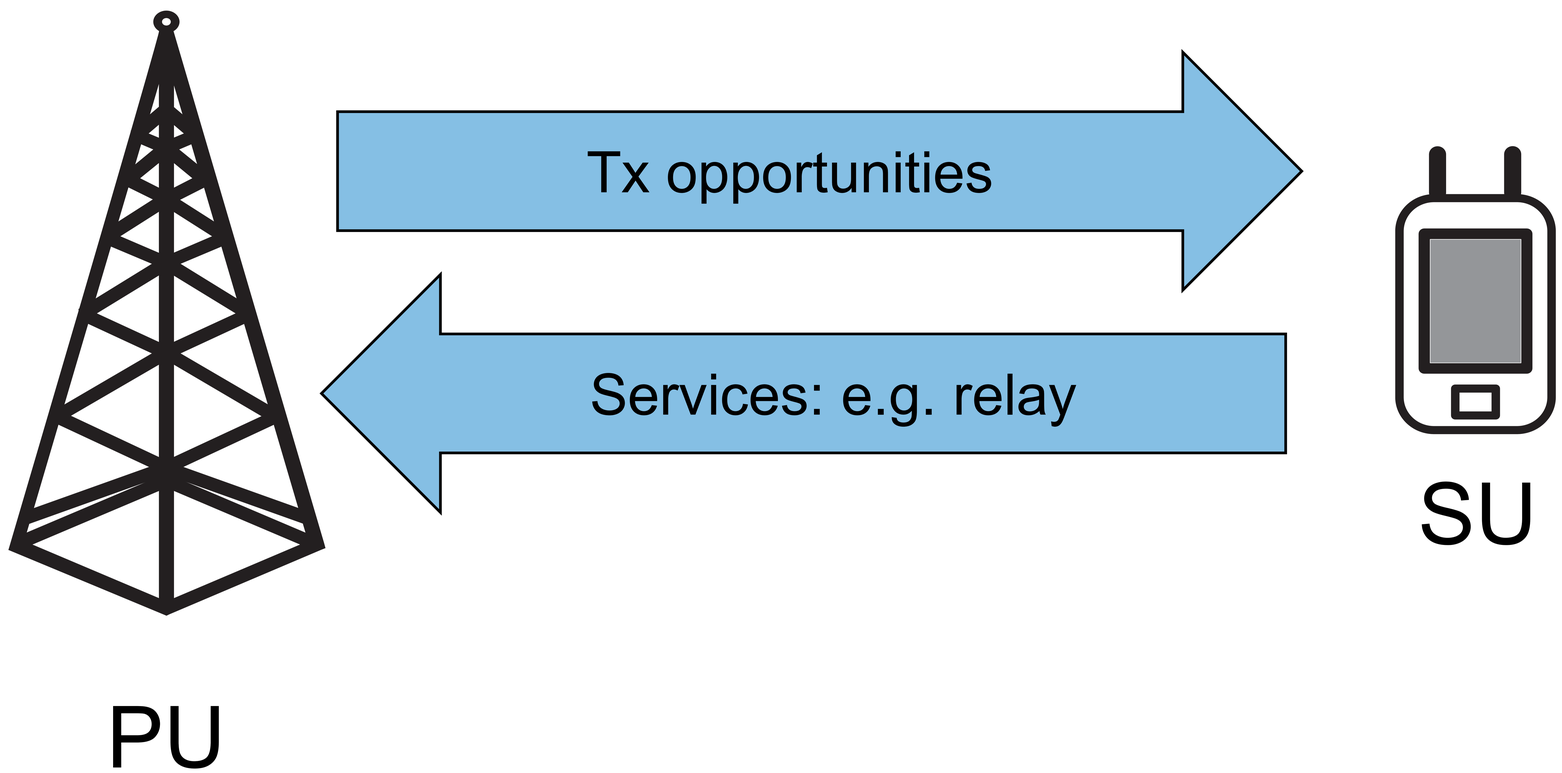
	Our work	[97]	[99]	[100]	[101]	[102]	[103]
Scope	Spec. trading	DSA and spec. trading	DSA	CSSA in imperfect info.	Self-org.	Game Th. DSA	Spec. auctions
Type of work	Survey	Survey	Book	Survey	Survey	Survey	Survey
Year	2013	2010	2008	2013	2013	2011	2012
Number of references	98	36	<30	15	15	74	32
Economic objectives	**E**	X	I	X	X	**E**	**E**
CSSA	**E**	X	**E**	**E**	**E**	M	M
Real-time variations	**E**	X	X	X	I	I	M
Imperfect information	**E**	I	**E**	**E**	I	**E**	M
Spatial reuse	**E**	X	X	M	X	X	**E**
Heterogeneity	**E**	M	M	X	I	M	M
Formulation frameworks	**E**	**E**	**E**	**E**	M	**E**	M
Market forms	**E**	**E**	**E**	X	X	X	M
Implementation issues	**E**	M	**E**	**E**	**E**	I	**E**
Protection against malfunctions	**E**	**E**	**E**	X	X	**E**	**E**

Future work on spectrum trading

- Bargaining
- Contract Theory

Future work on spectrum trading (II)

Cooperative Spectrum Sharing



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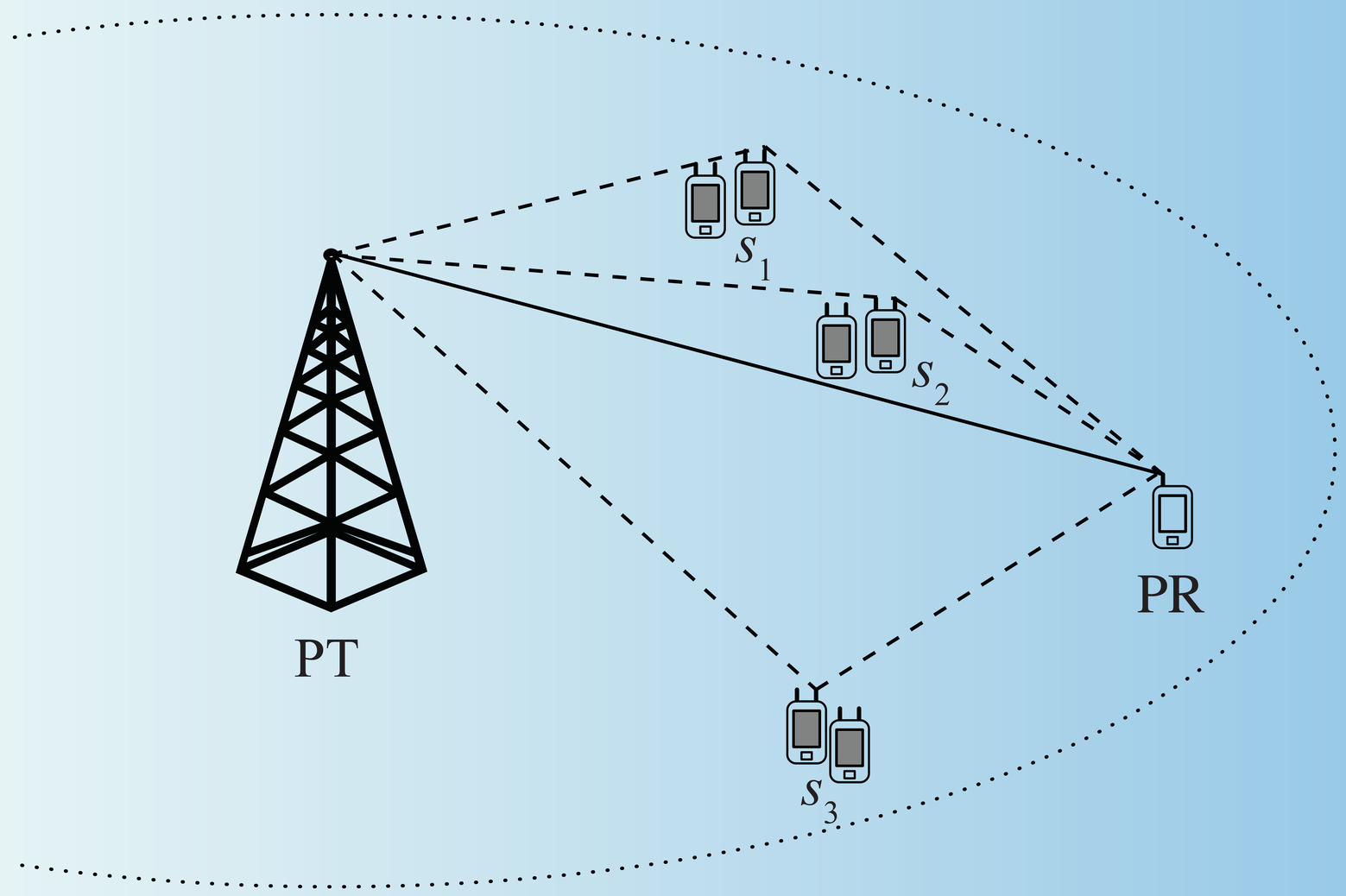
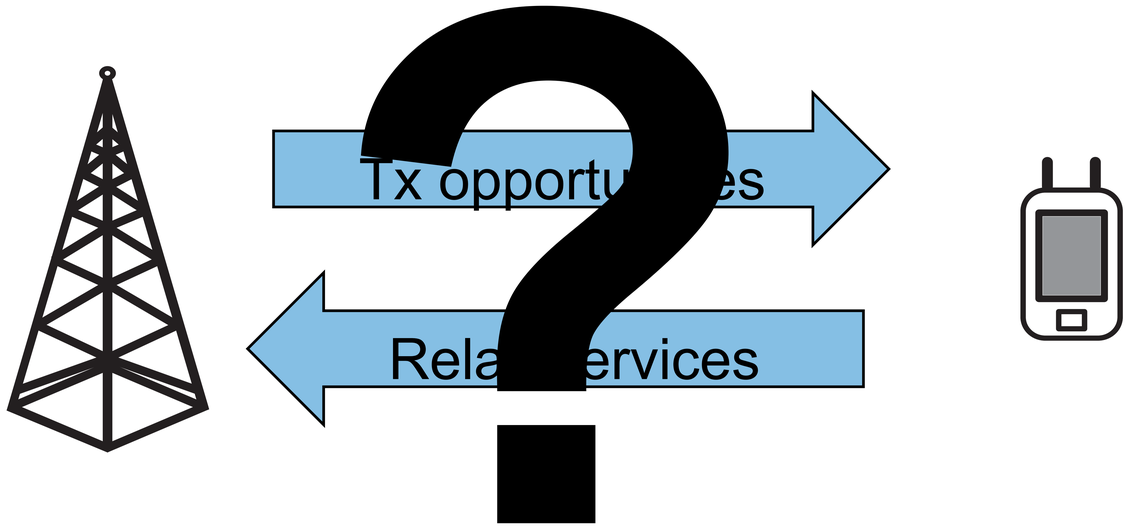


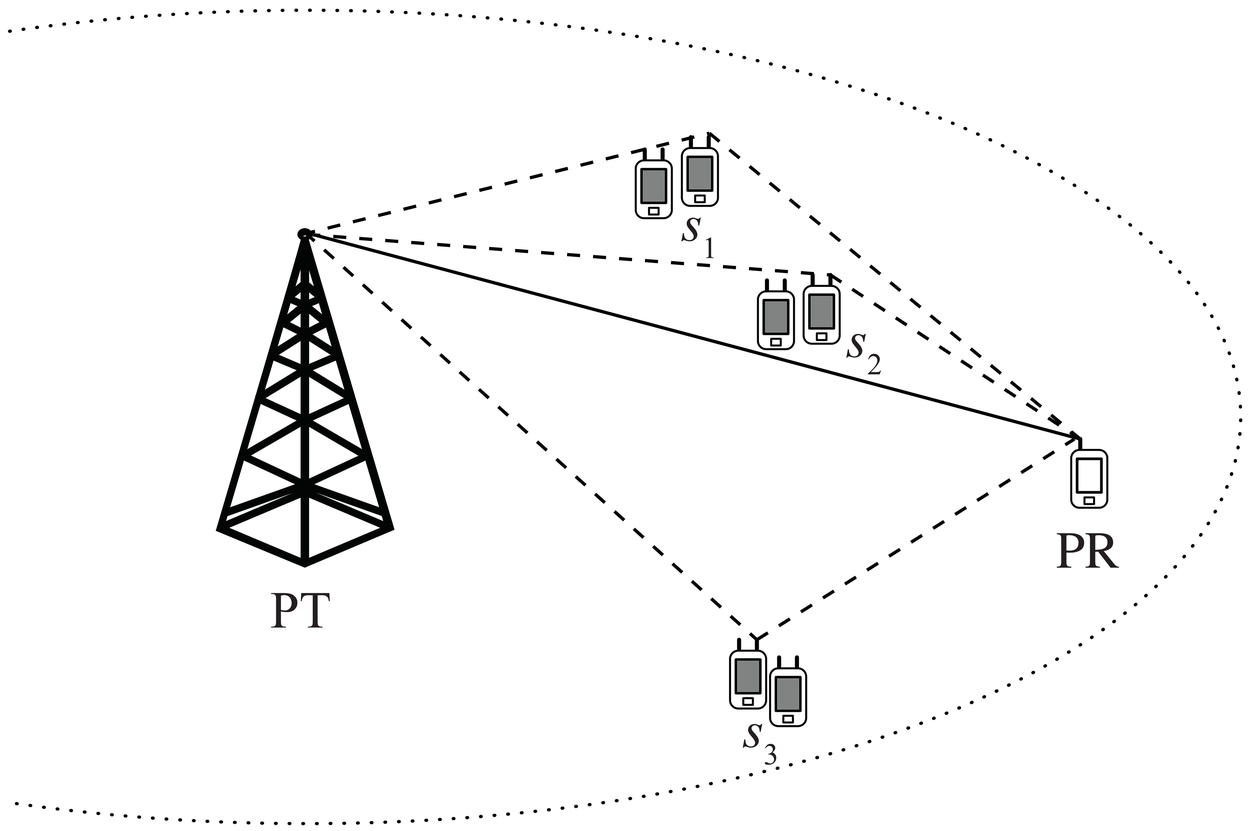
A Superprocess with Upper Confidence Bounds for Cooperative Spectrum Sharing

Motivation



Exploration – exploitation trade-off

Contribution



Multi-armed bandits (MABs)

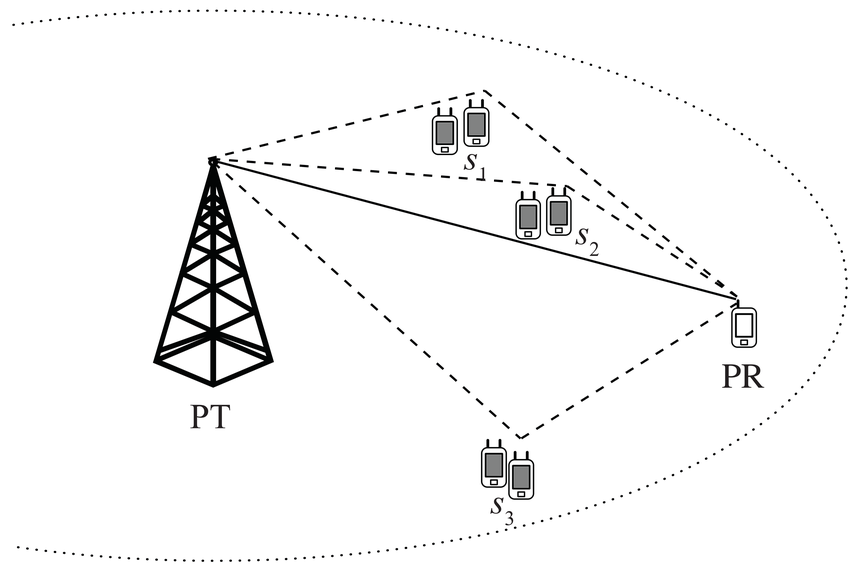
MDP / Markovian MAB

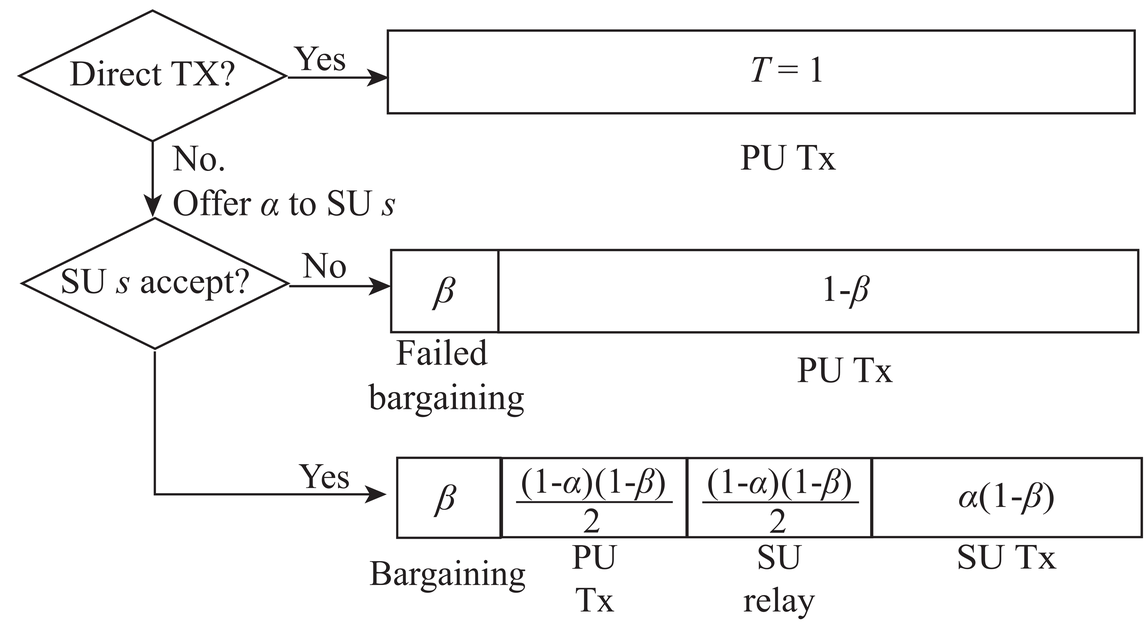
+

Stochastic MAB

→ Two heuristic algorithms

Problem formulation





- Action: $u = (s, \alpha)$
- Reward: $W^{(n)}(s, \alpha) = \begin{cases} (1-\beta)(1-\alpha)\log(\Gamma_s^{(n)}) & \text{if } \alpha \text{ is accepted} \\ (1-\beta)\log(1+\Gamma_{P,P}^{(n)}) & \text{otherwise} \end{cases}$
- Objective: min $r^{(n)} = \max_u \mathbb{E}\left[\sum_{k=1}^{n}\left(W^{(k)}(u) - W_\pi^{(k)}\right)\right]$

Problem formulation: the reward

$$W^{(n)}(s,\alpha) = (1-\beta)(1-\alpha)\underline{\log(\Gamma_s^{(n)})}$$

$\sim$

$N(\mu_{\gamma_s}, \sigma_{\gamma_s})$

Stochastic MABs

$\arg\max_s J_s^{(n)}$

if α is accepted

$\sim$

Deterministic observation

Superprocess

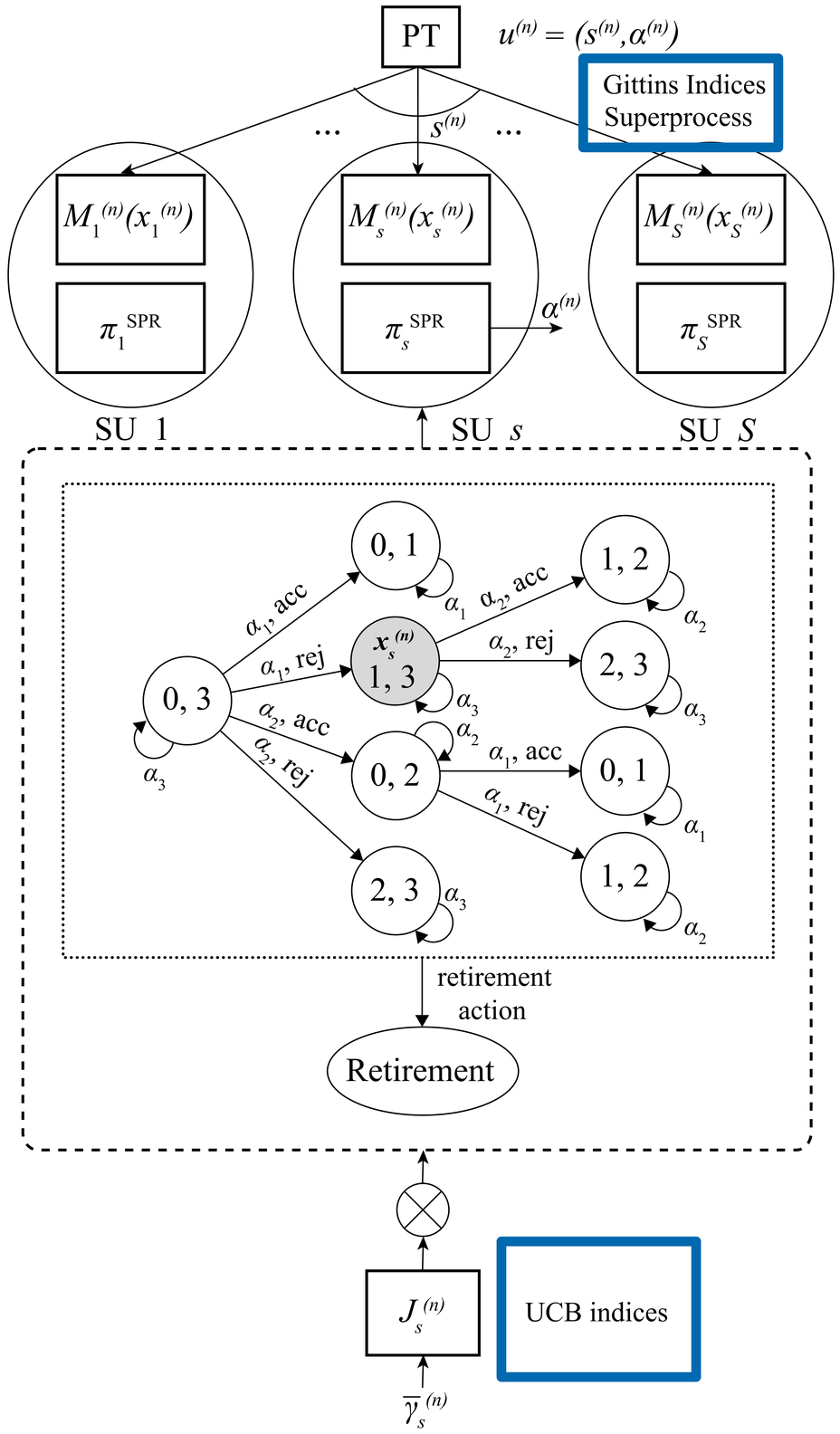
$\arg\max_s M_s^{(n)}(x)$

Gittins indices

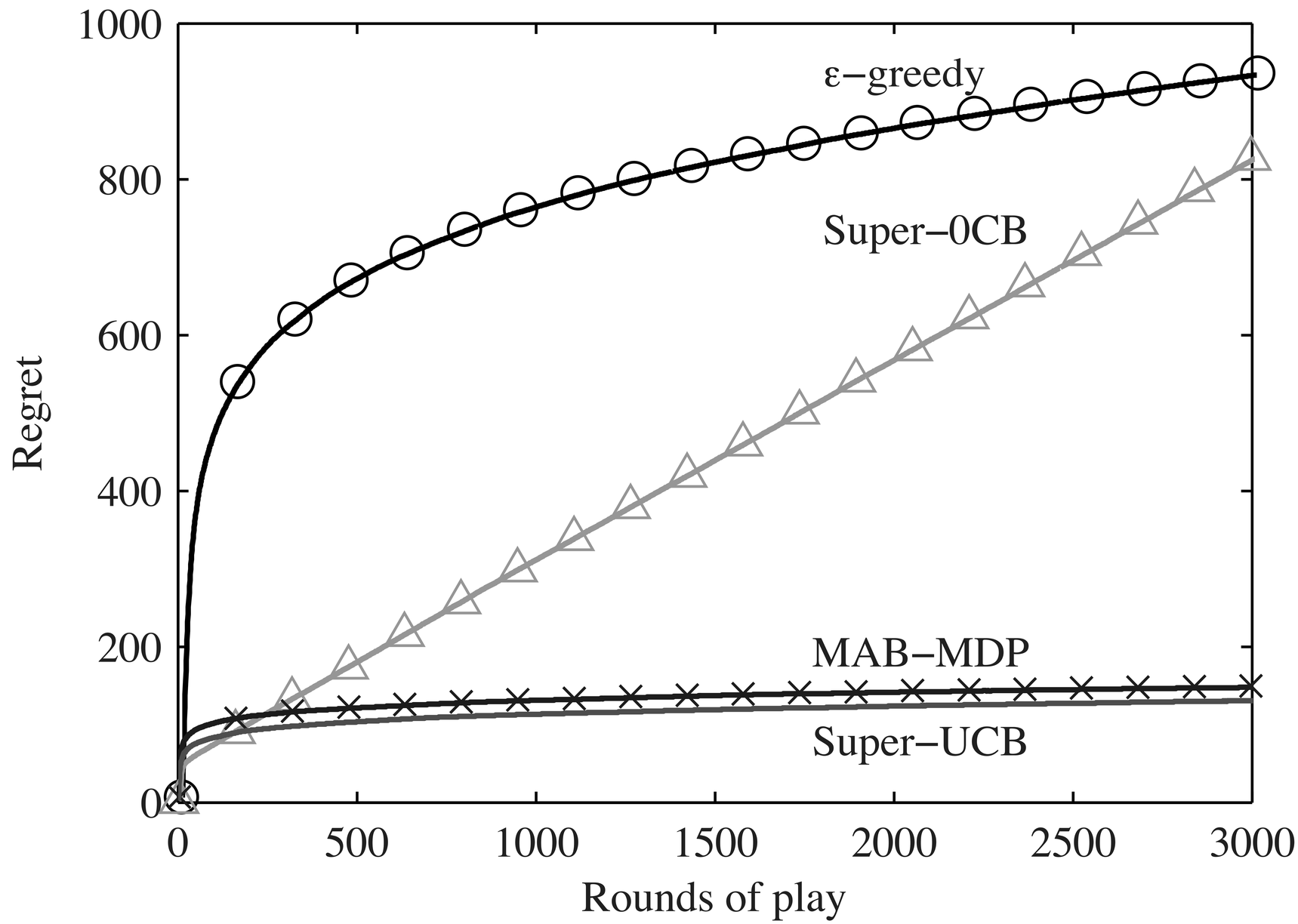
π_s^{SPR}

$$V_s^{(n)}(x,M) = \max\left\{M, \max_{\alpha_a \in \mathcal{A}} \sum_{x' \in \mathcal{X}_s} P_s(x,x',\alpha_a)\left(\phi_s^{(n)}(x',\alpha_a) + \delta V_s^{(n)}(x',M)\right)\right\}$$

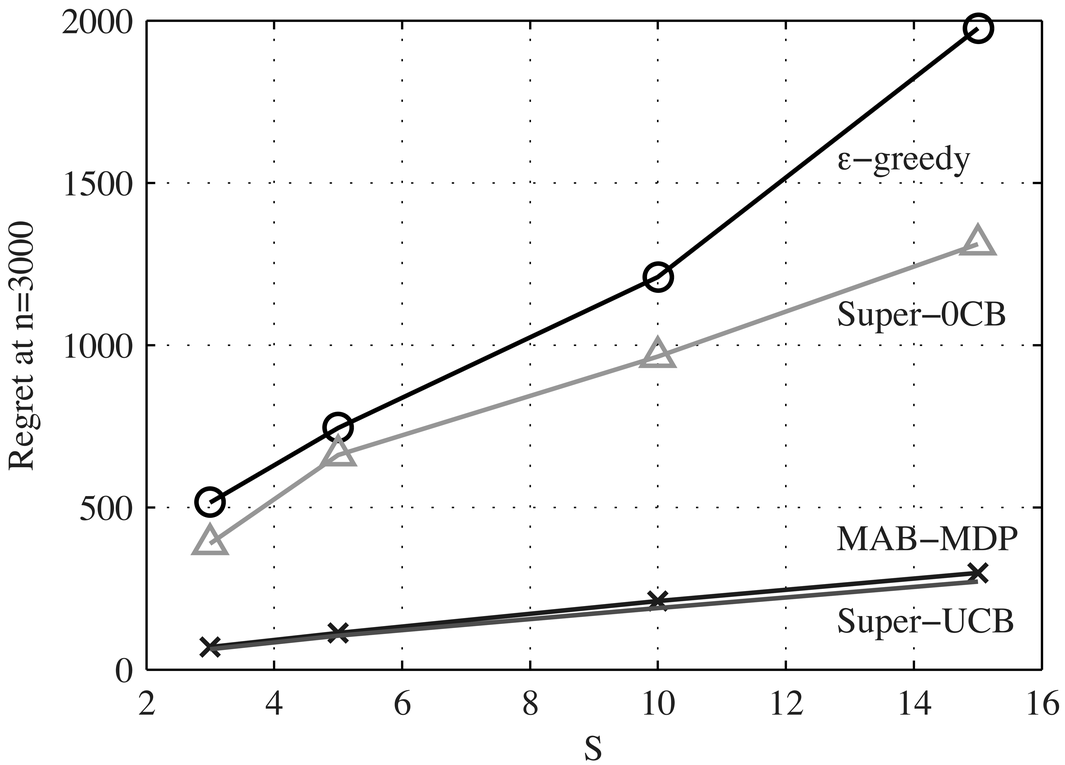
Super-UCB


PT
$u^{(n)} = (s^{(n)}, \alpha^{(n)})$
Gittins Indices Superprocess
$s^{(n)}$
$M_1^{(n)}(x_1^{(n)})$
π_1^{SPR}
$M_s^{(n)}(x_s^{(n)})$
π_s^{SPR}
$\alpha^{(n)}$
$M_S^{(n)}(x_S^{(n)})$
π_S^{SPR}
SU 1
SU s
SU S
0, 3
0, 1
1, 2
$x_s^{(n)}$
1, 3
2, 3
0, 2
0, 1
1, 2
2, 3
α_1, acc
α_1, rej
α_2, acc
α_2, rej
α_1, acc
α_1, rej
α_1
α_2
α_3
retirement action
Retirement
$J_s^{(n)}$
UCB indices
$\bar{\gamma}_s^{(n)}$

Results: low-regret MAB-MDP & Super-UCB

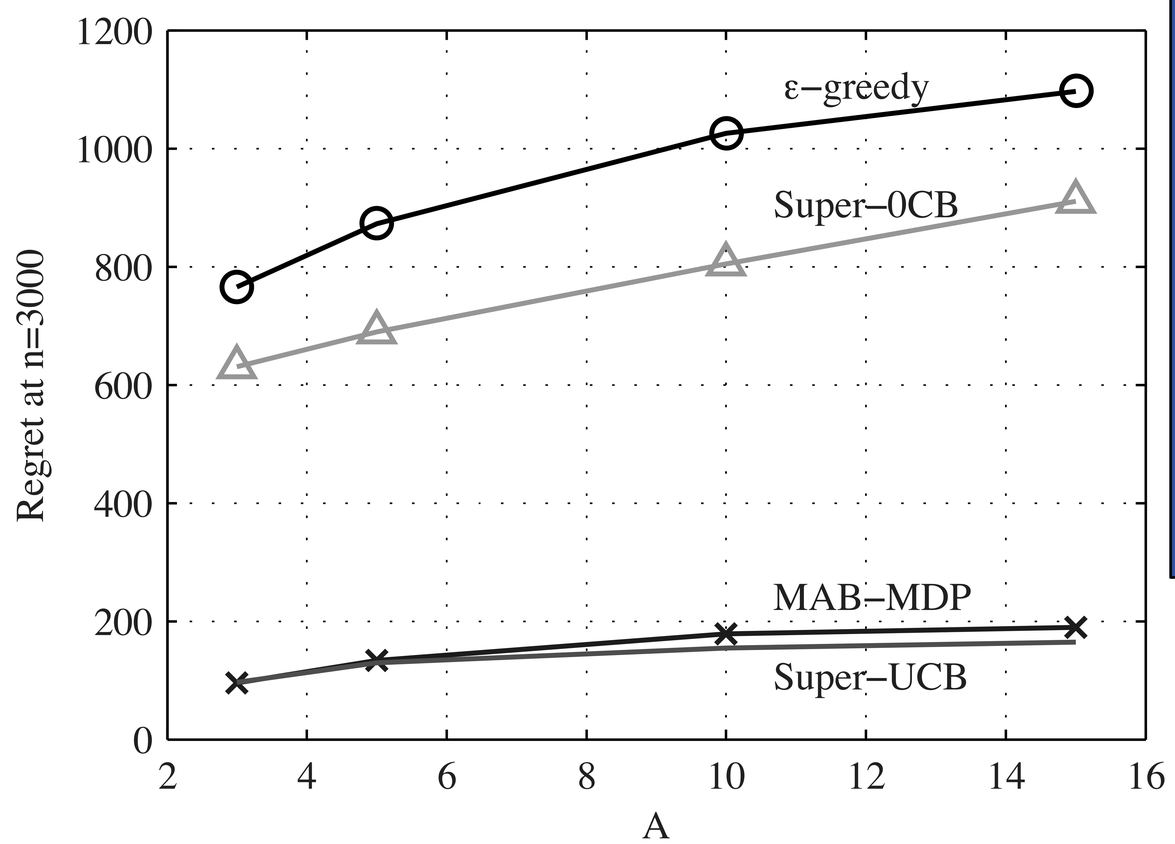


Results(II): scalability



Vs SUs

Vs offers



Novelty of our work

Unlike ours, previous works consider:

- More information about the scenario
- Cooperative behaviors
- Stochastic optimization: no learning
- Broadcast communication: more strategy from SUs

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INDEX

I. Opportunistic Spectrum Access

- Background Detection of Primary User Activity
- Bandwidth Reservation as a Coexistence Strategy
- Uncertainty-Aware OSA in Coexistence-Friendly Systems

II. Automated Spectrum Trading

- The Big Picture
- A Superprocess with Upper Confidence Bounds for Cooperative Spectrum Sharing

Final Remarks

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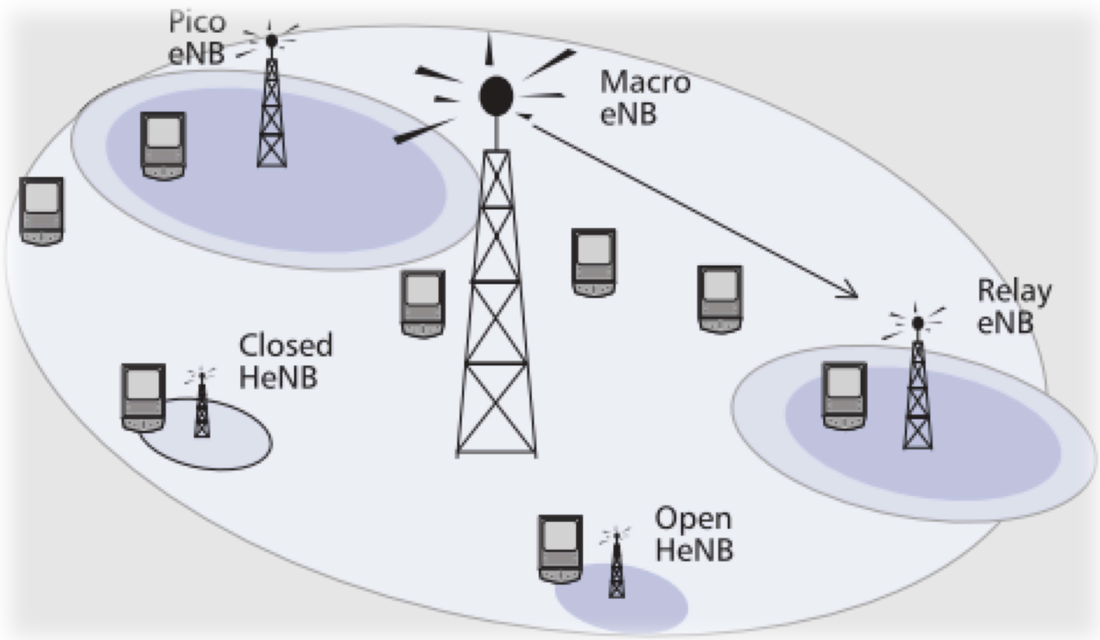
Final Remarks

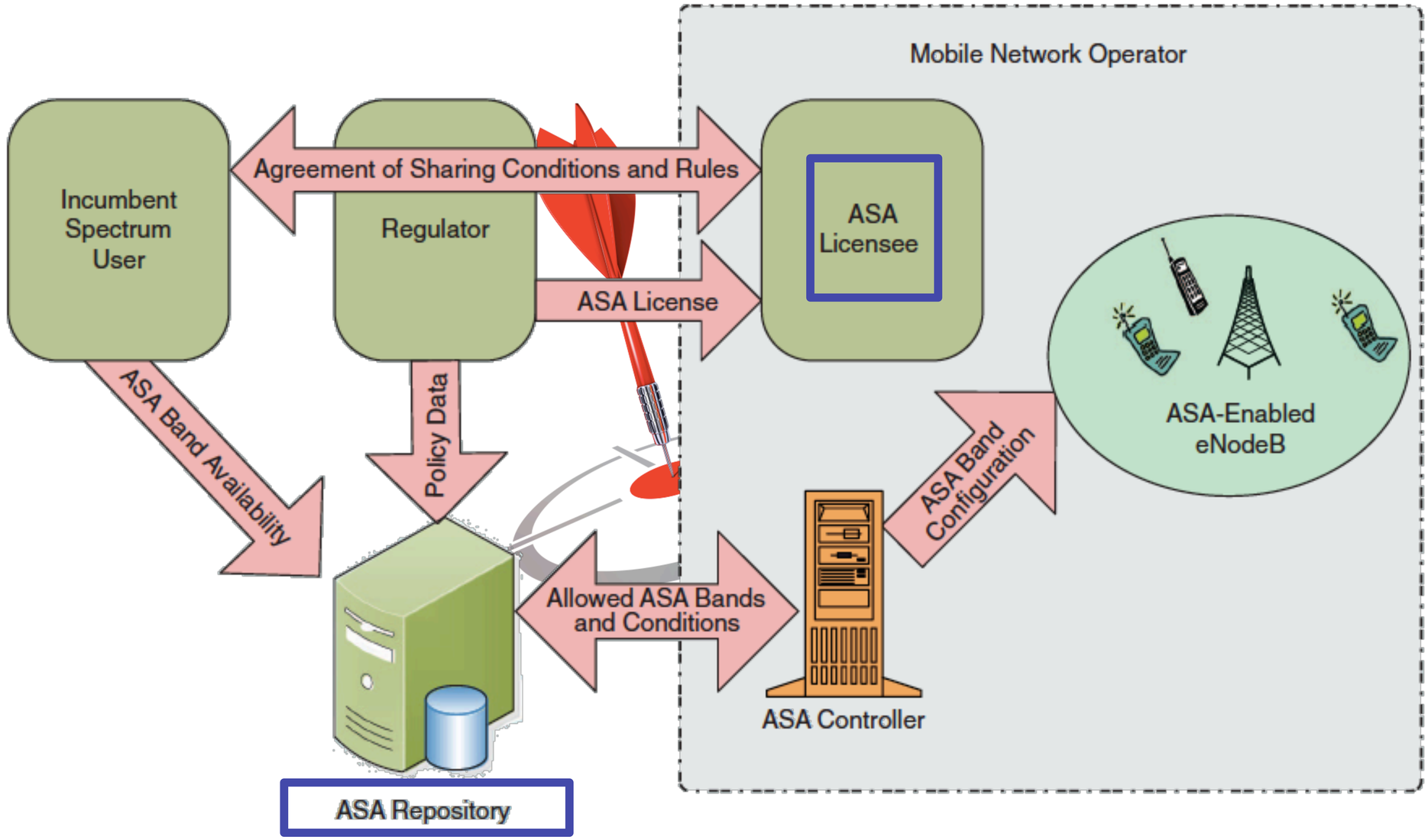
- Implications
- Future Work

Relevance of the thesis

CTIA
The Wireless Association®



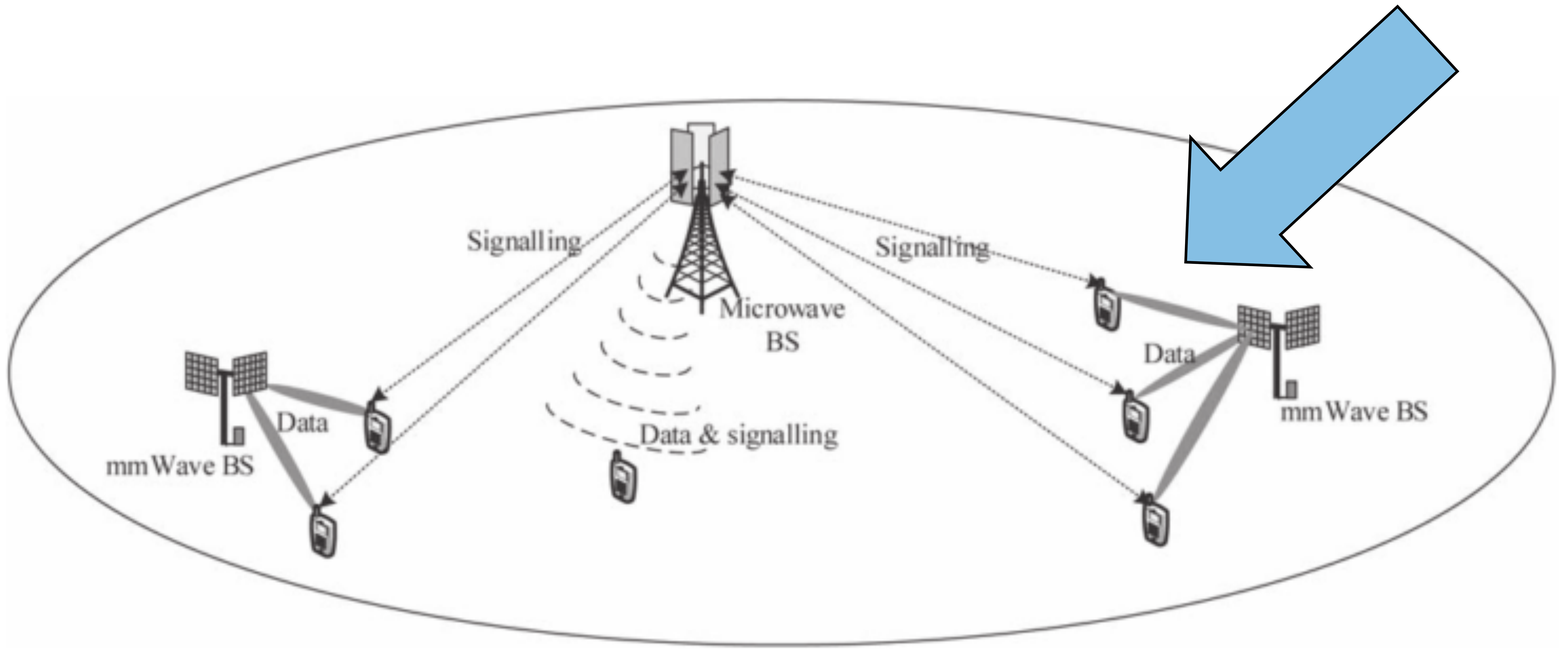
Future work: improve sensing accuracy



Future work on regulation issues

- Enforcement and monitoring
- Standardization
- Incentive mechanisms
- Micro-economic and long-term studies

Future work: millimeter-wave spectrum



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Thank you for your attention