New directions in cognitive radio and spectrum sharing

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presenting joint work with:
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U.C. Berkeley

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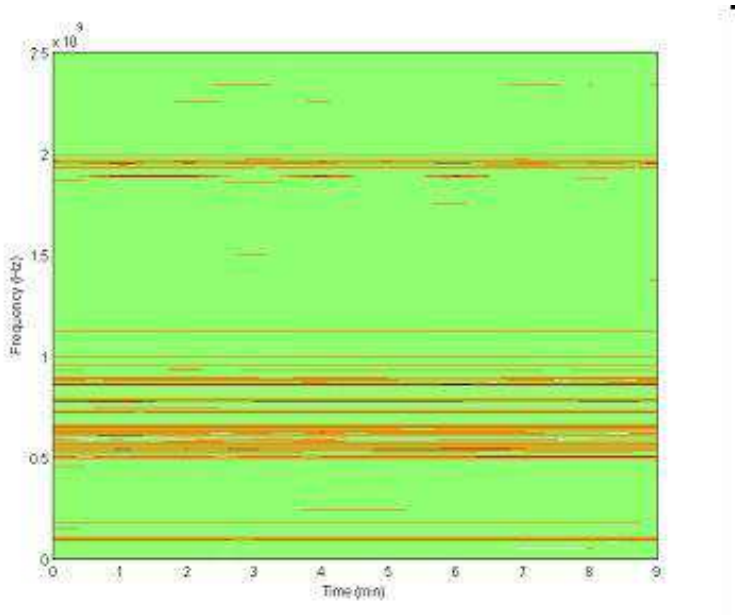
Spectrum, spectrum, everywhere, but . . .



- Available spectrum looks scarce.
- Measurements suggest the allocated spectrum is vastly underutilized.

Examine the problem from first principles

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In the future, technical solutions must bridge these scales!

Rethink *robustness architecture* to enable rate/reliability gains.

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Secondary has permission	**Markets**	**UWB**
Secondary must take care	**Denials**	**Opportunistic**

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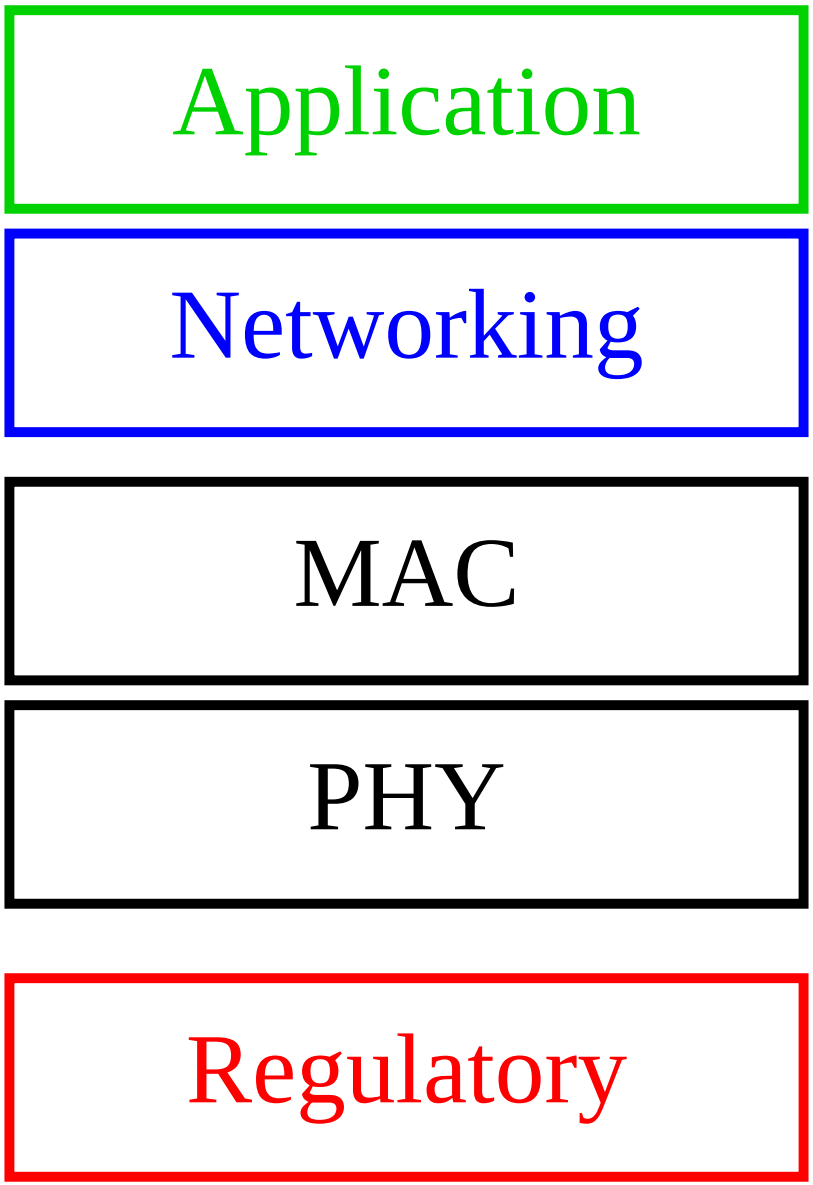
- Even future "licensed" systems will likely have opportunistic features.

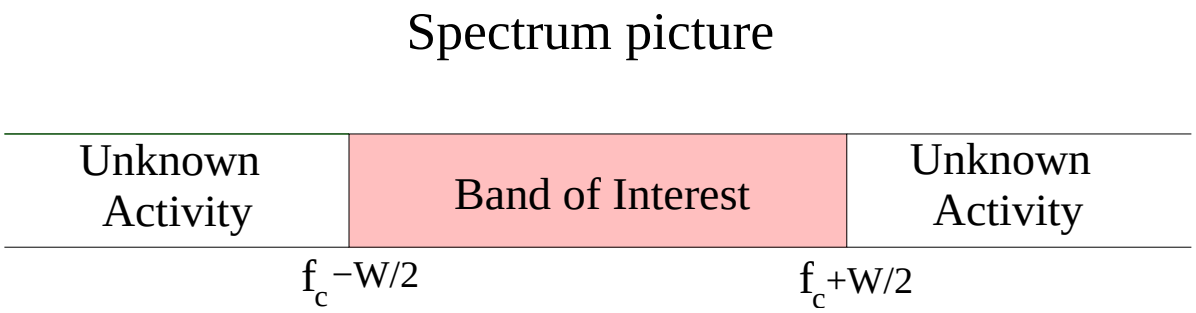
Layering revisited



Outline

- Motivation
- **Spectrum sensing: uncertainty is key challenge**
  - Single-detector sensitivity
  - Overhead-oriented metrics
  - Cooperation and multiband sensing
- Technical questions in regulation
  - A simple model of *a posteriori* enforcement
  - Do you know who I am?
- Conclusions

Sensing the primary's presence



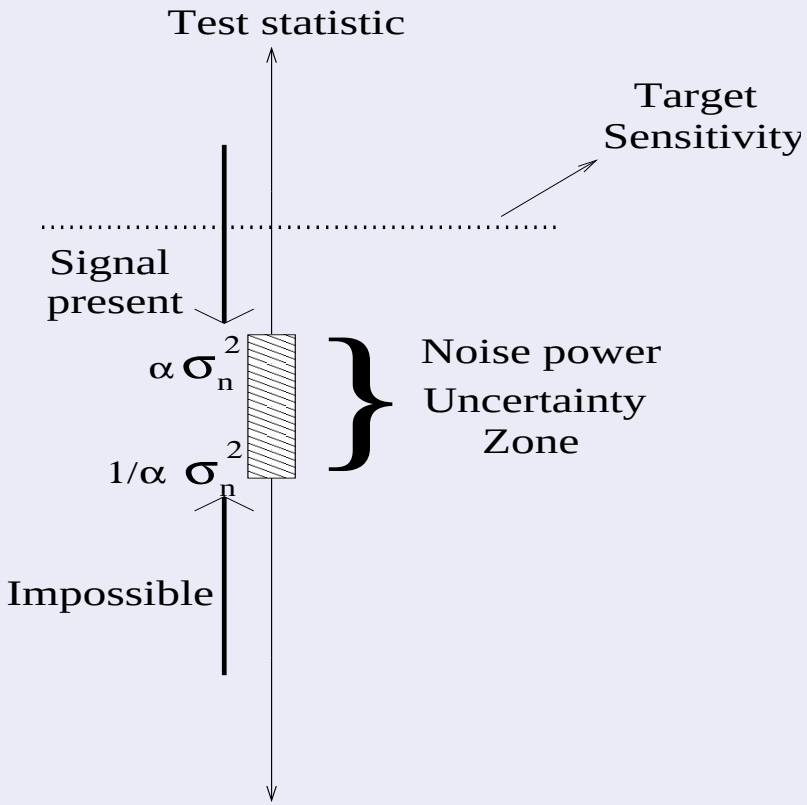
- Look for the primary in the 'band of interest'
- Within band model:
  - Primary signal: $X(t)$
  - Background and receiver noise: $W(t)$

Impact of uncertainty: energy detector

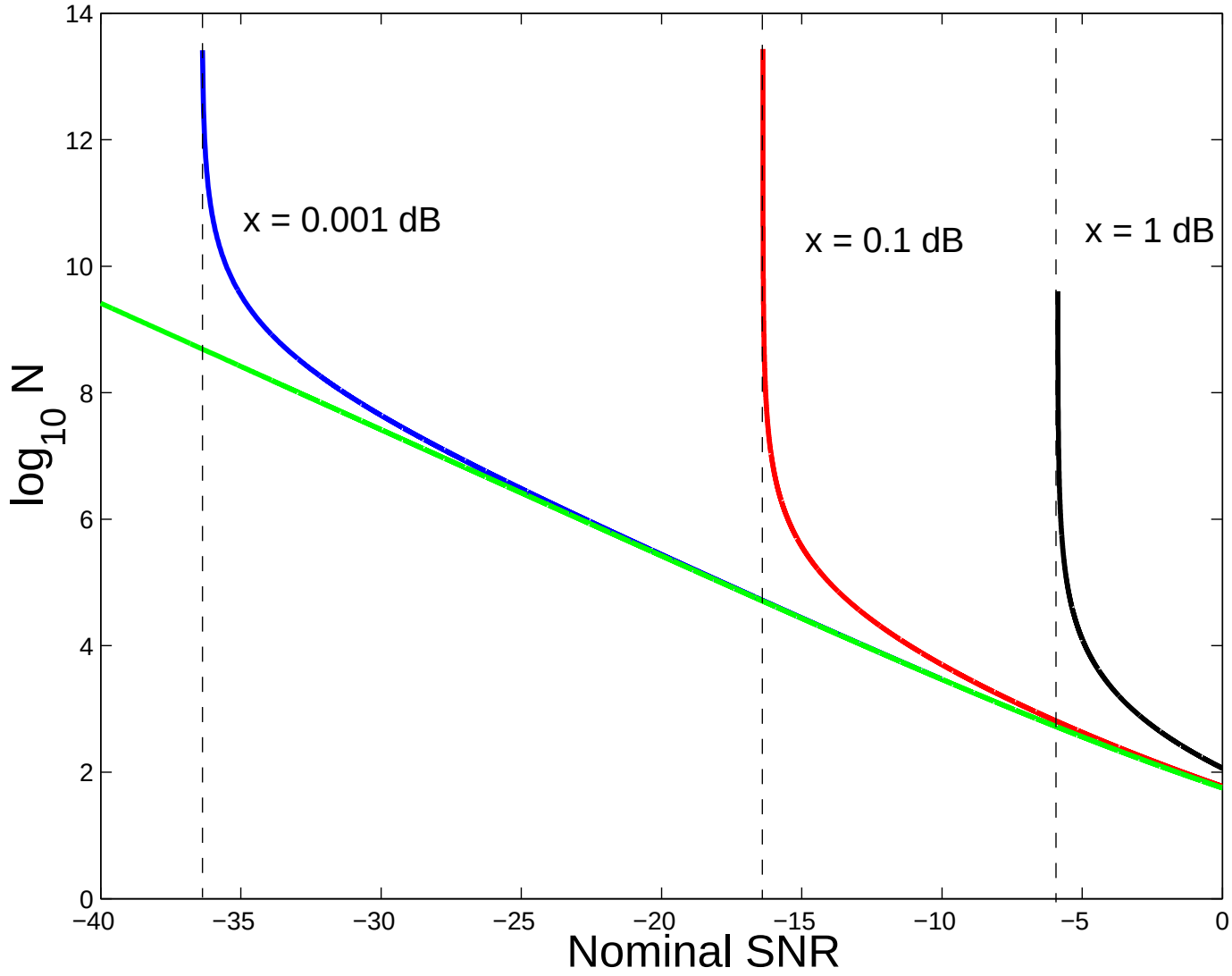
- Actual noise power, $\sigma_a^2 \in [\frac{1}{\alpha}\sigma_n^2, \alpha\sigma_n^2]$
- If

$$\begin{aligned} P + \sigma_a^2 &\leq \alpha\sigma_n^2 \\ \Rightarrow P &\leq \frac{\alpha^2 - 1}{\alpha}\sigma_n^2 \end{aligned}$$

Energy detector fails to detect the signal



SNR wall for energy detector



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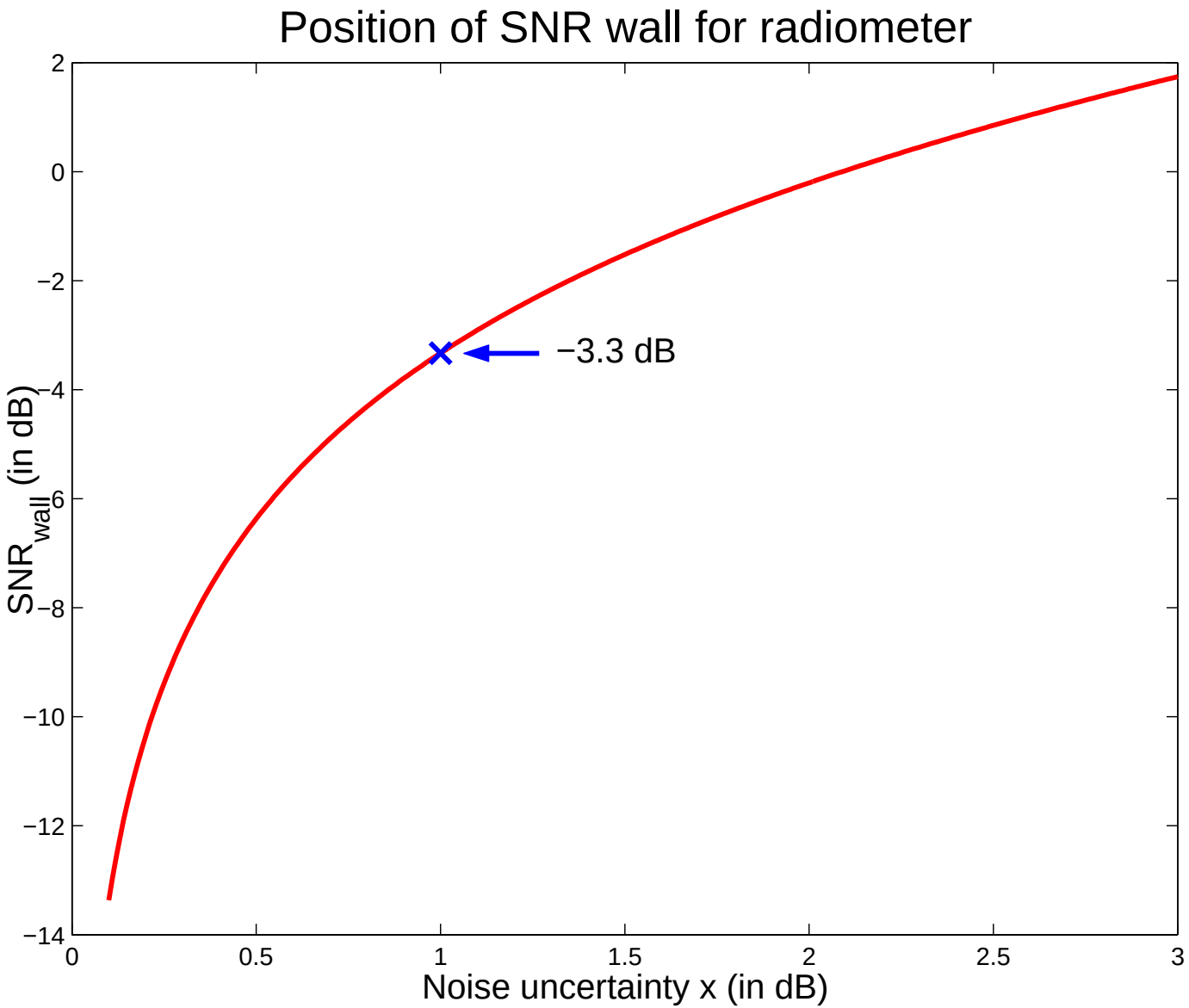
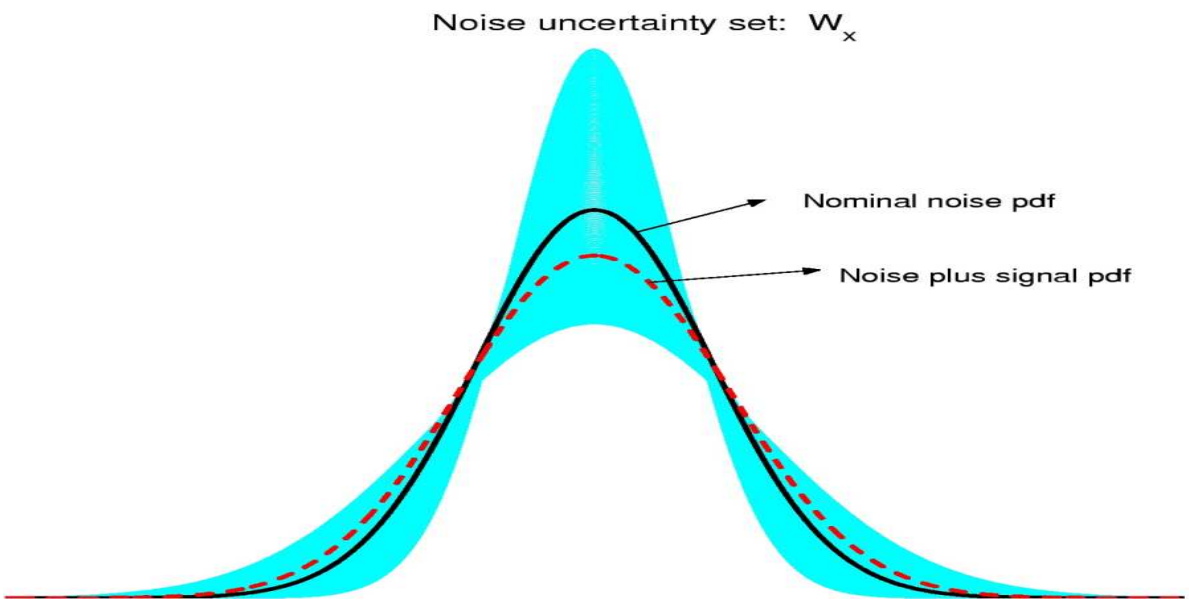


Primary structure vs environmental uncertainty



Primary	Detector	Key Uncertainty
Constellation	*any*	Noise distribution
Pilot	coherent	Phase-coherence time
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Pulse-shape	cyclostationary	Delay-coherence time

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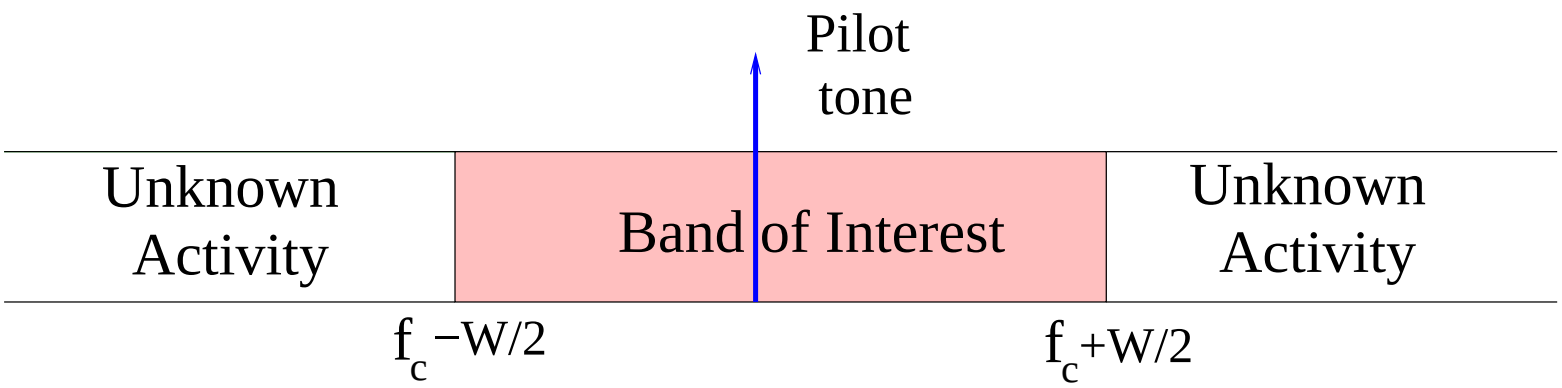
Spectrum picture



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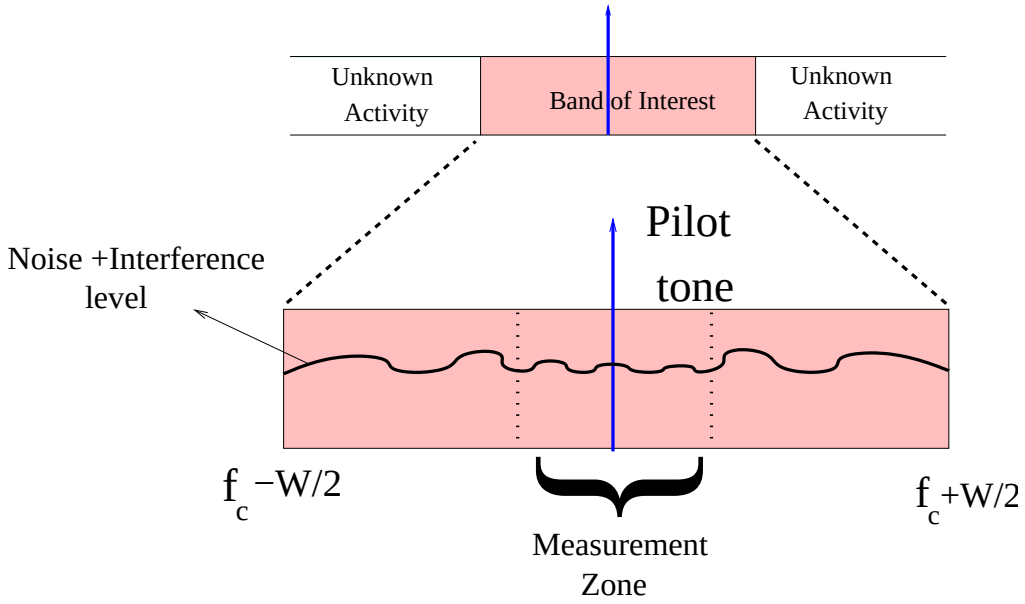

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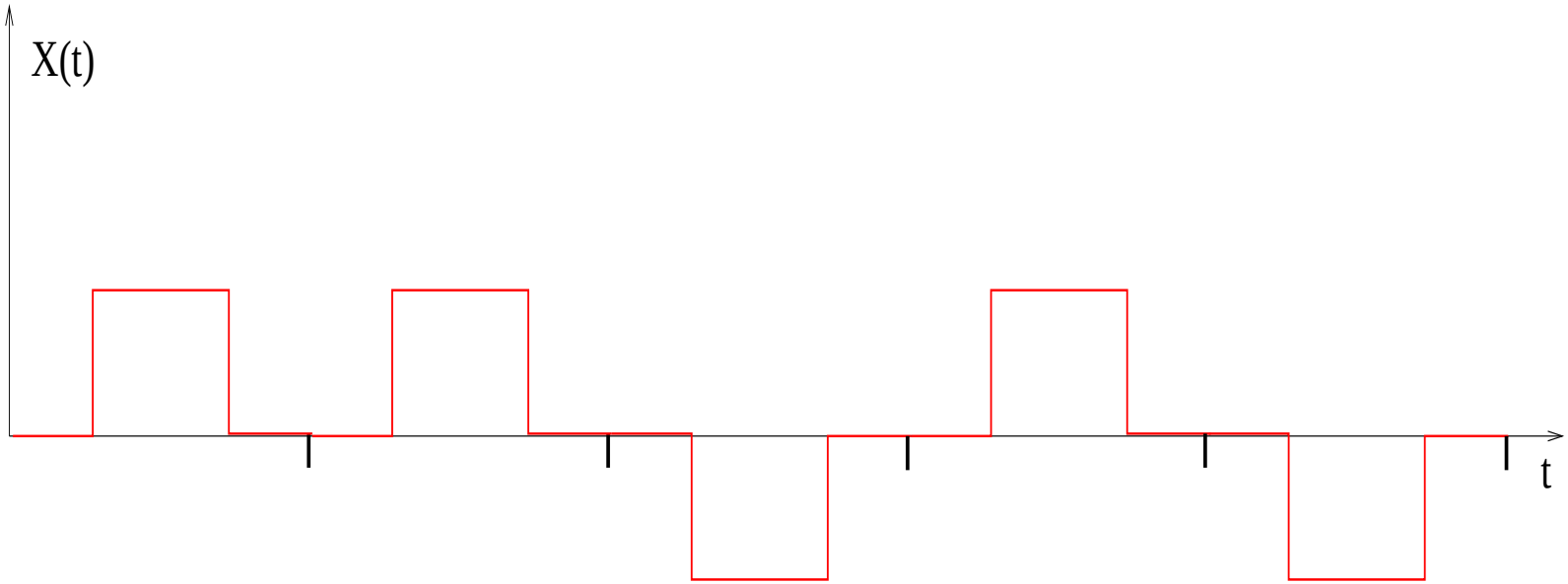

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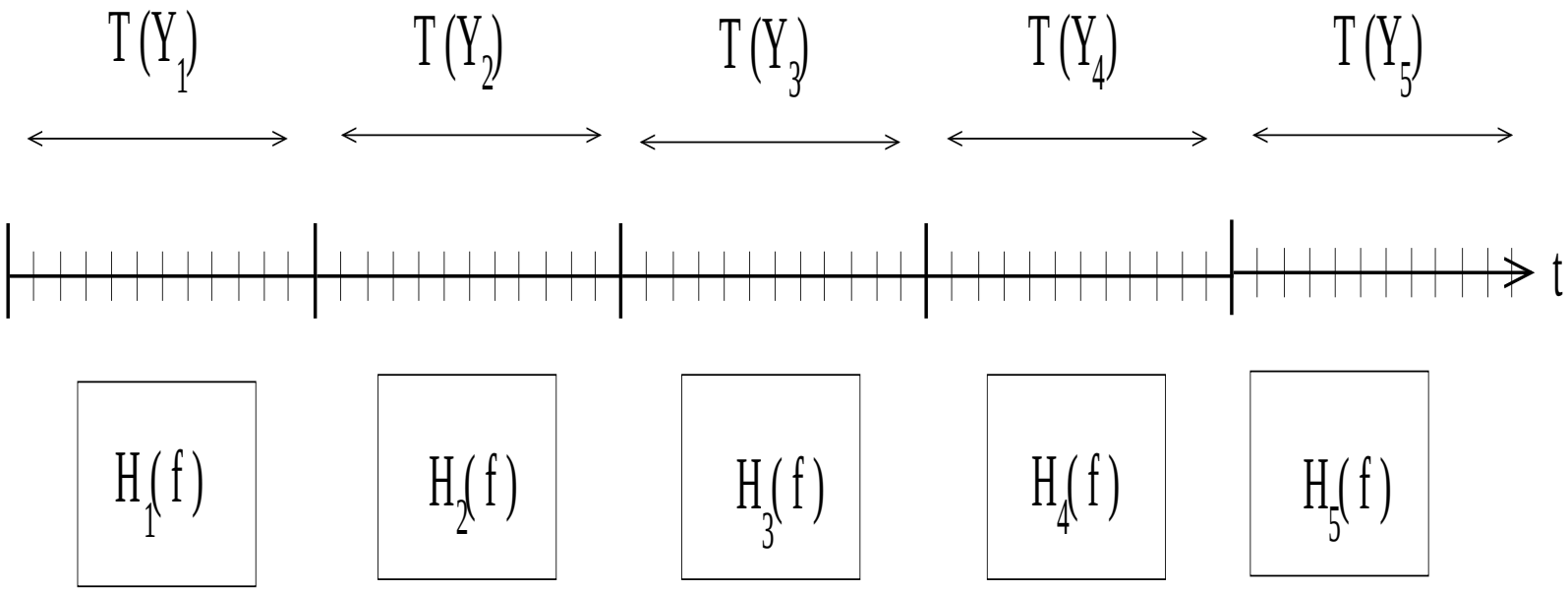

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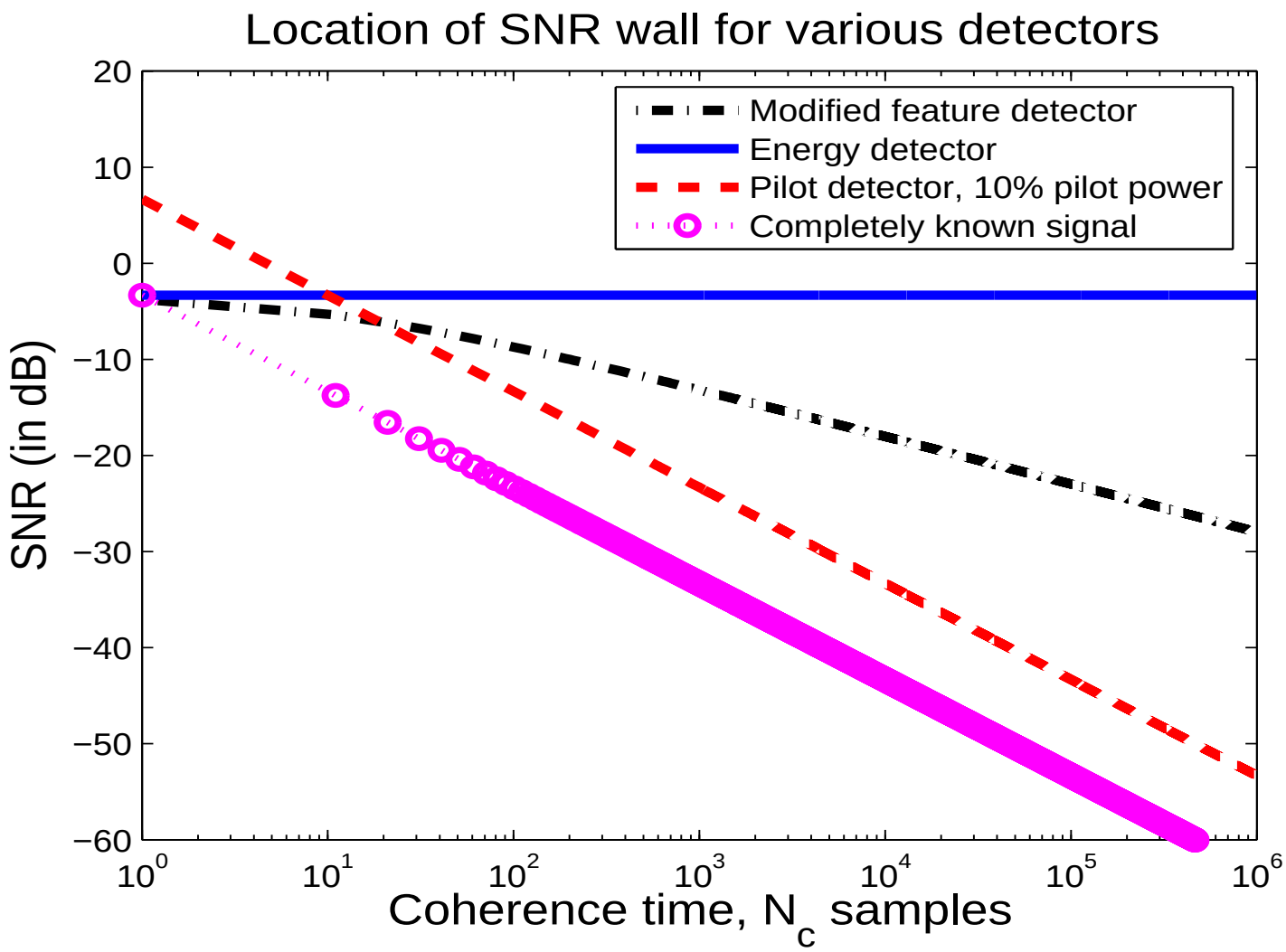
Detector robustness with coherence time



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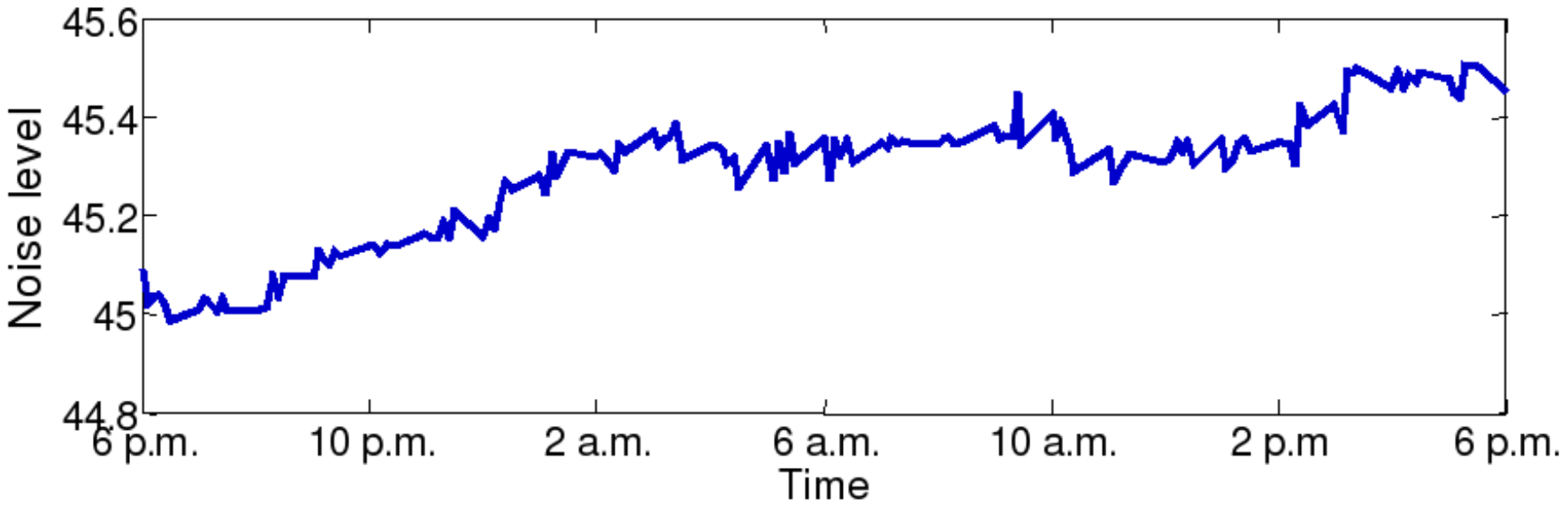

Noise levels move around over a day.

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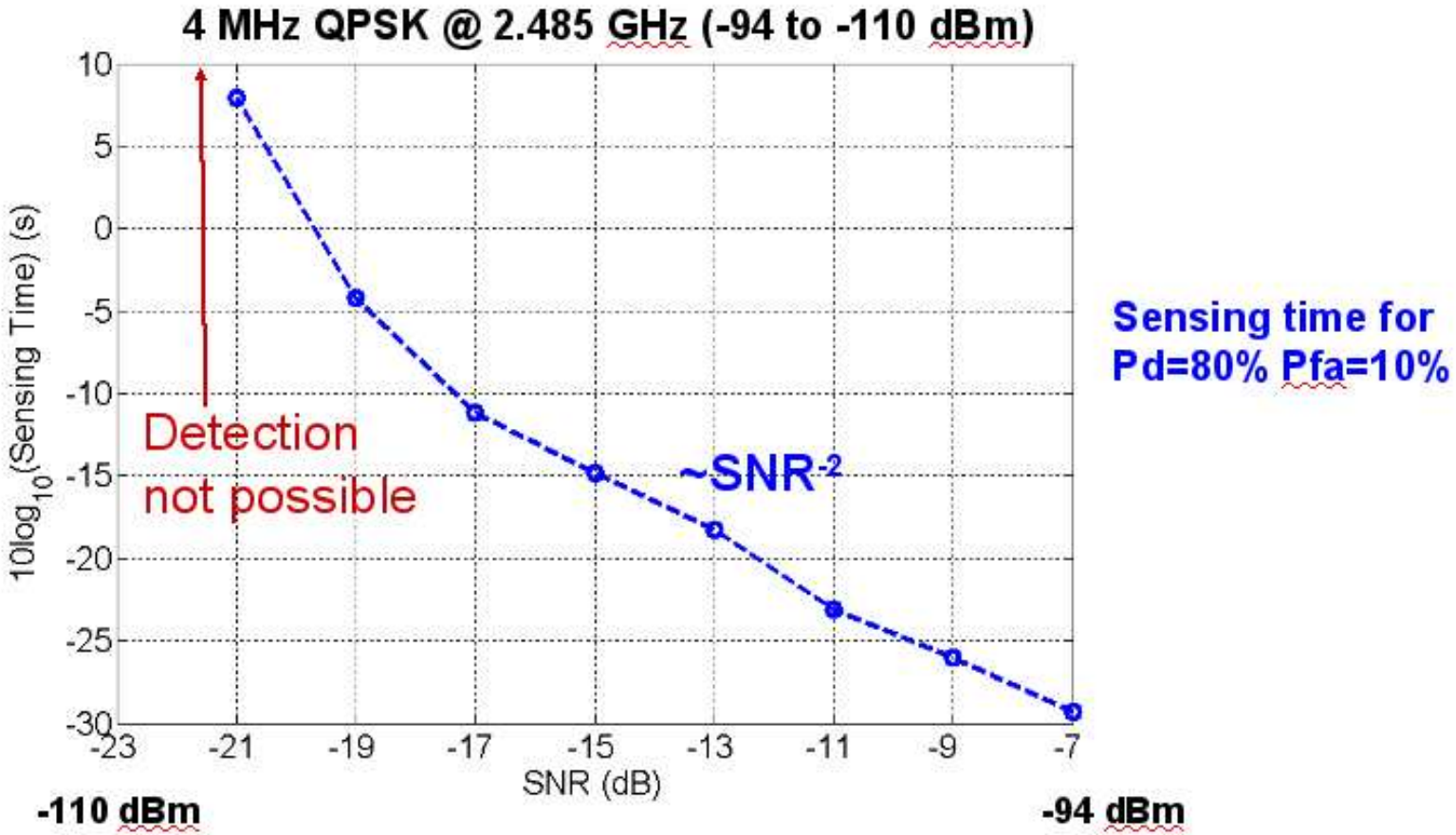

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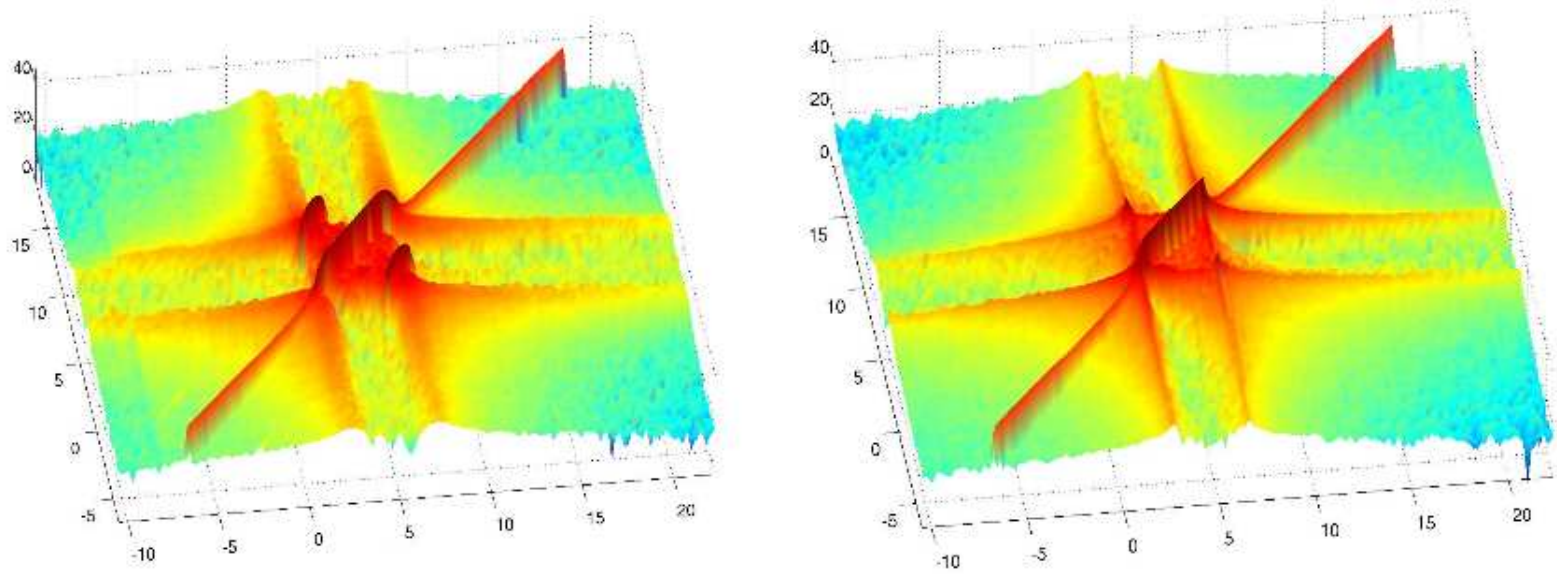

The spectral correlation function shows spectral redundancy in a transformed domain.

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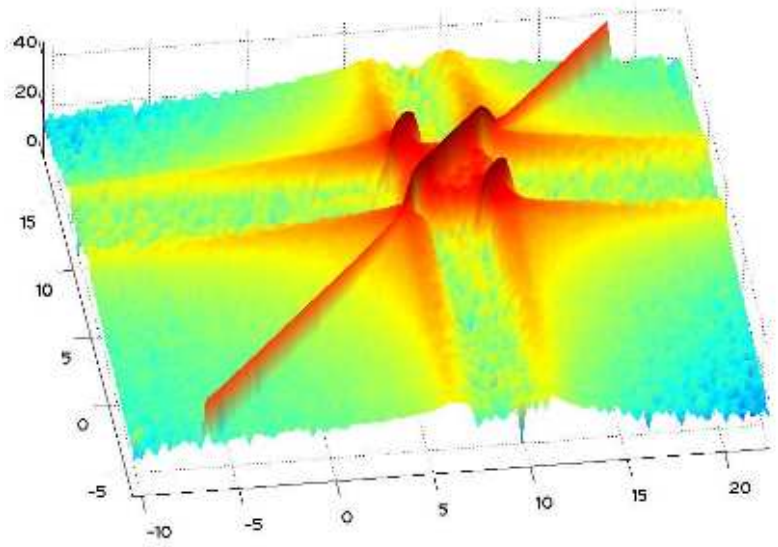
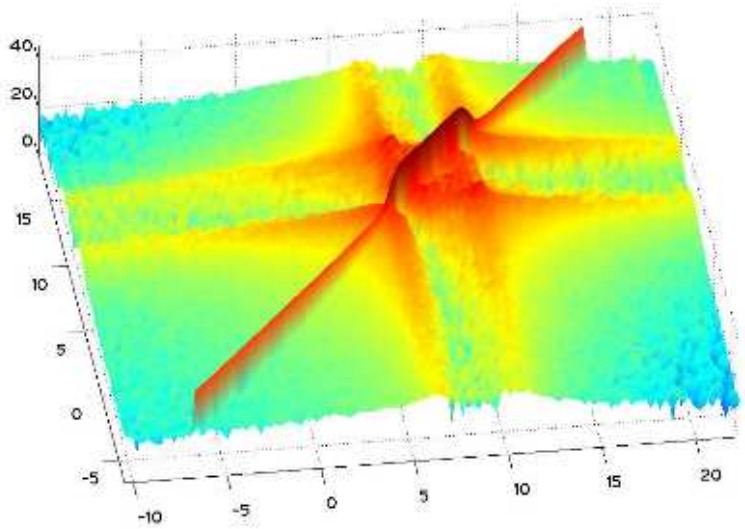
16000 spectral averages and perfect sampling



16000 spectral averages and 100 Hz sampling offset (25 ppm)



But this redundancy is blurred away by fast fading.

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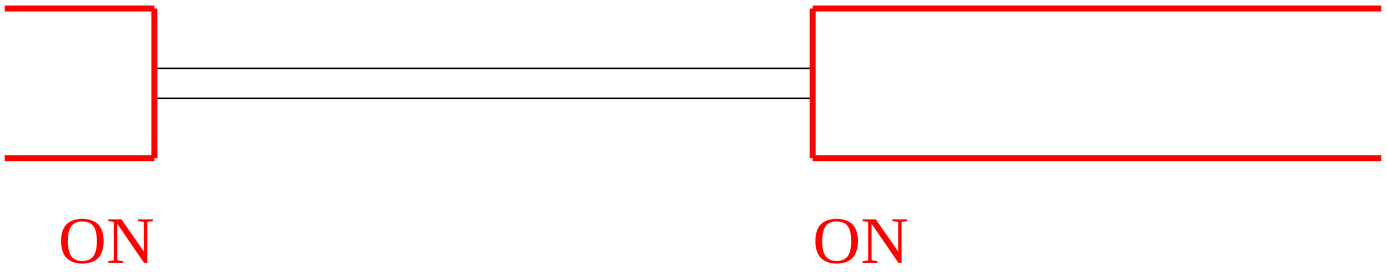
How to model the requirement of safety



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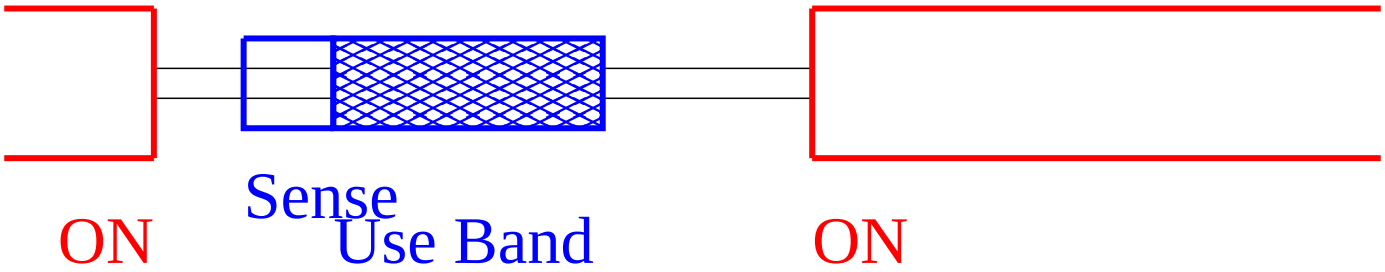

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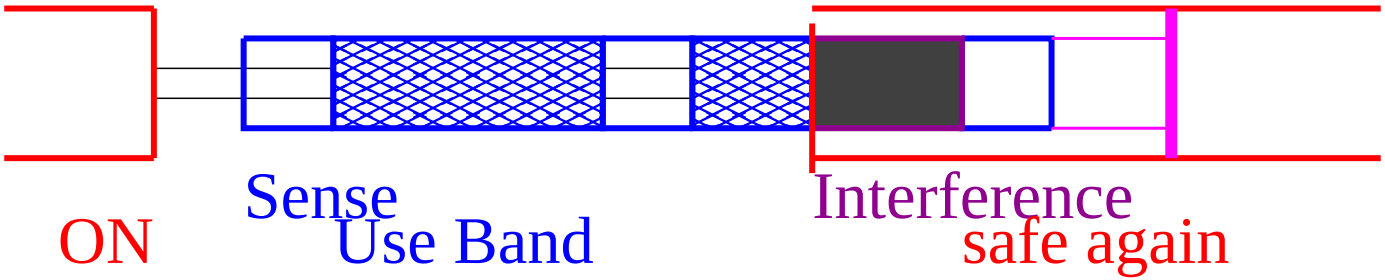

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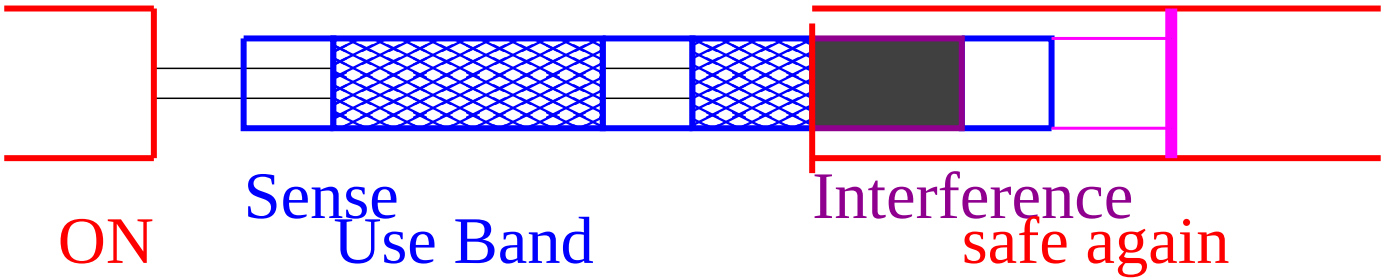
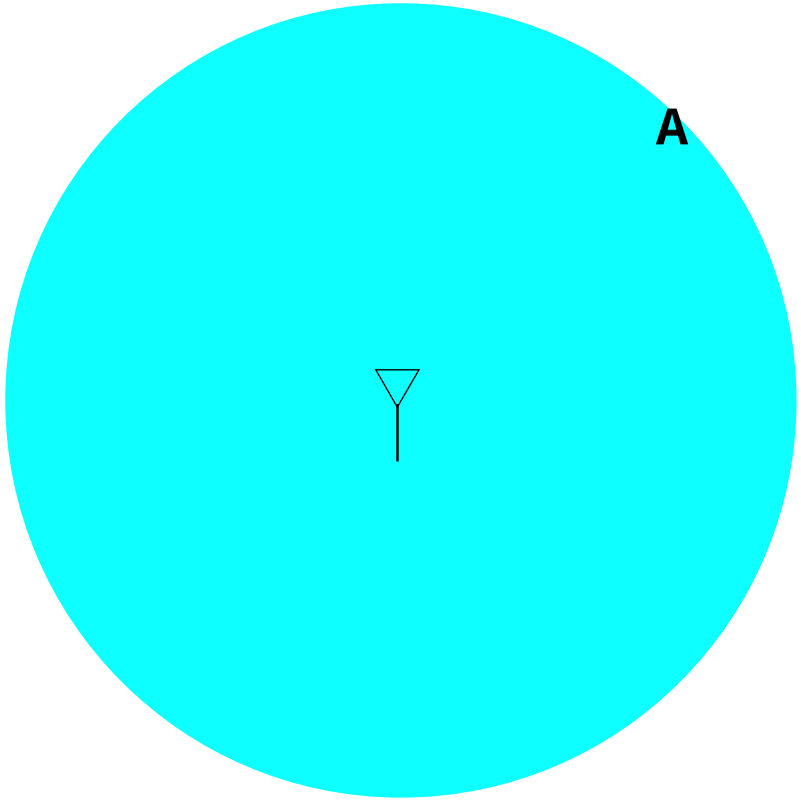
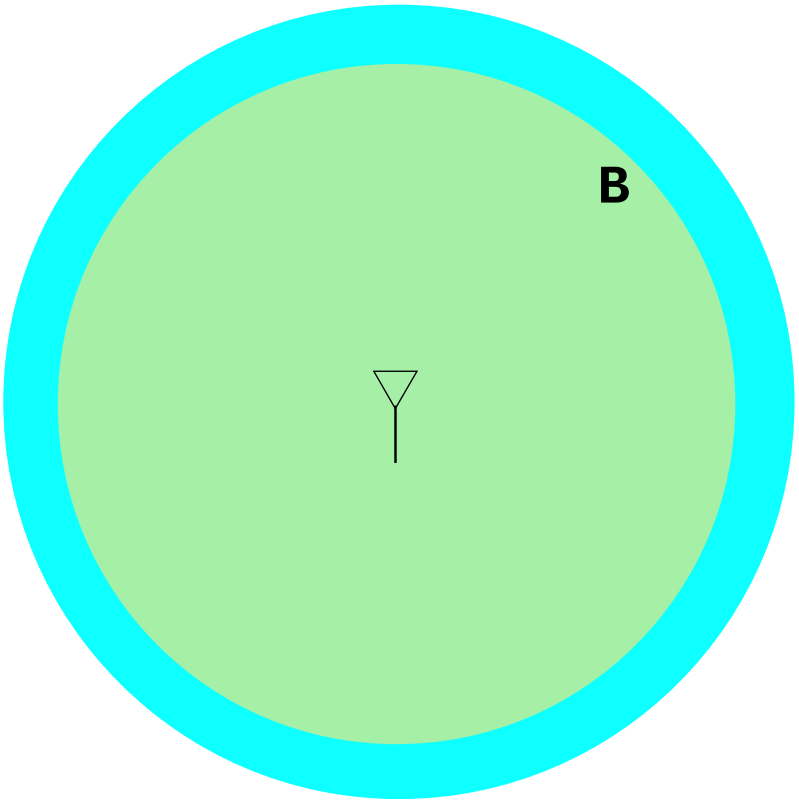


- Consider time-domain
- Can sense a whitespace and use it.
- Some interference unavoidable.
- Otherwise **fear** of return makes it impossible to recover.

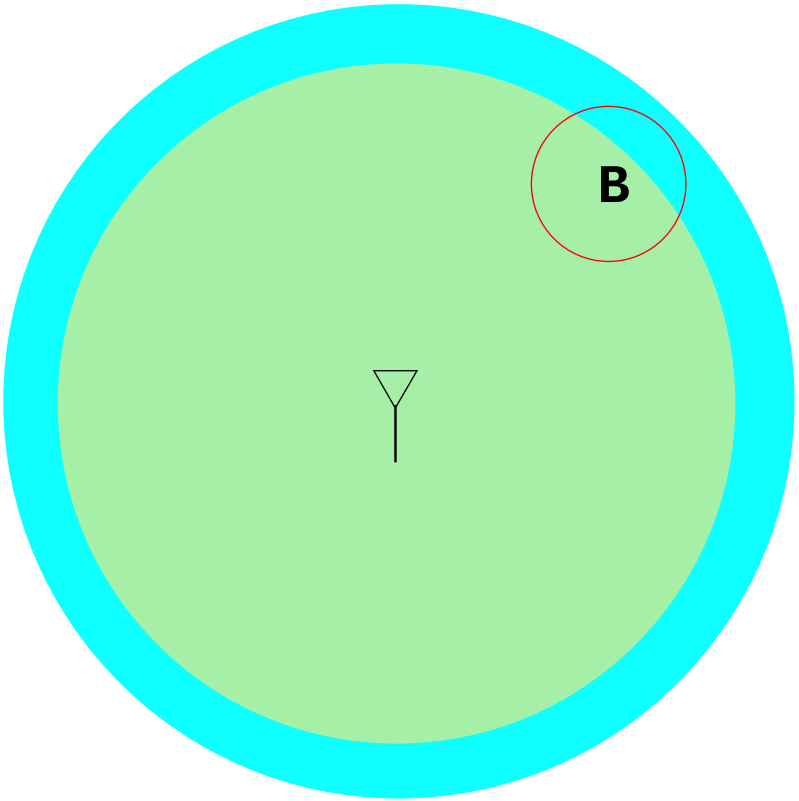
Consider strong primary transmitters



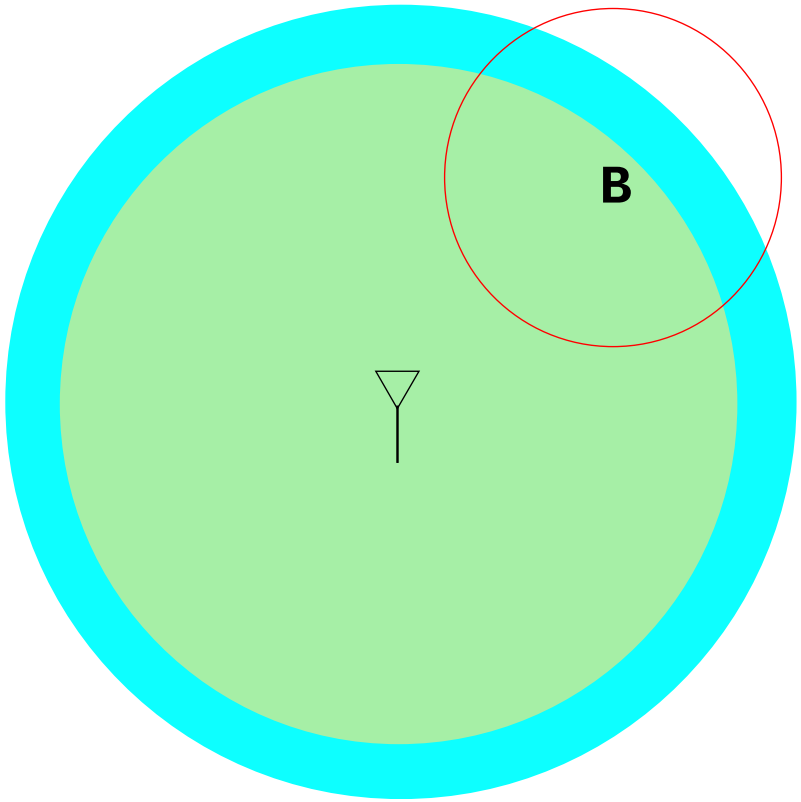
Define a protected radius



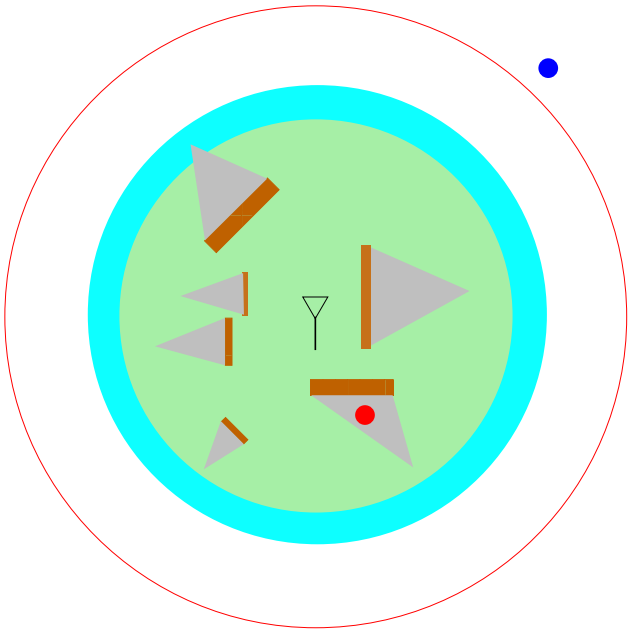
Mice can get close...

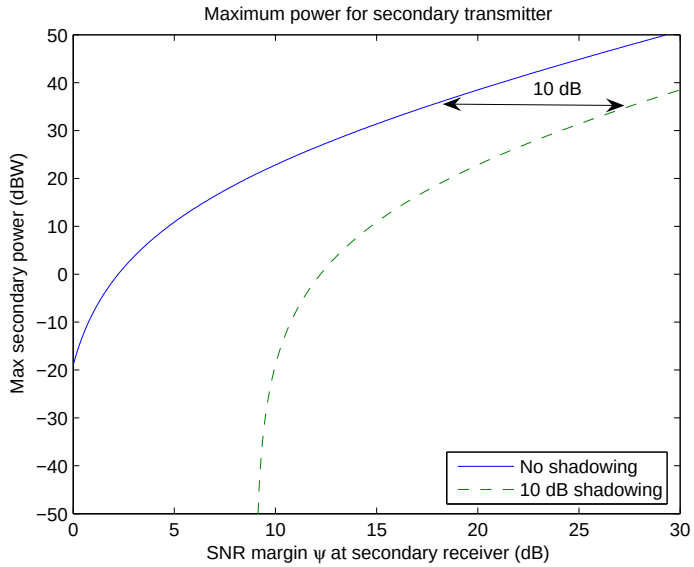


But keep the lions far away!



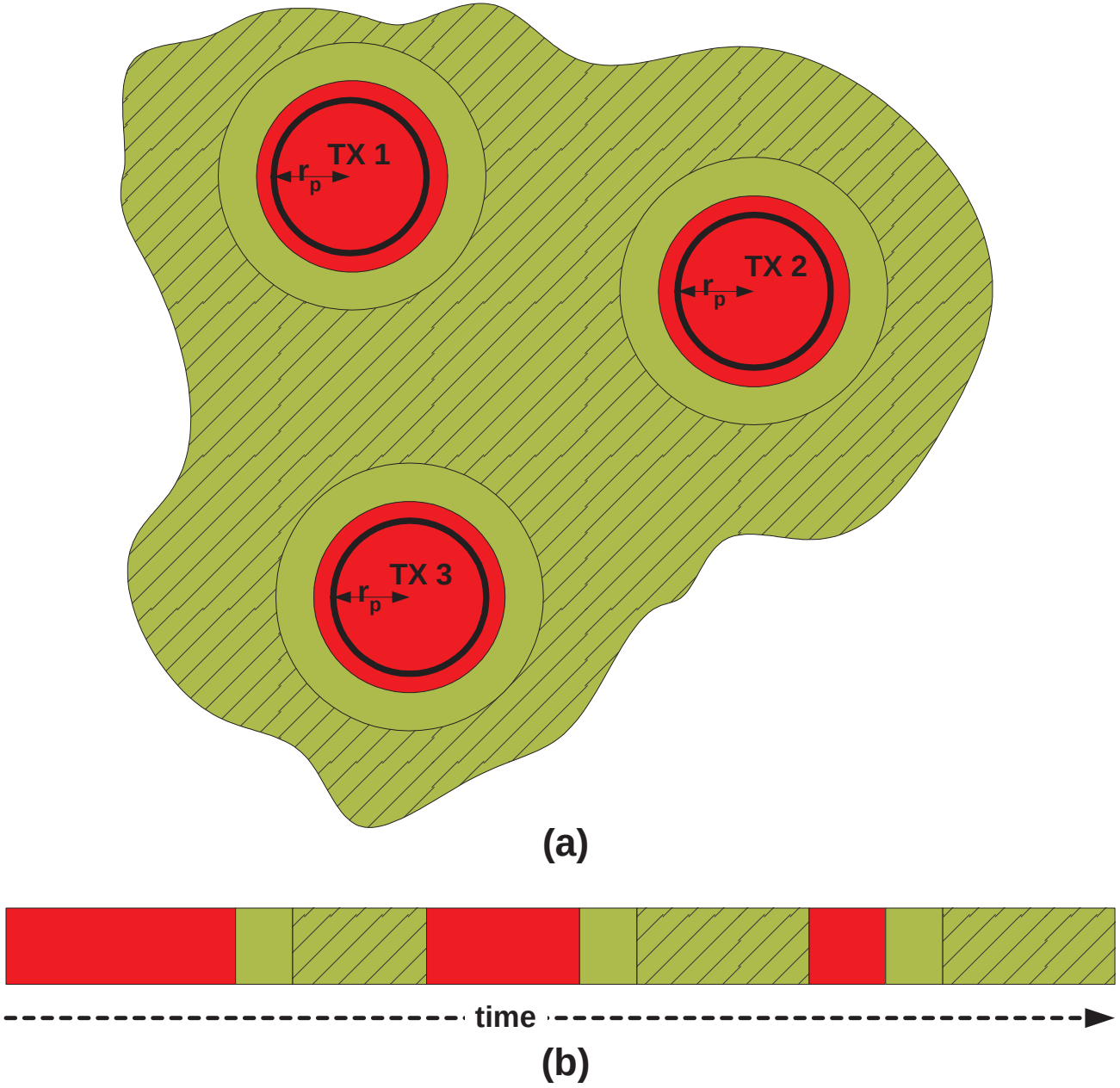
Fading





- If you hear a weak signal, are you far away, or just locally faded?
- The possibility of 10 dB of fading results in a 10 dB shift of the required detection margin
- **How to choose X dB of fading margin?**

The spatial equivalents



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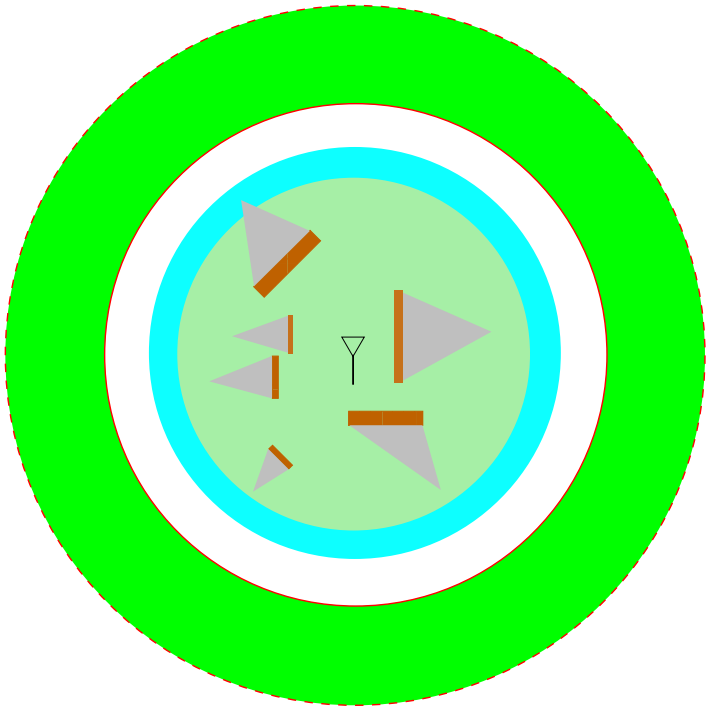

Safe, but might be faded
(fading uncertainty)
Will recover using diversity.

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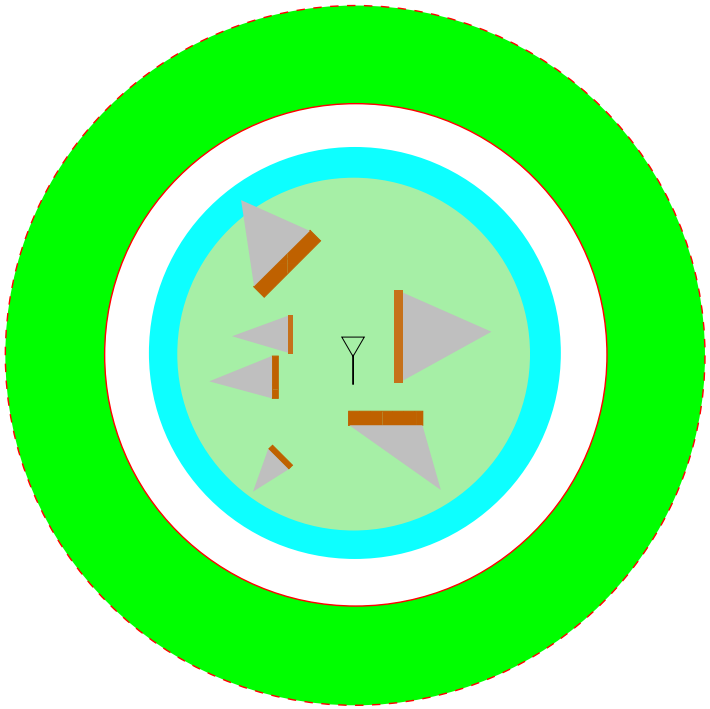

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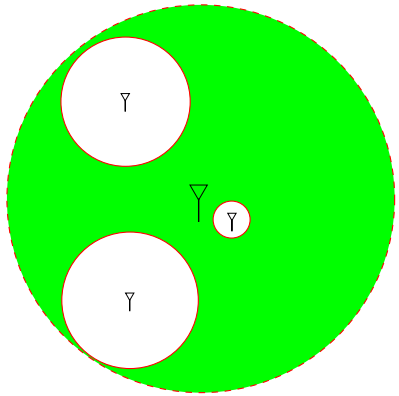

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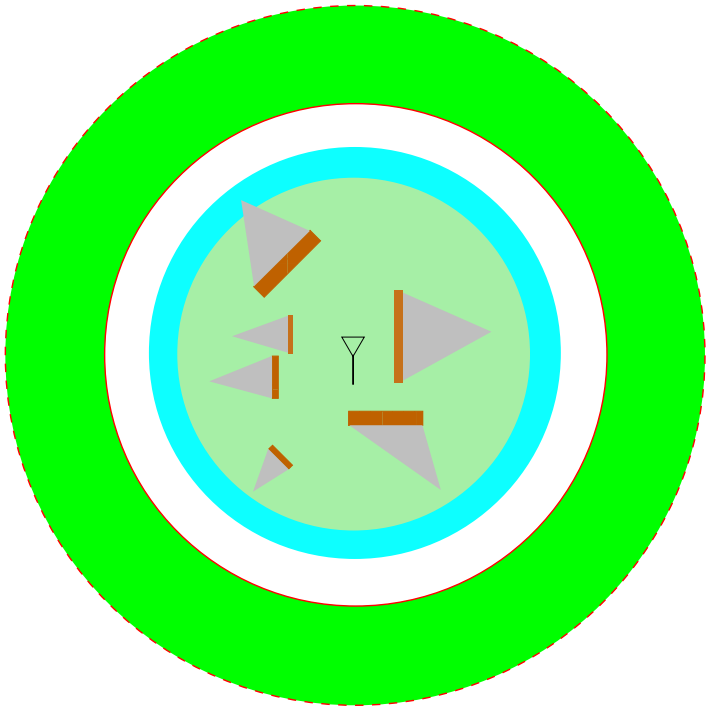

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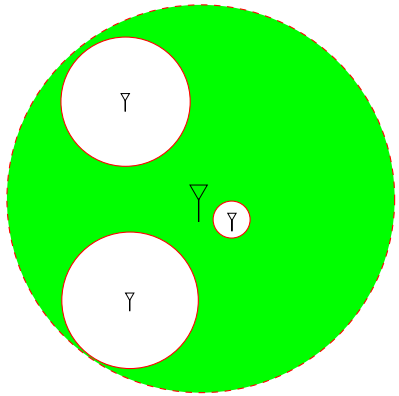

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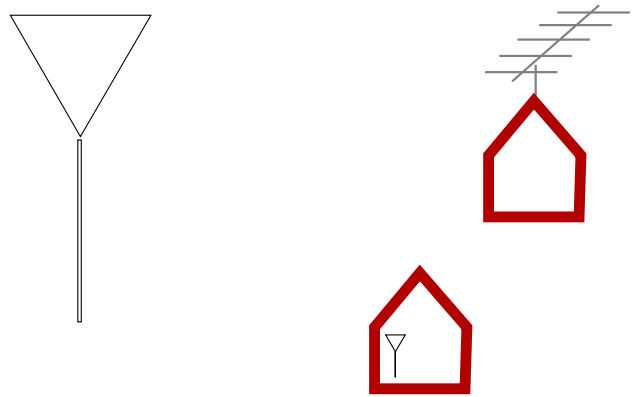
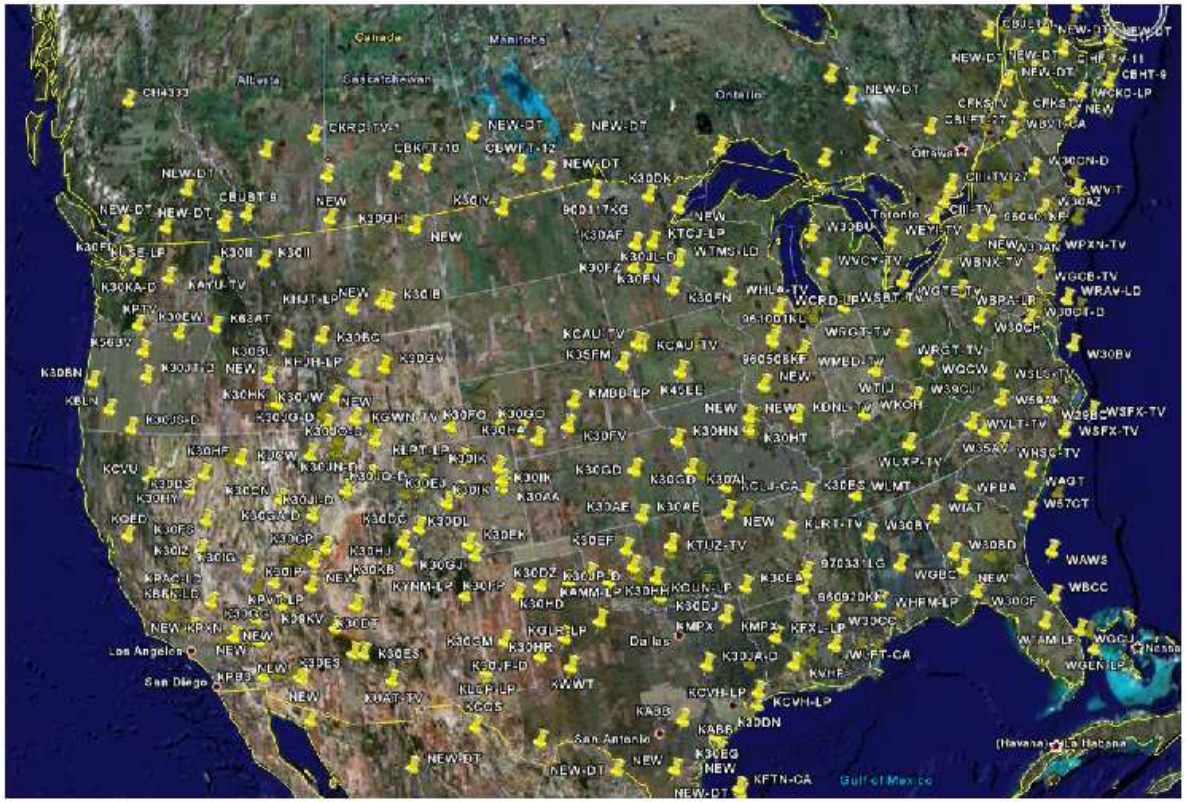


Safe, but not shadowed enough

Example Distribution of Primary Users



Performance: Weighted Probability of Area Recovered

$$WPAR = \int_{r_n}^{\infty} w(r) P_{FH}(r)\, r dr$$

- $P_{FH}(r)$ is the probability of finding a spectrum hole at distance r from primary.
- $w(r)$ is a weighting function satisfying $\int_{r_n}^{\infty} w(r)\, r\, dr = 1$.

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- e.g. exponential: $w(r) = K \exp(-\kappa r)$

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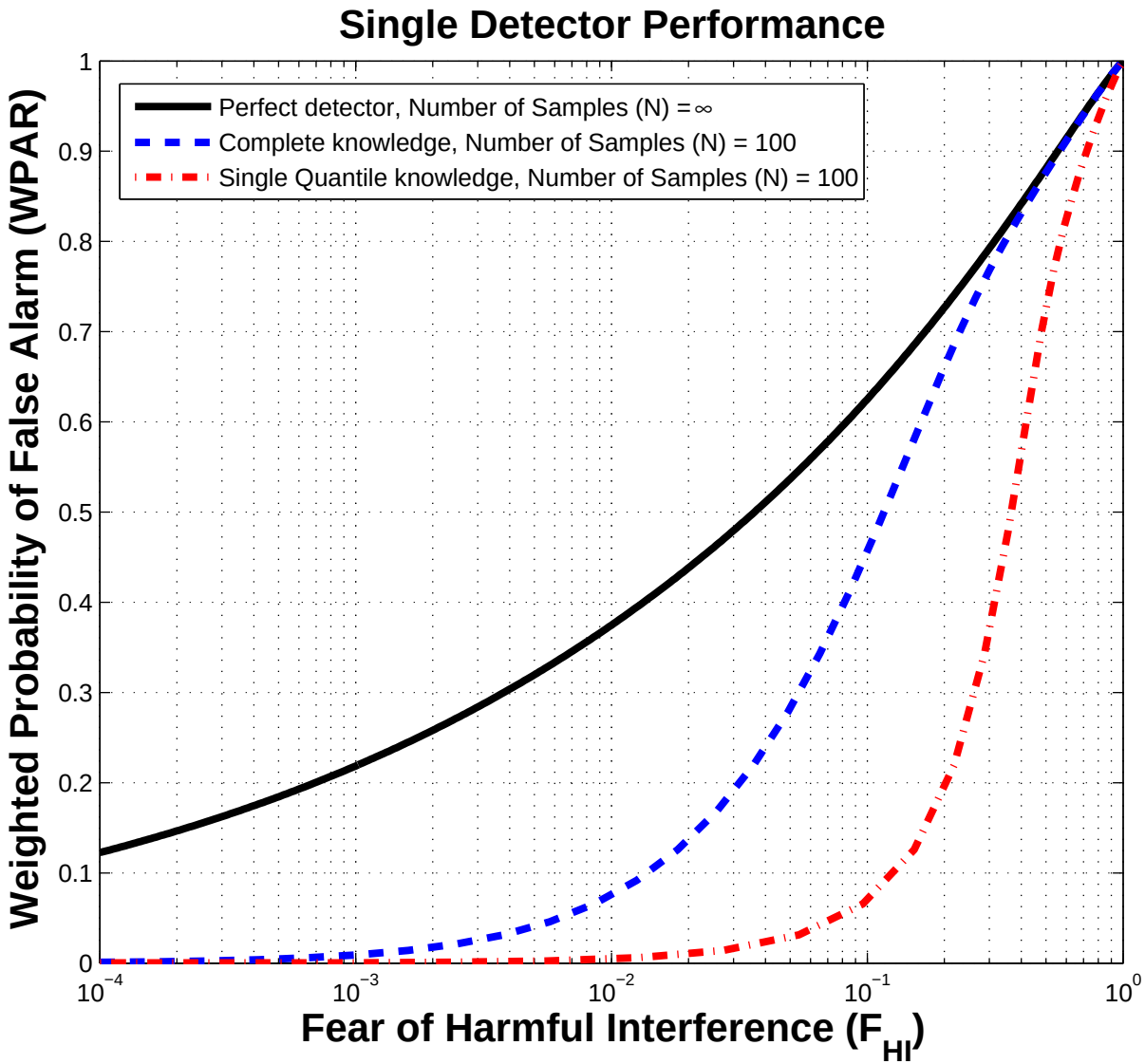
  - Primary does not and **should not** trust full model for:
    - ★ Noise distribution
    - ★ Secondary deployment assumptions
    - ★ Fading distribution
- This *fear* must by accounted for:

$$F_{HI} = \sup_{0 \leq r \leq r_n} \sup_{F_r \in \mathbb{F}_r} \mathcal{P}_{F_r}(D = 0 | r_{actual} = r)$$

where $\mathbb{F}_r$ is the uncertain distribution underlying algorithm D.

The story so far in these metrics



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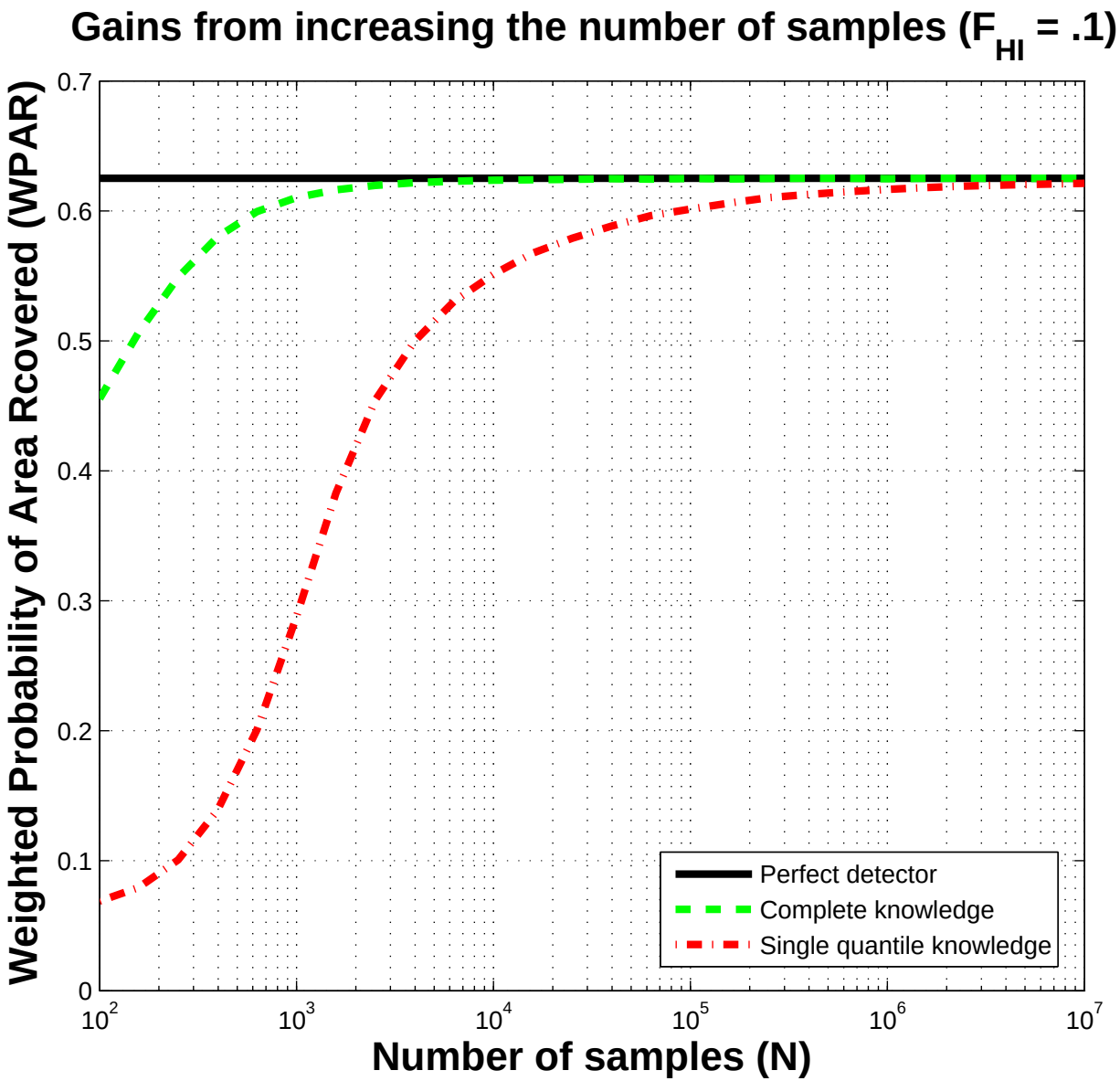

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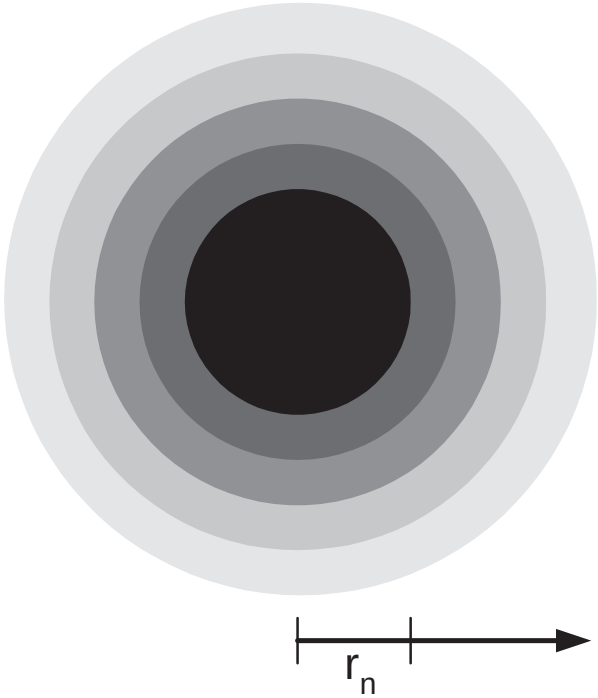
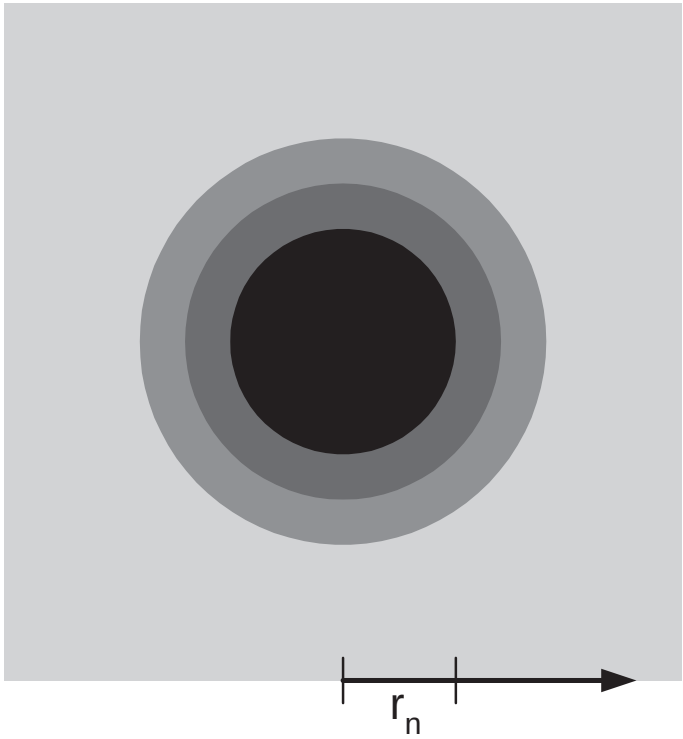


No Noise uncertainty

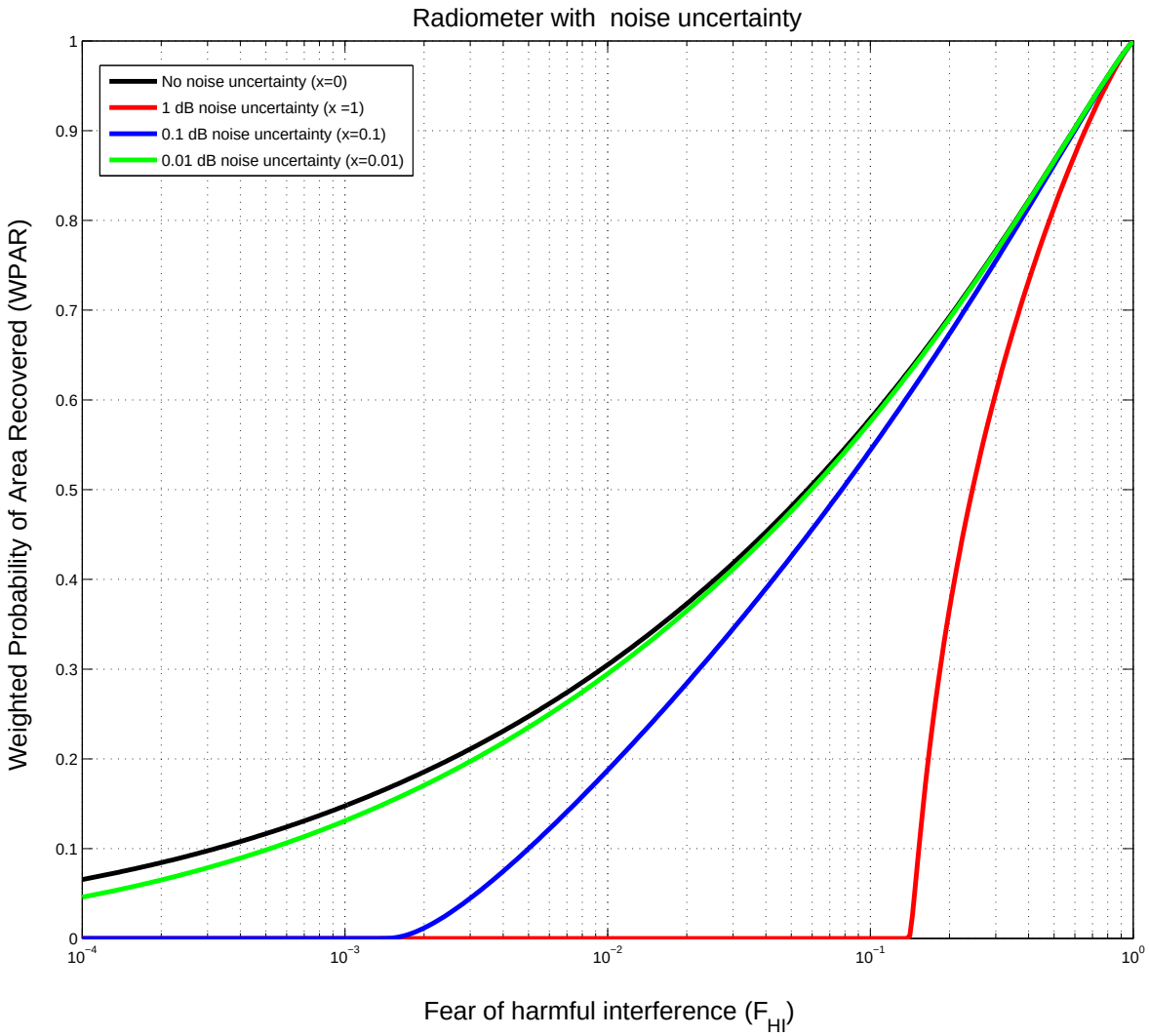


With Noise uncertainty

Area never recoverd

Area recovered

The story so far in these metrics



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Spatial domain: How can cooperation help?

It lessens the required detector performance

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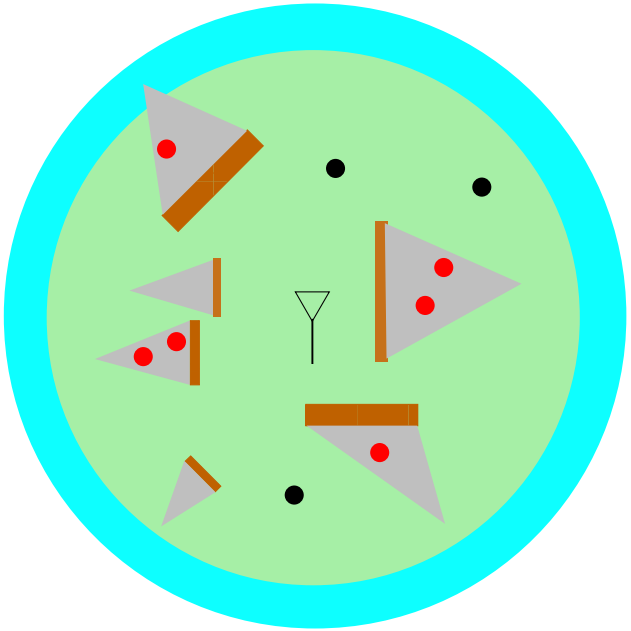

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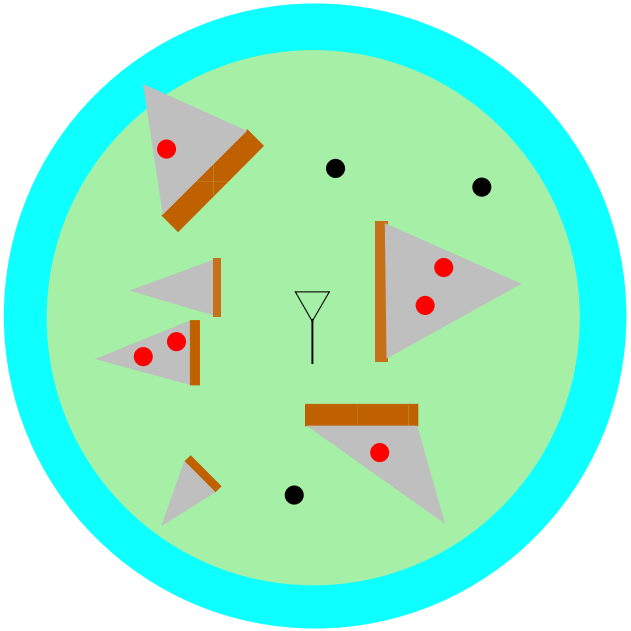

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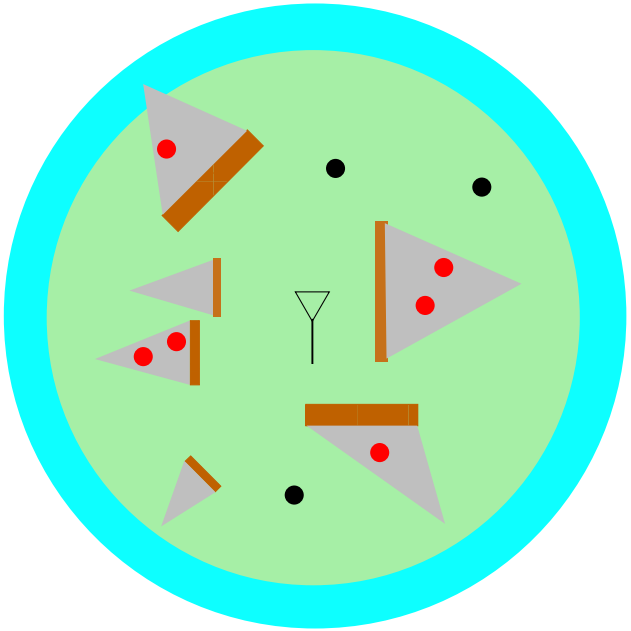

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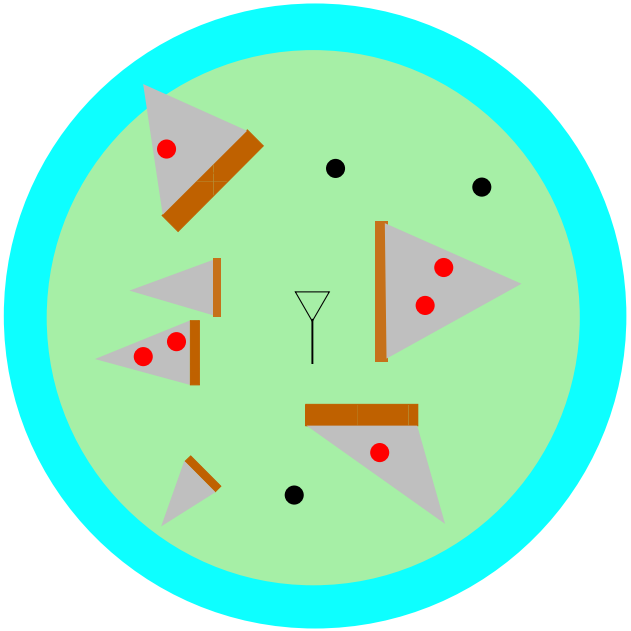

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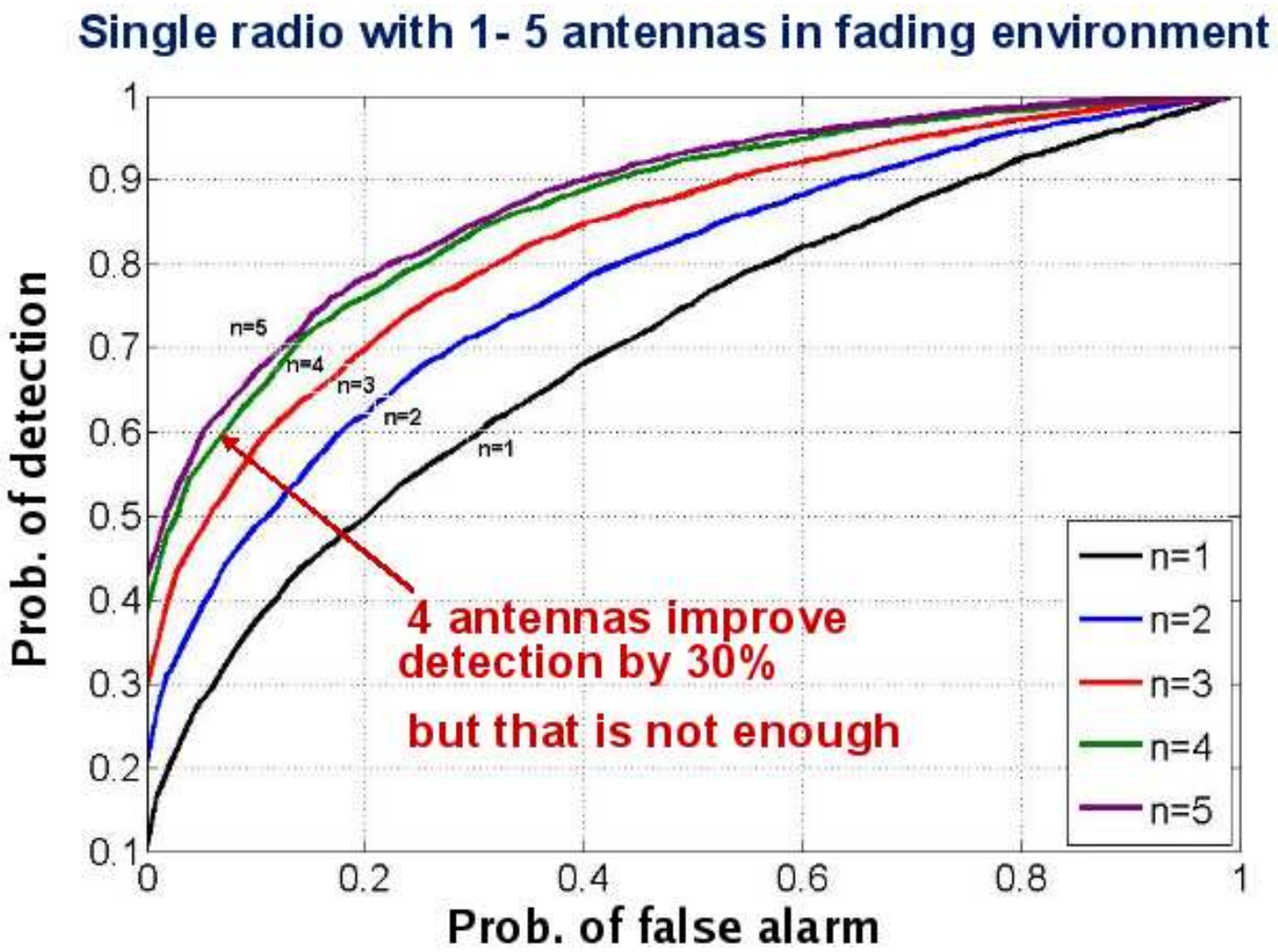
Does cooperation really work?

- Experimental validation
- Used BEE2 and 2.4 GHz radio front-ends



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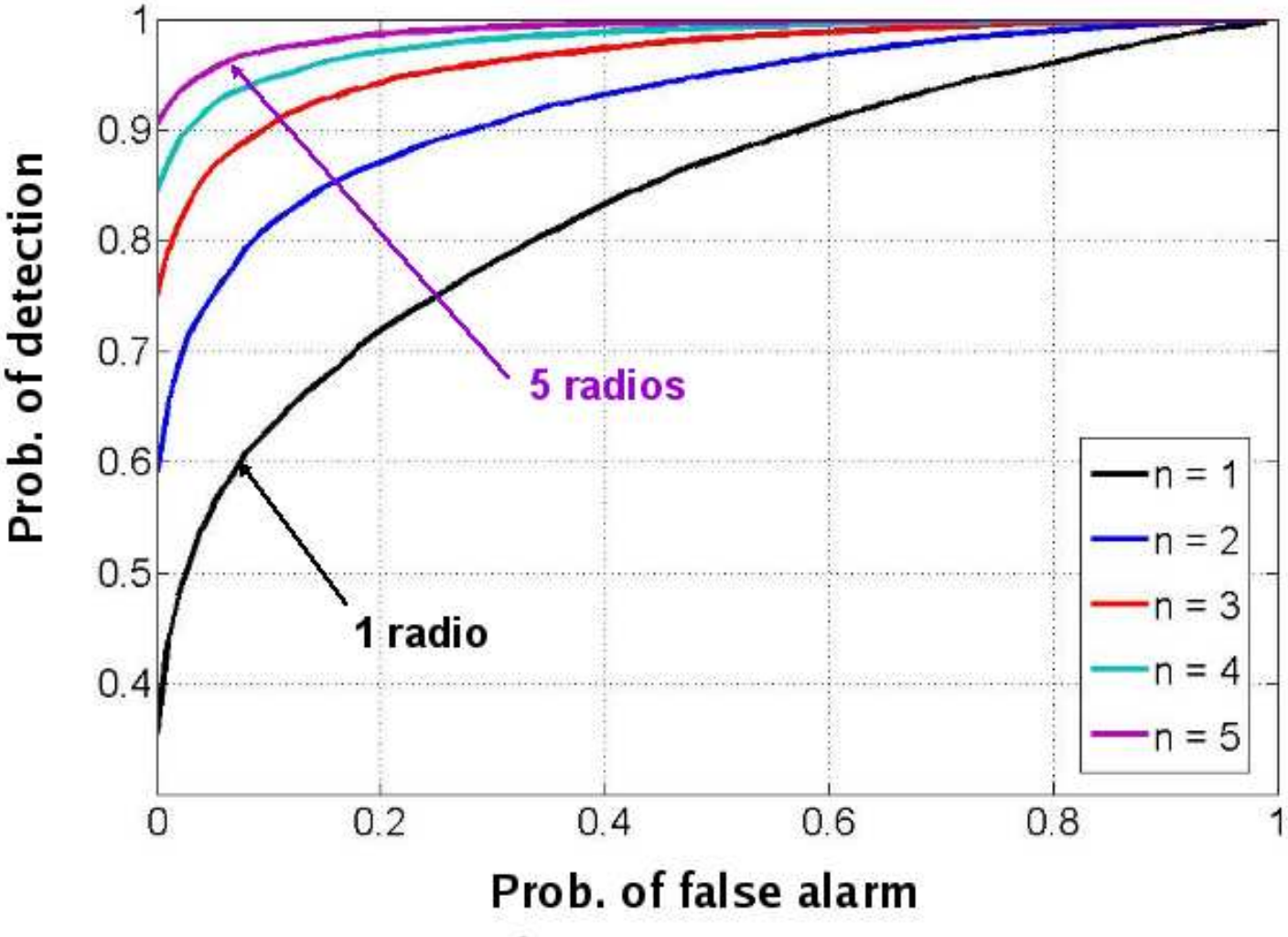
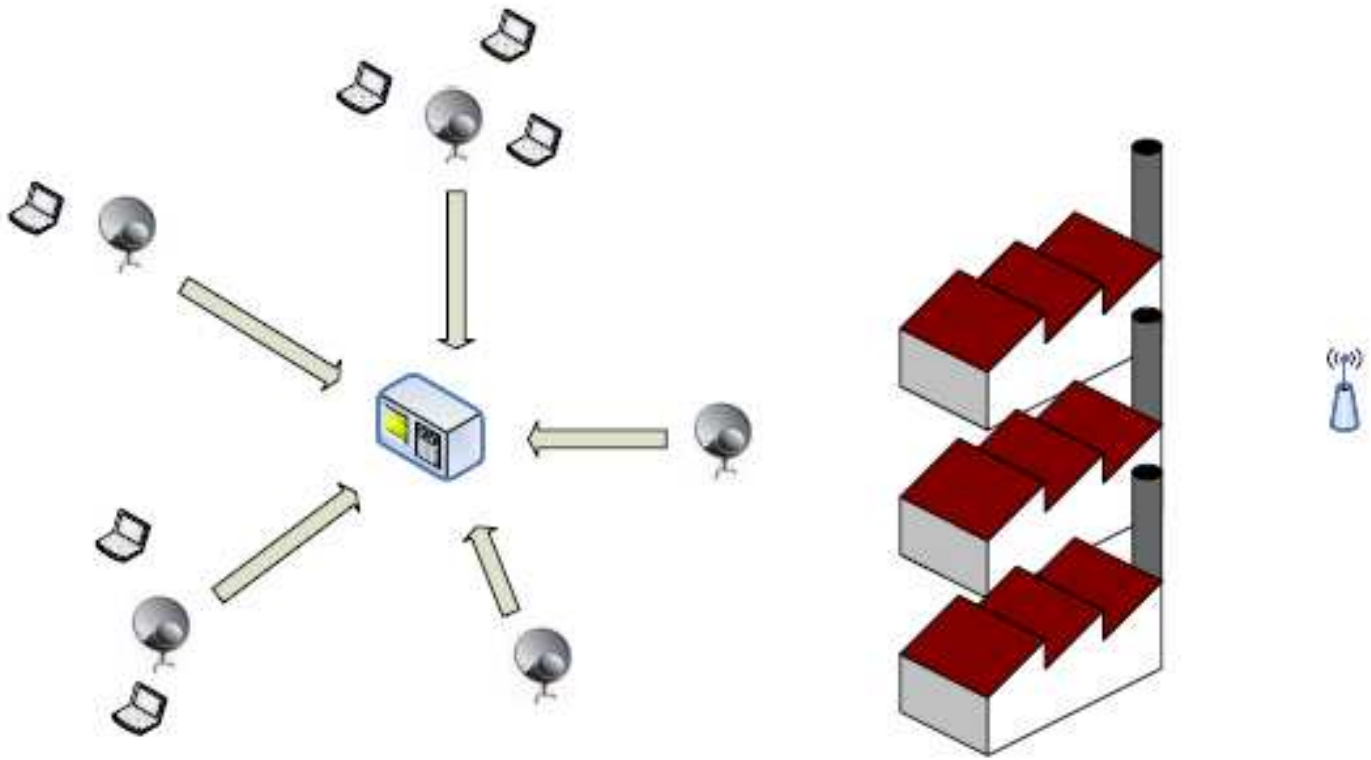
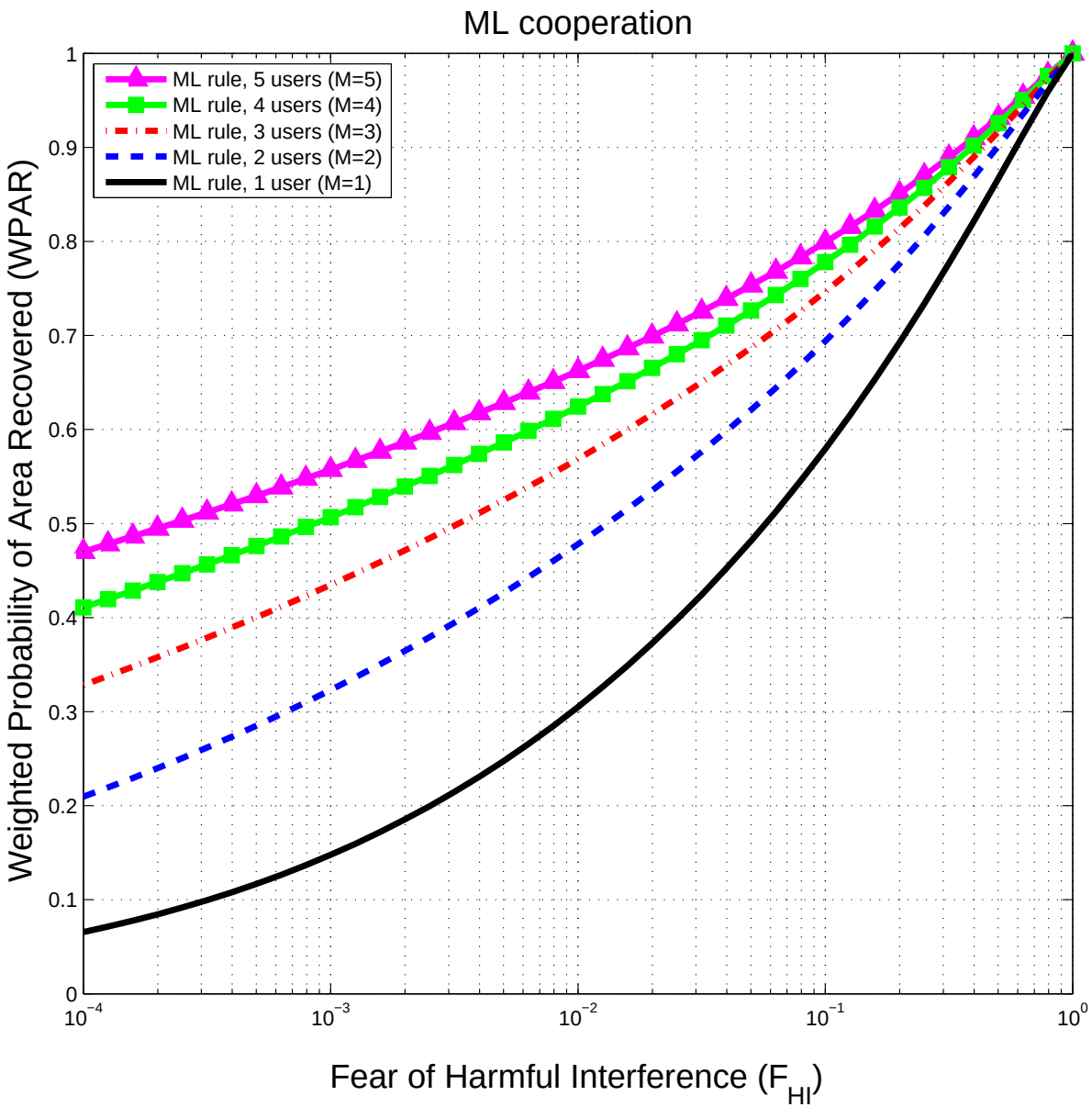


Time-domain: How can cooperation help?



Interference diversity!

Cooperation story in correct metrics



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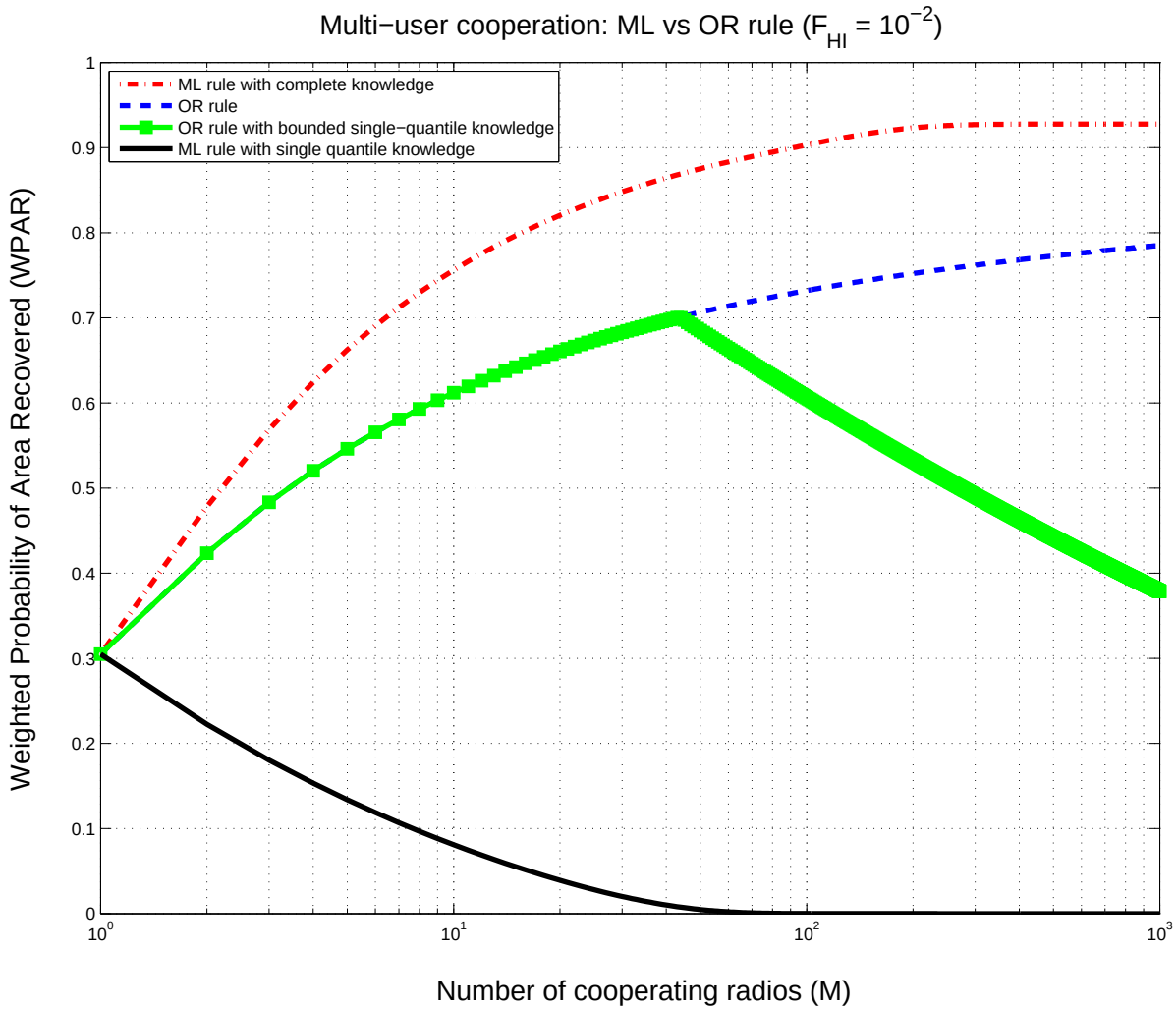

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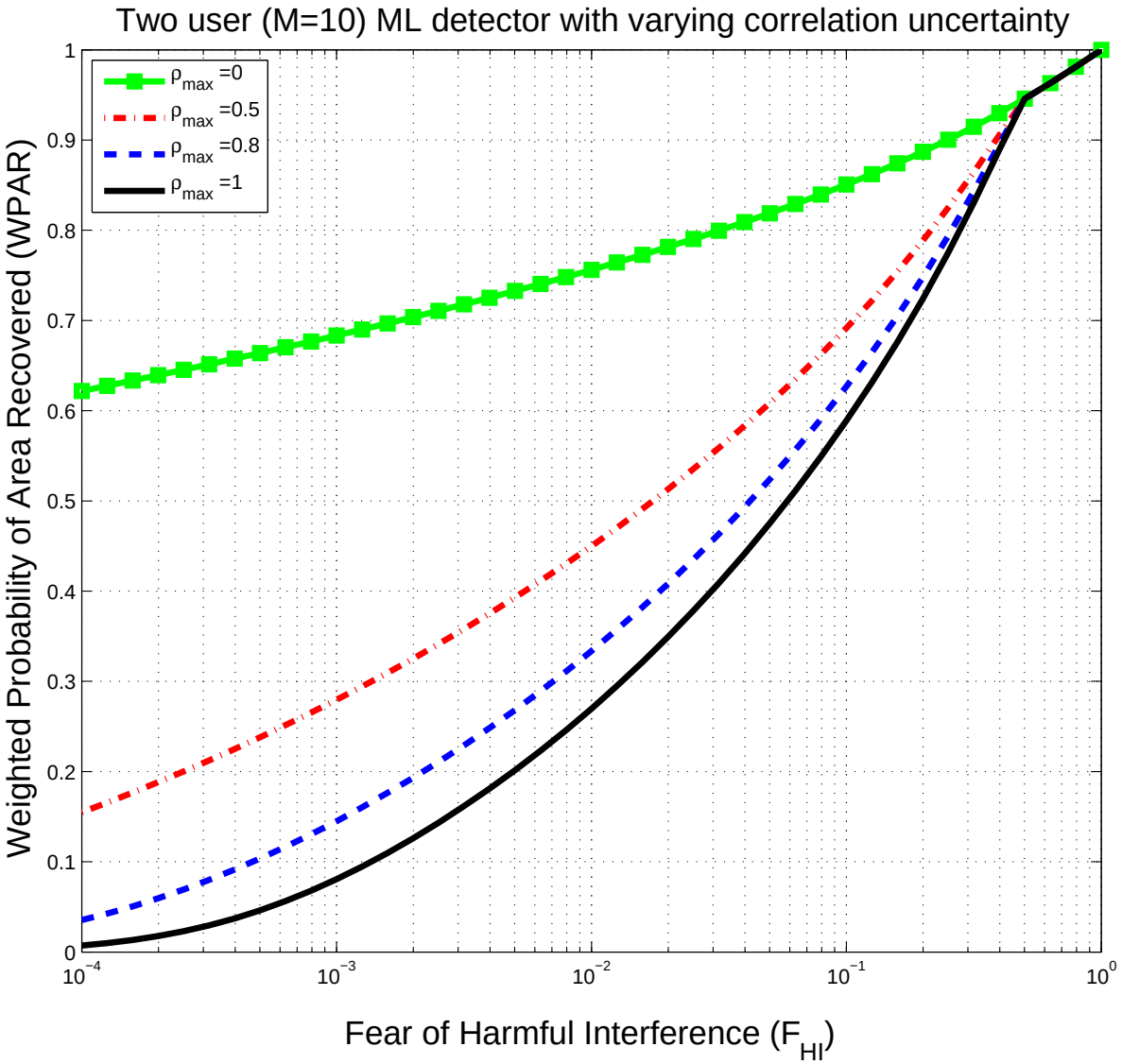
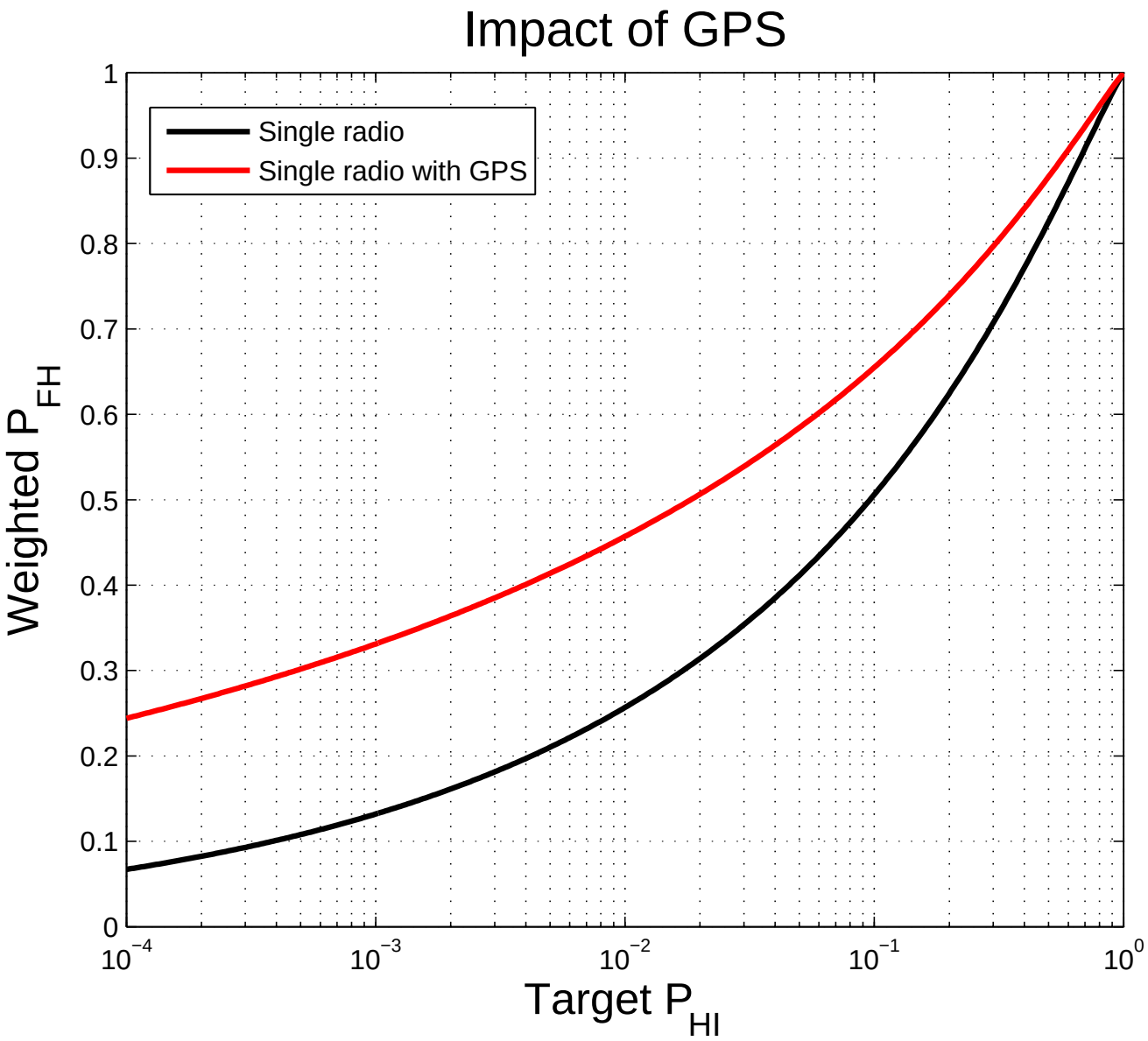


Multiband detection: hope for the future



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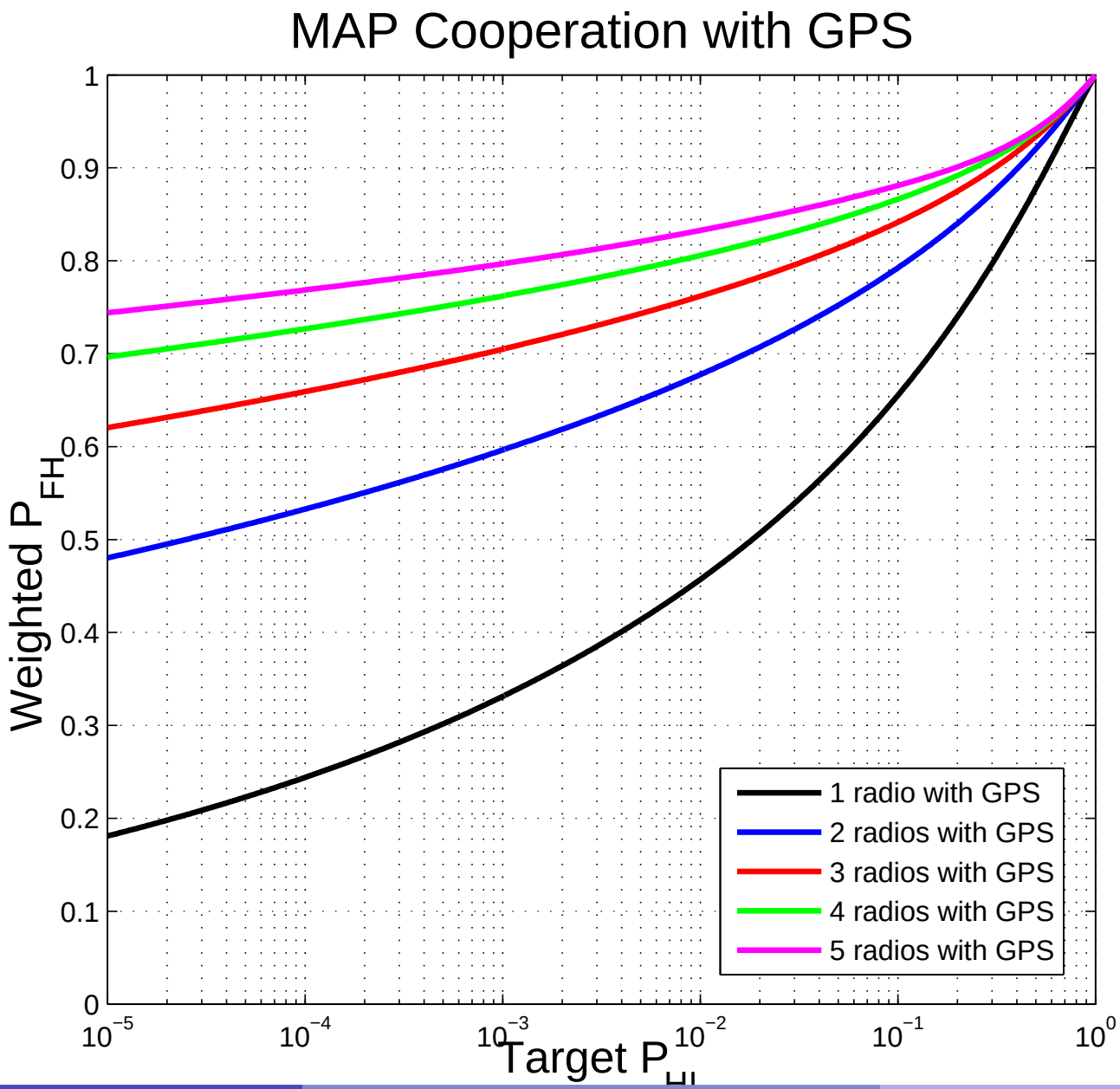

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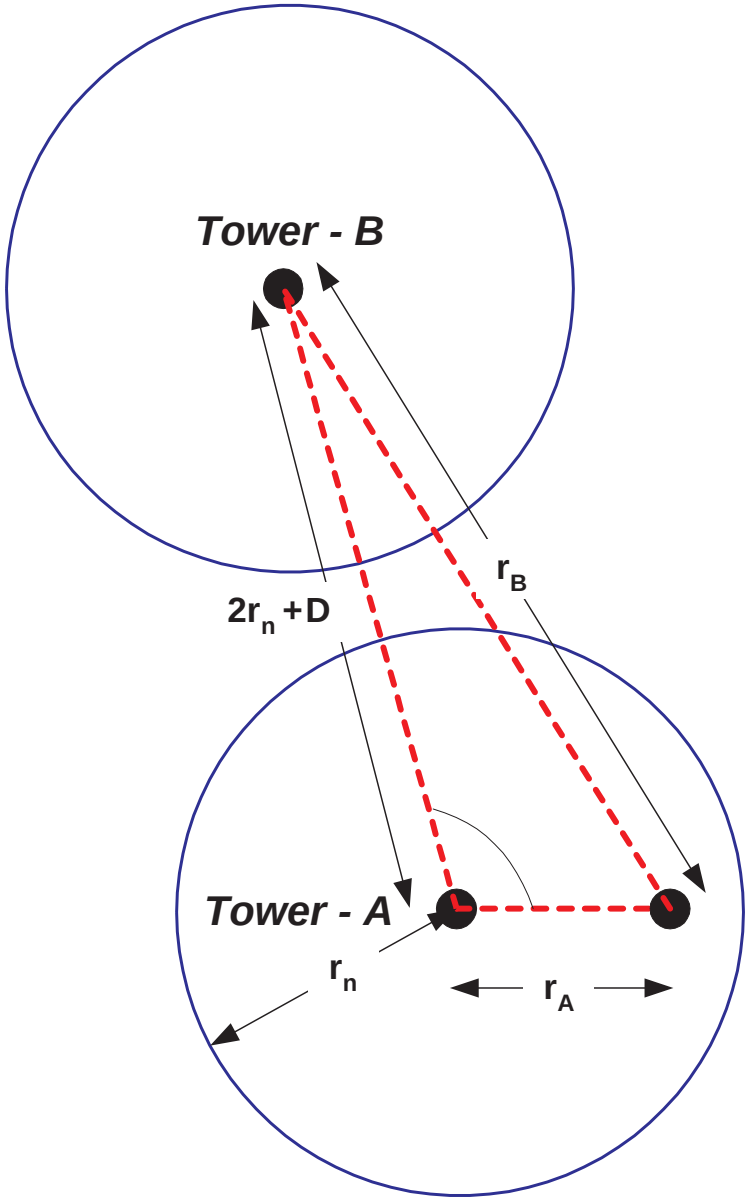

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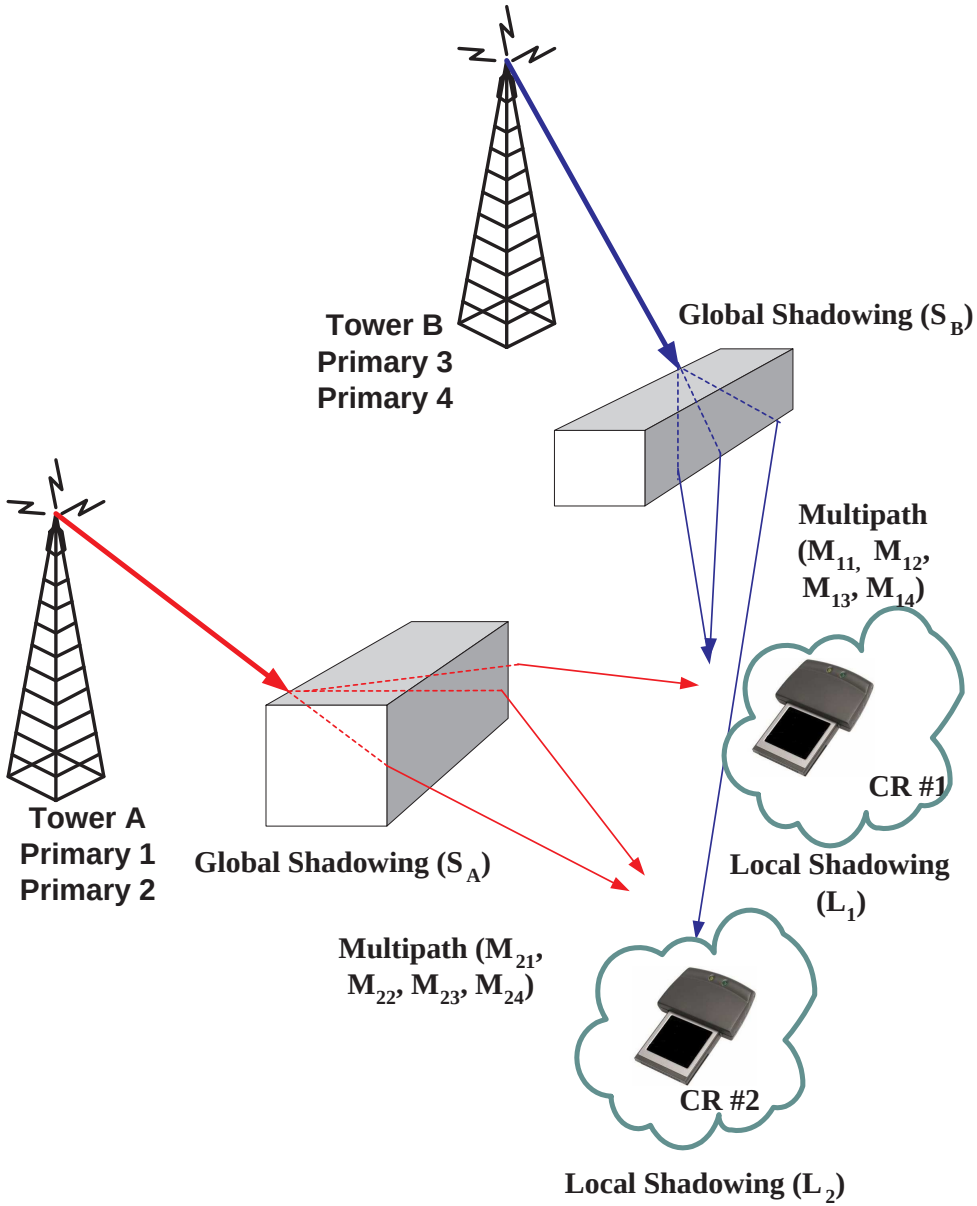

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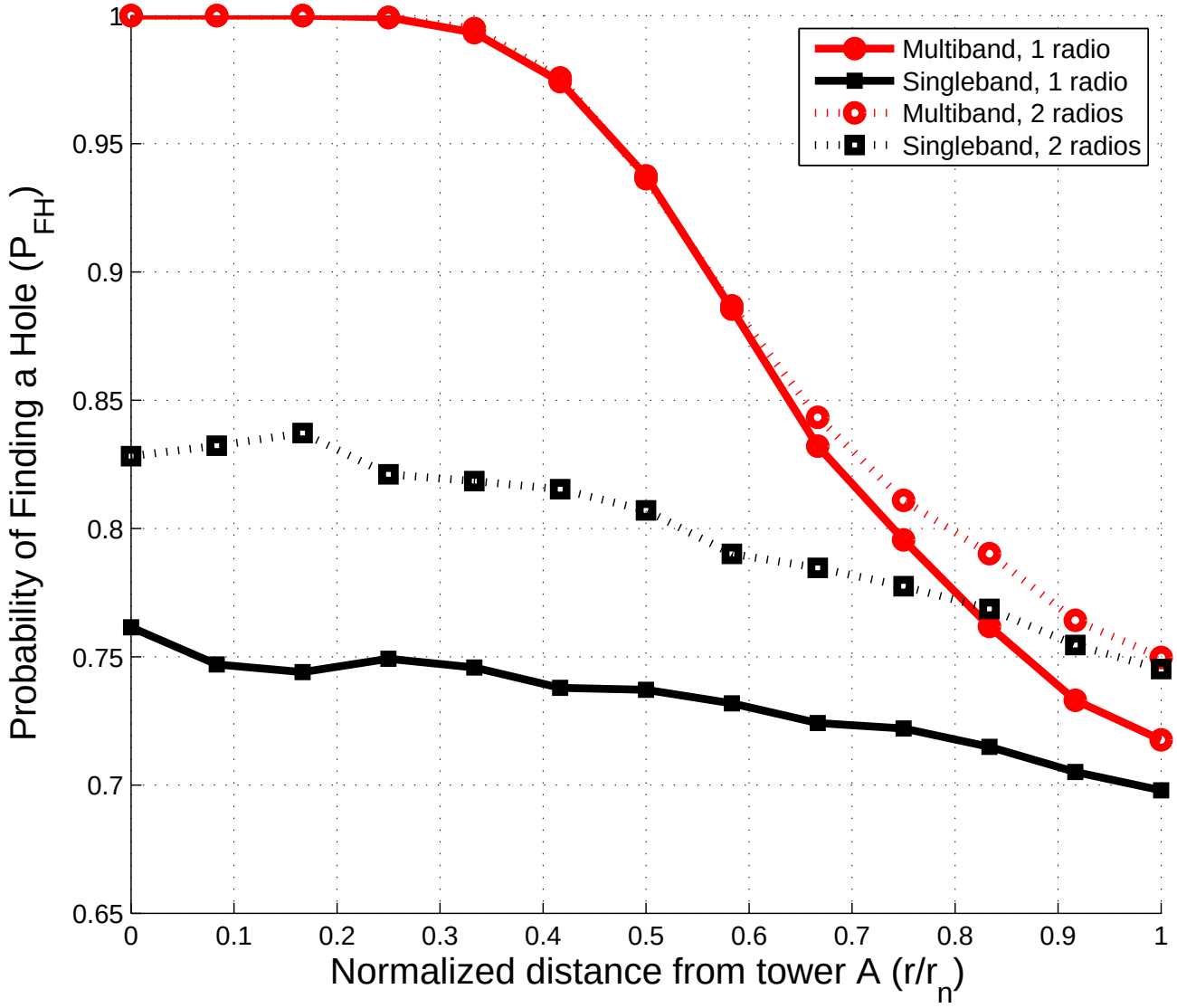

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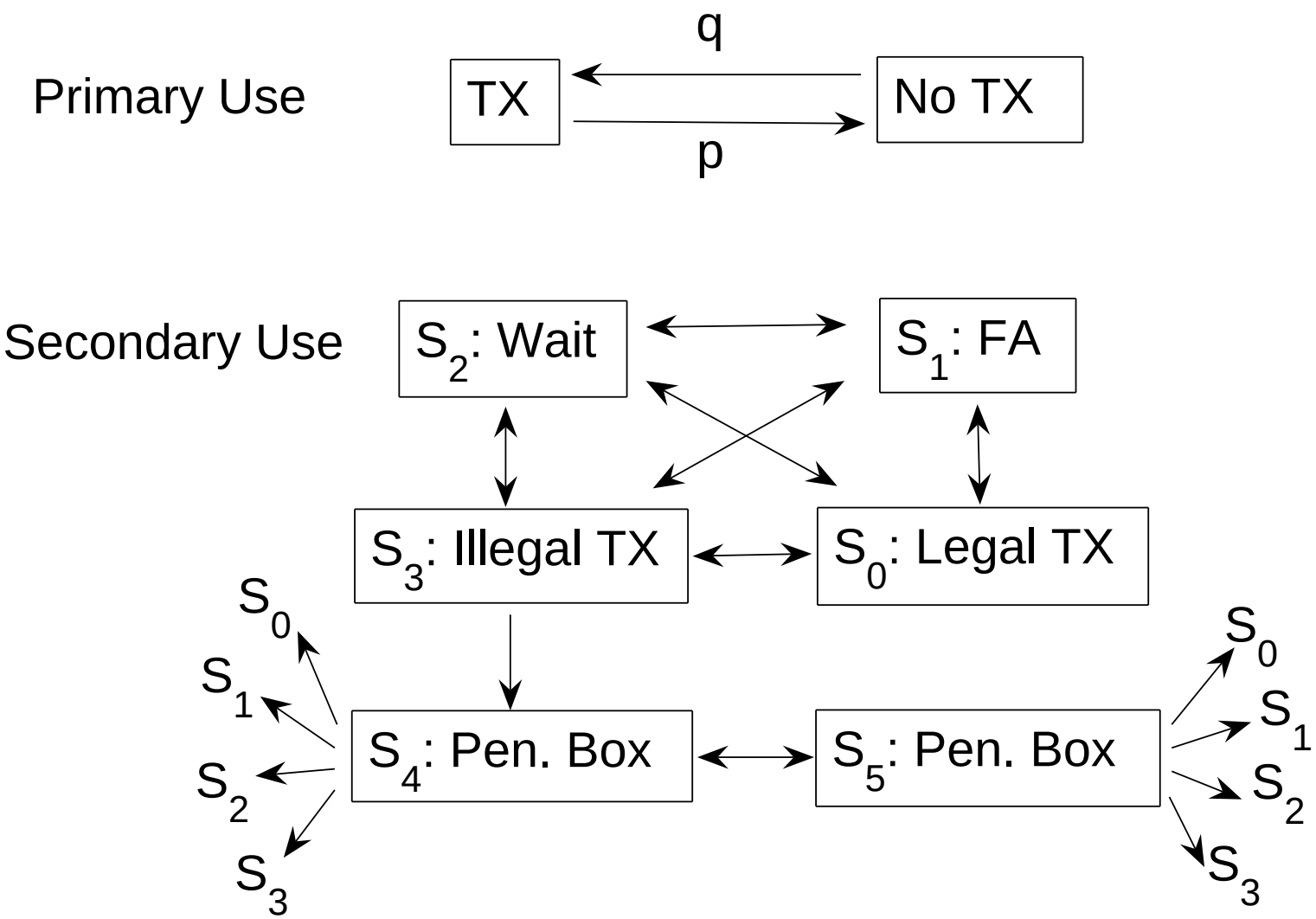
- Shift to some *a posteriori* enforcement
  - Ideas already present in Coase ’59 and de Vany ’69.
  - Users incur liability for harmful interference and are punished

A toy model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q
TX
No TX
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Secondary Use
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S0
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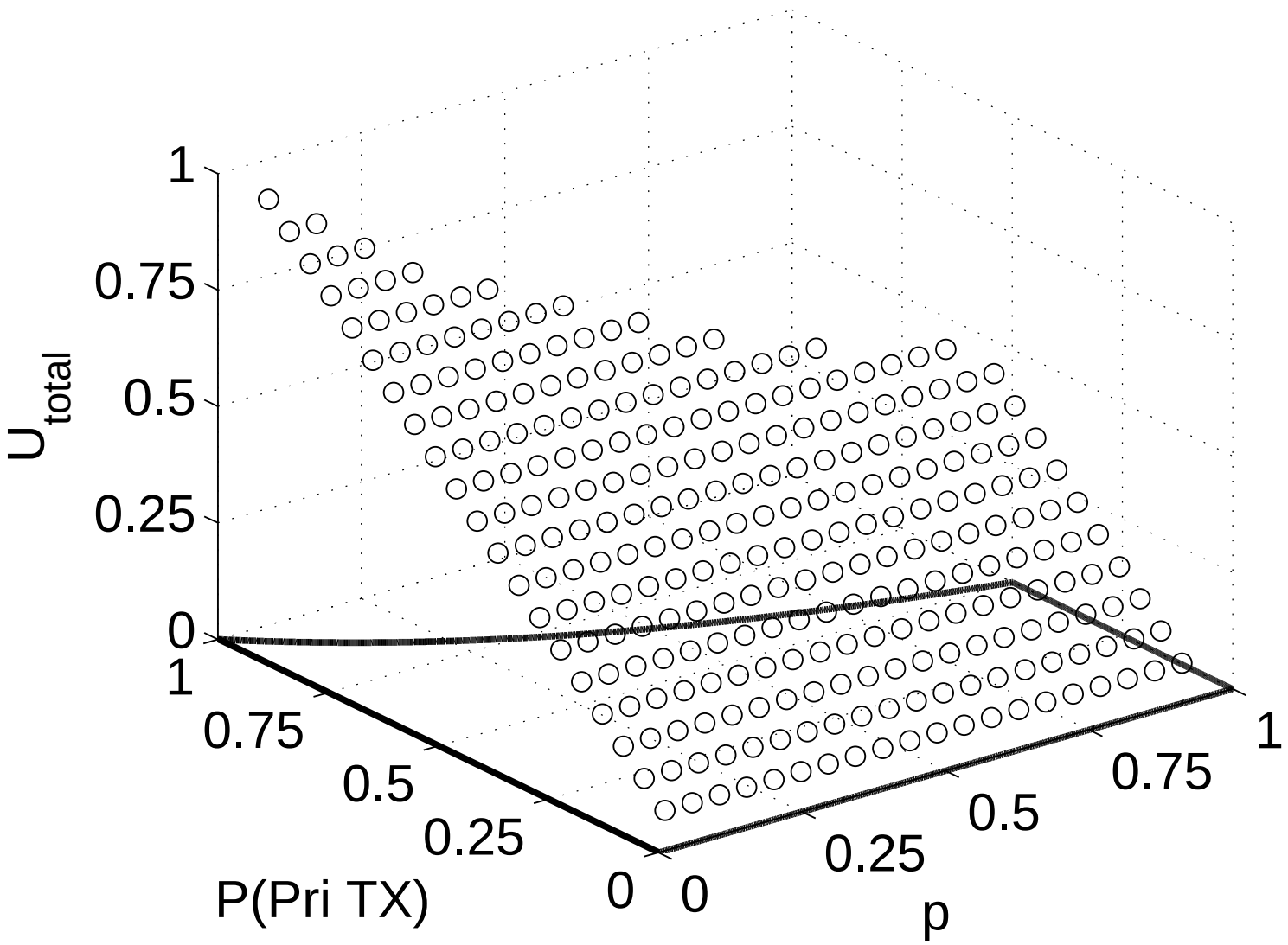

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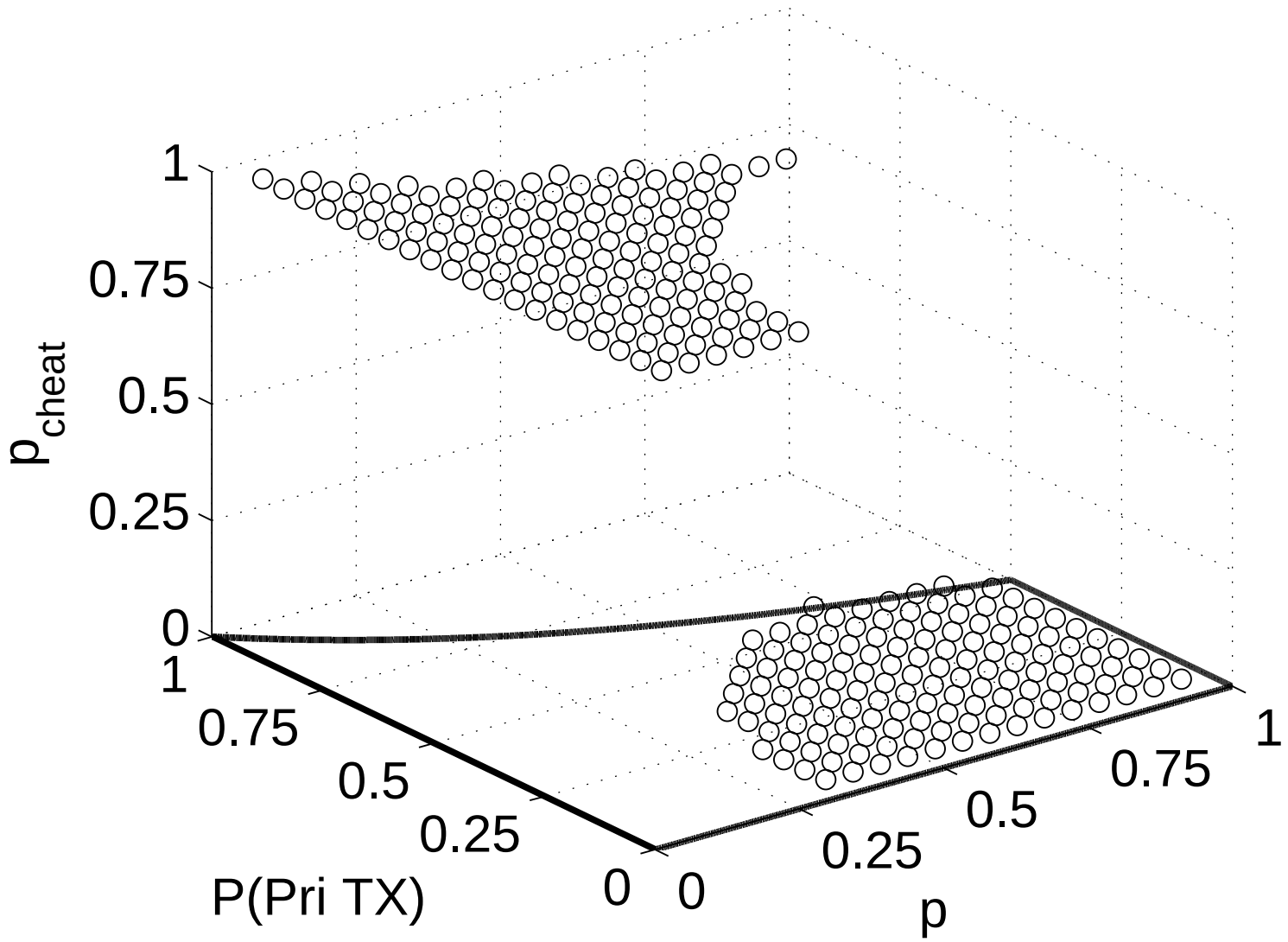

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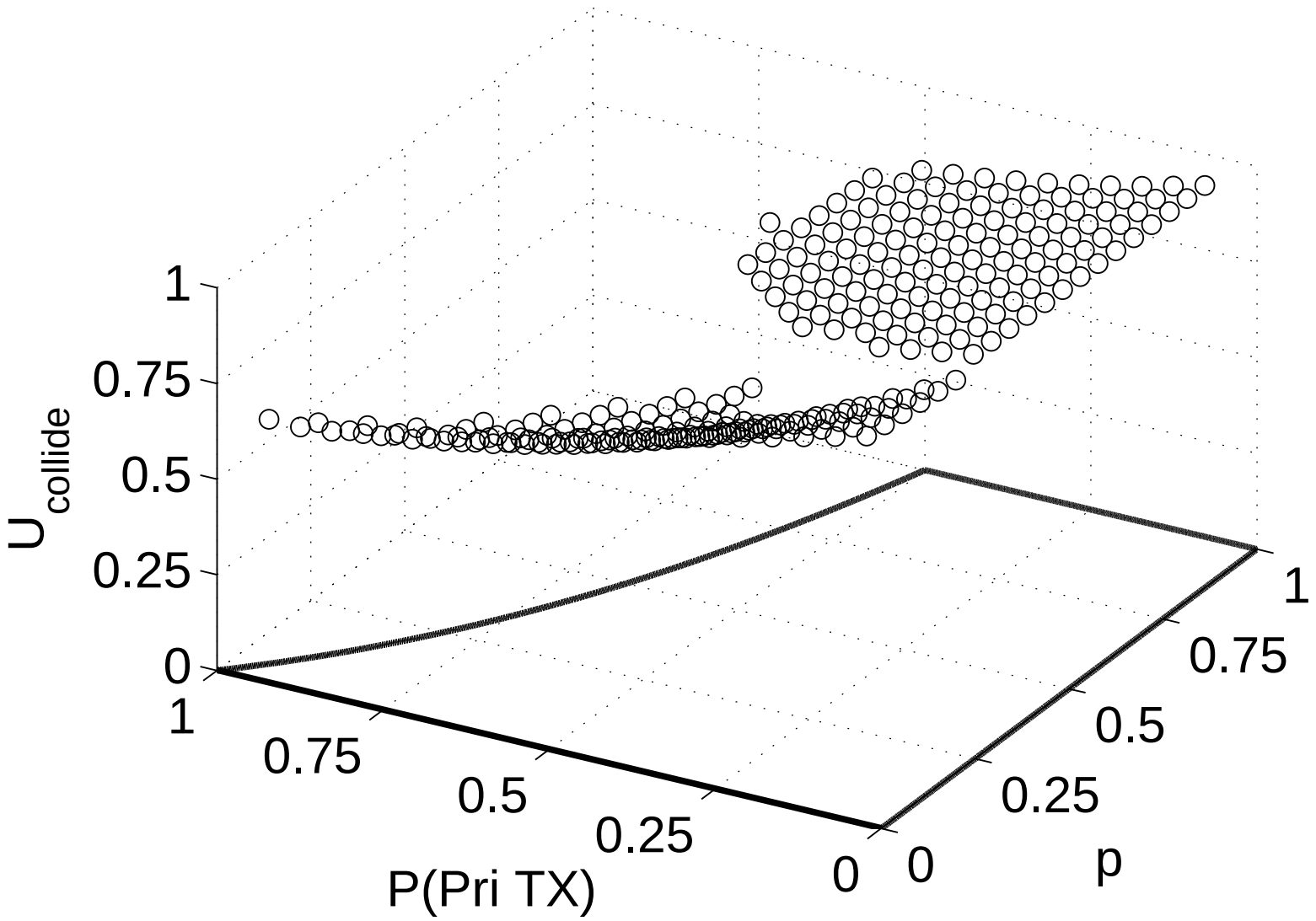

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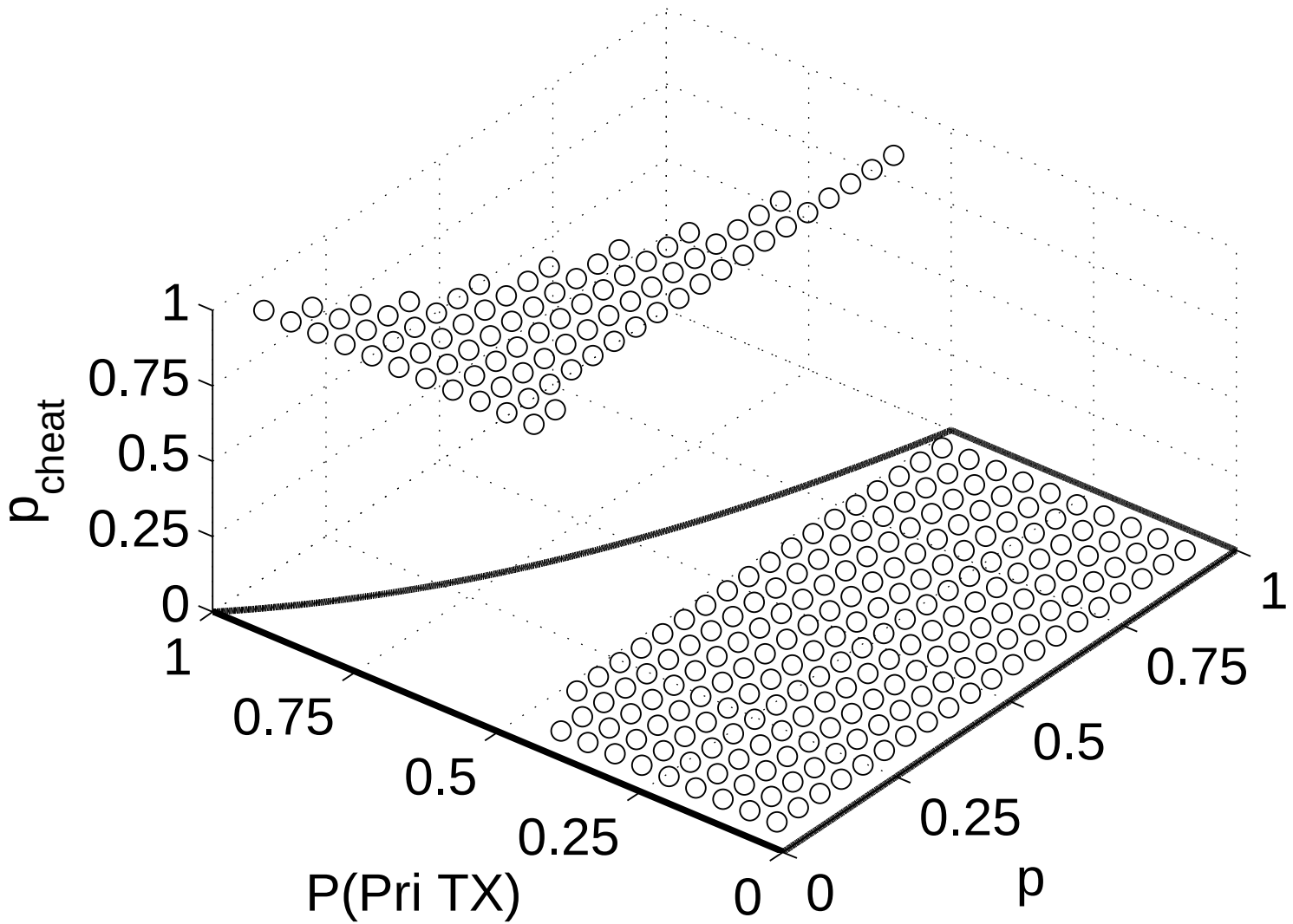

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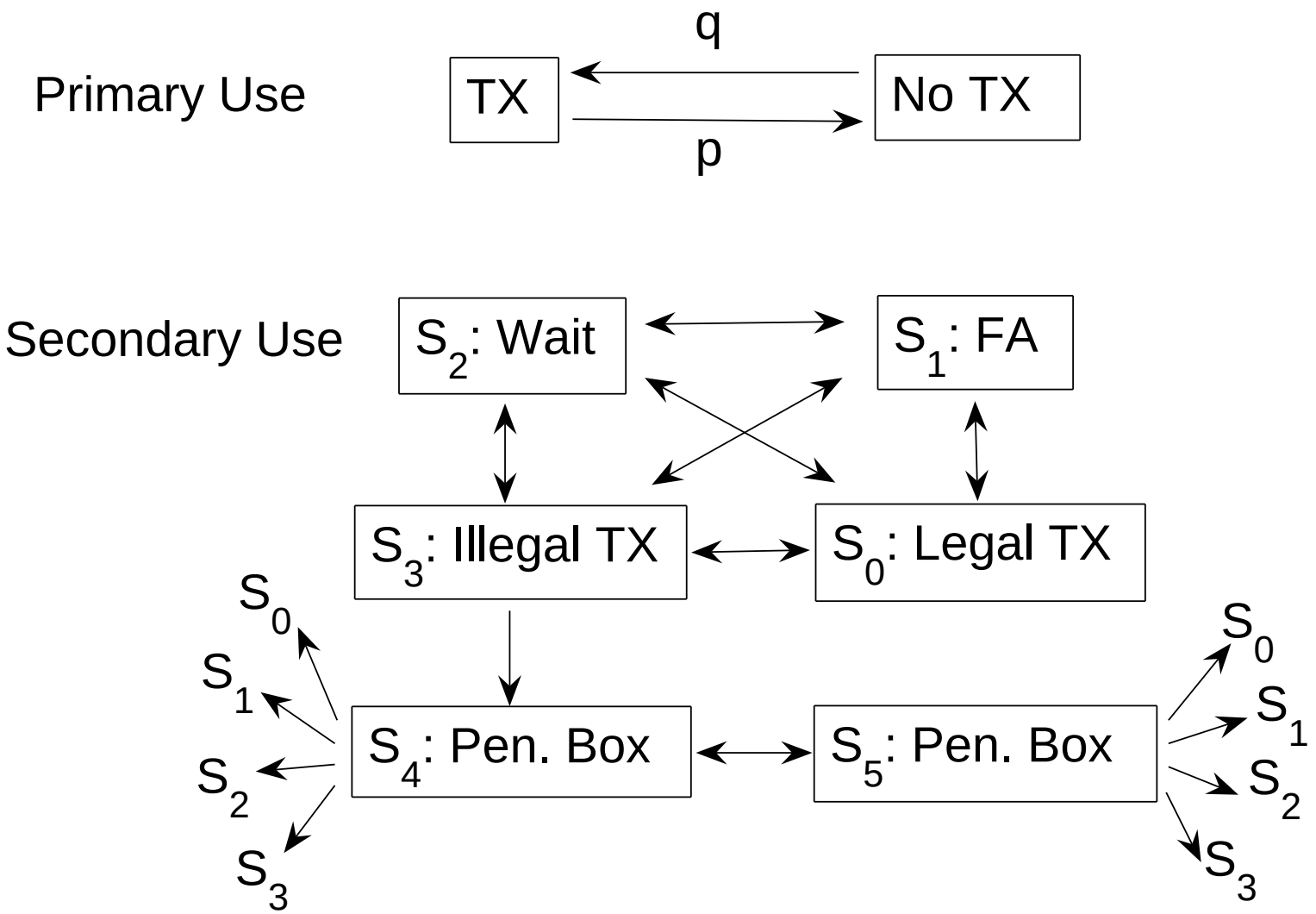
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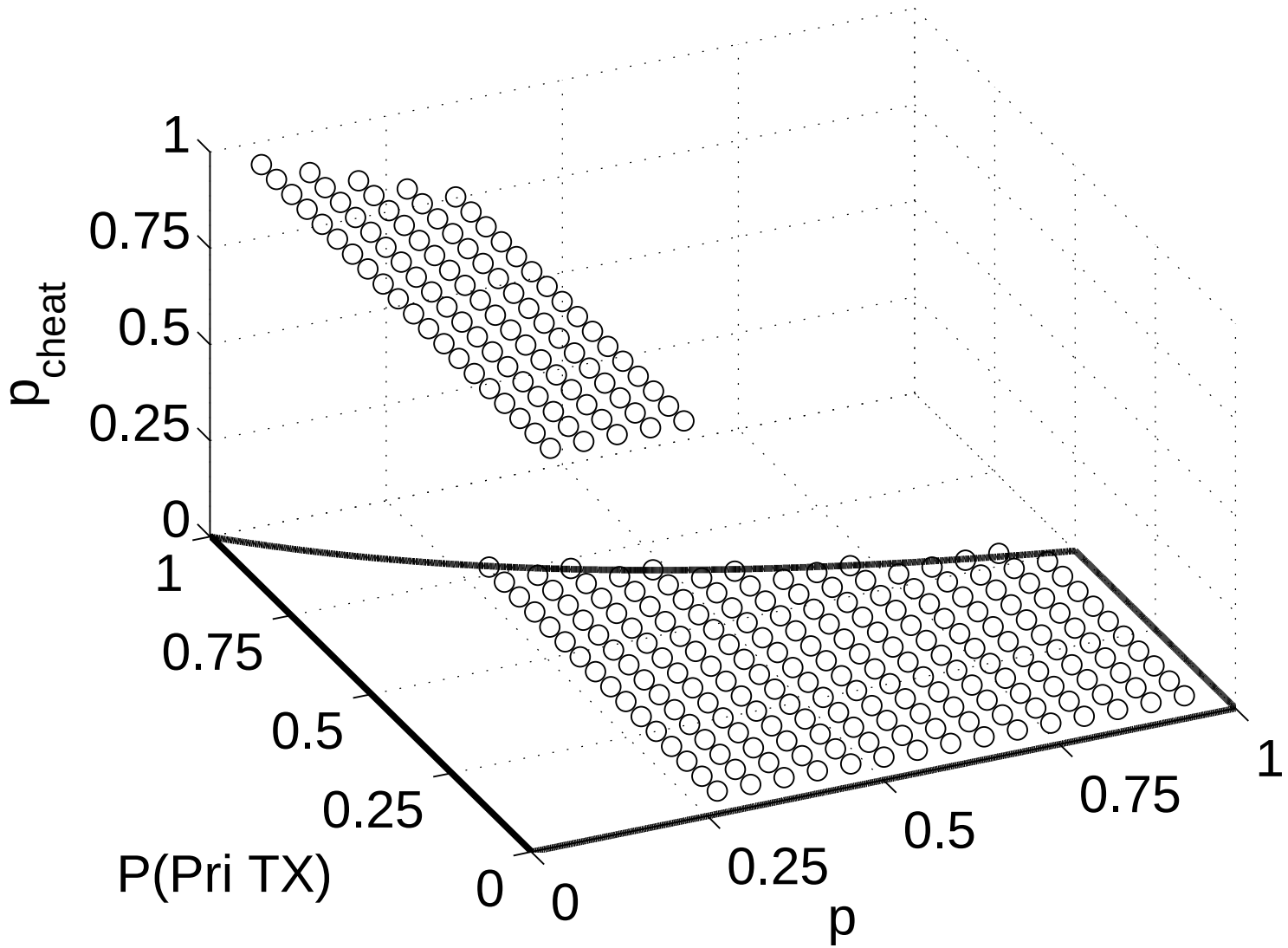

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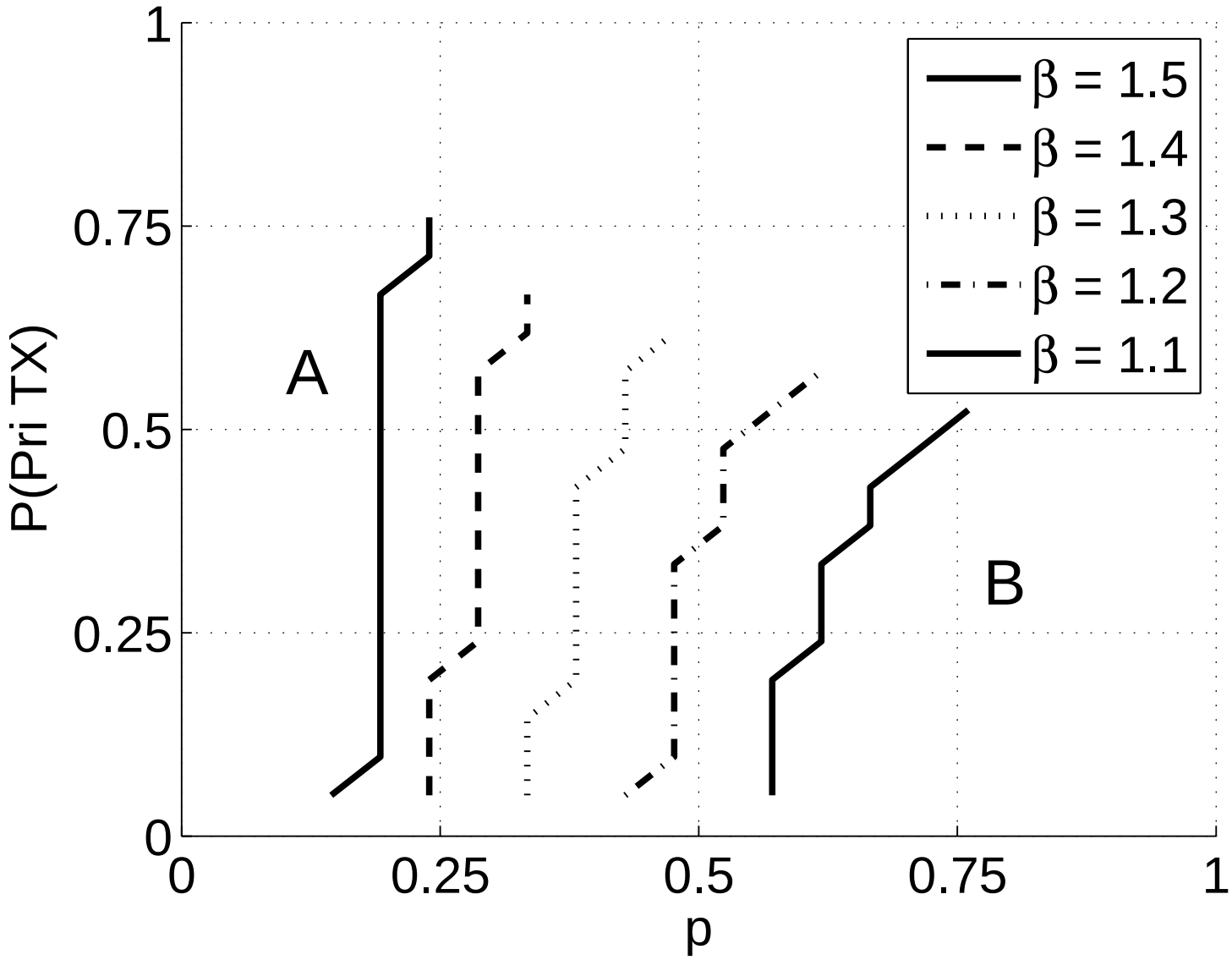

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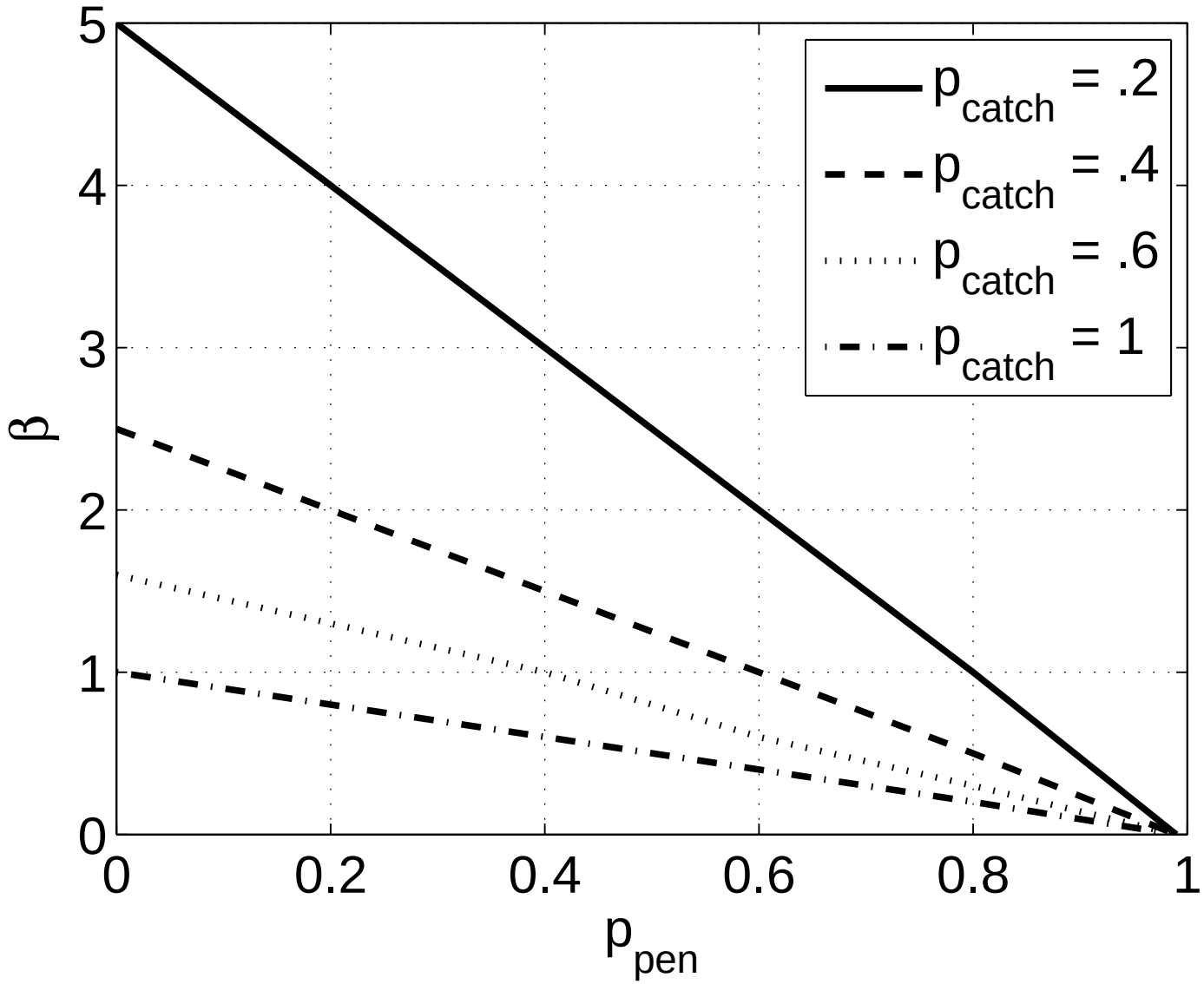

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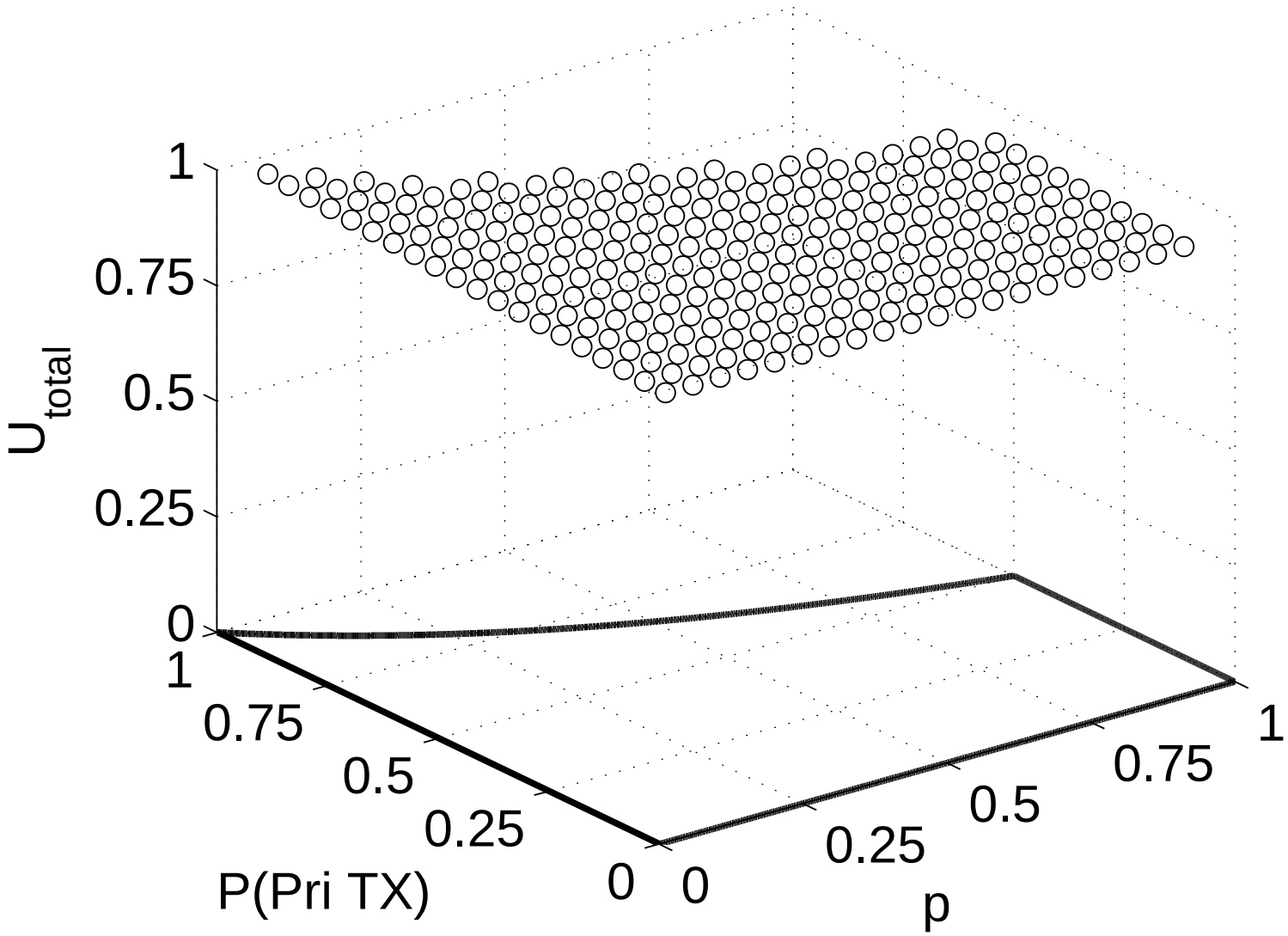

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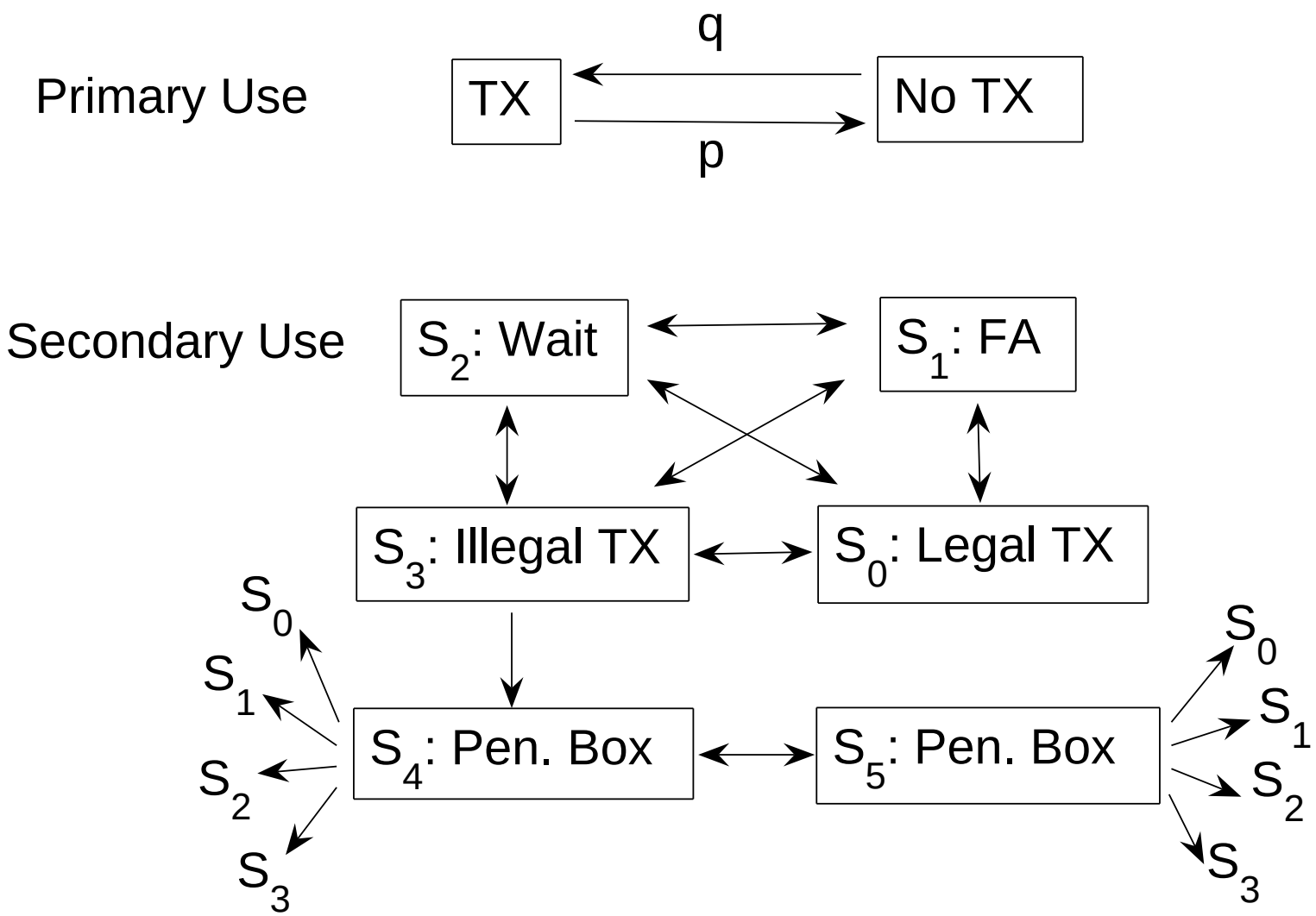
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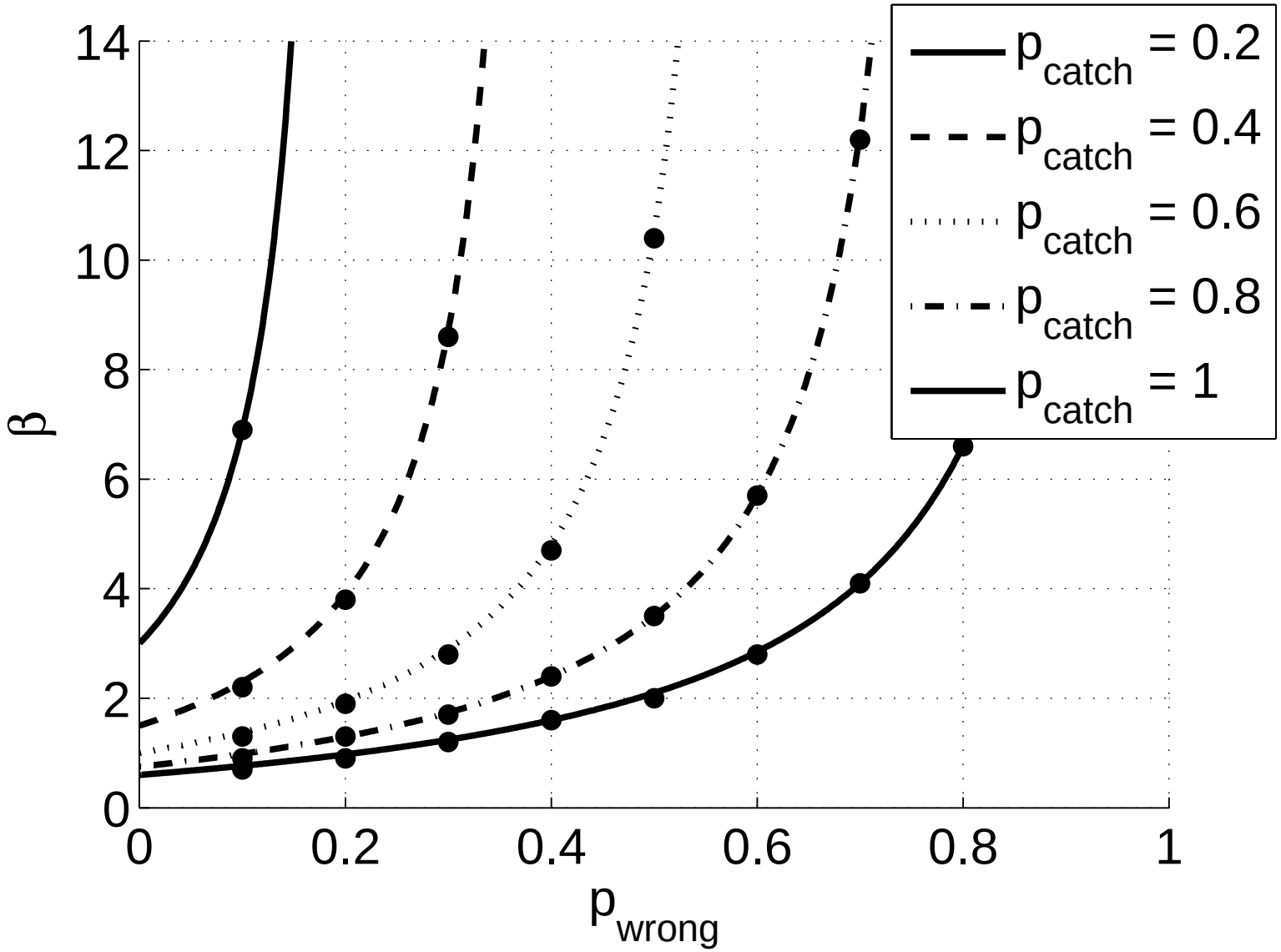
β
p_wrong
0
2
4
6
8
10
12
14
0
0.2
0.4
0.6
0.8
1
p_catch = 0.2
p_catch = 0.4
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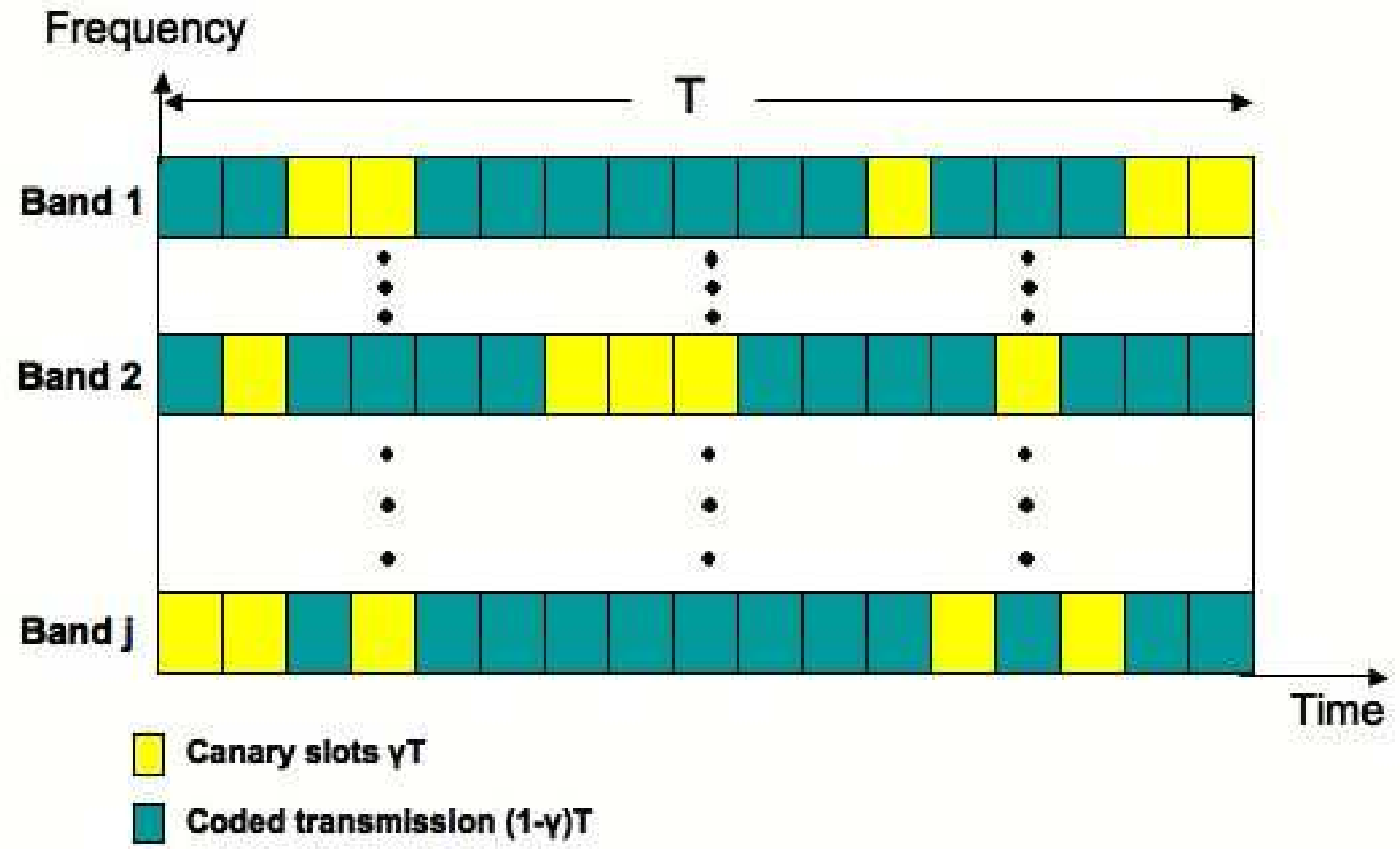

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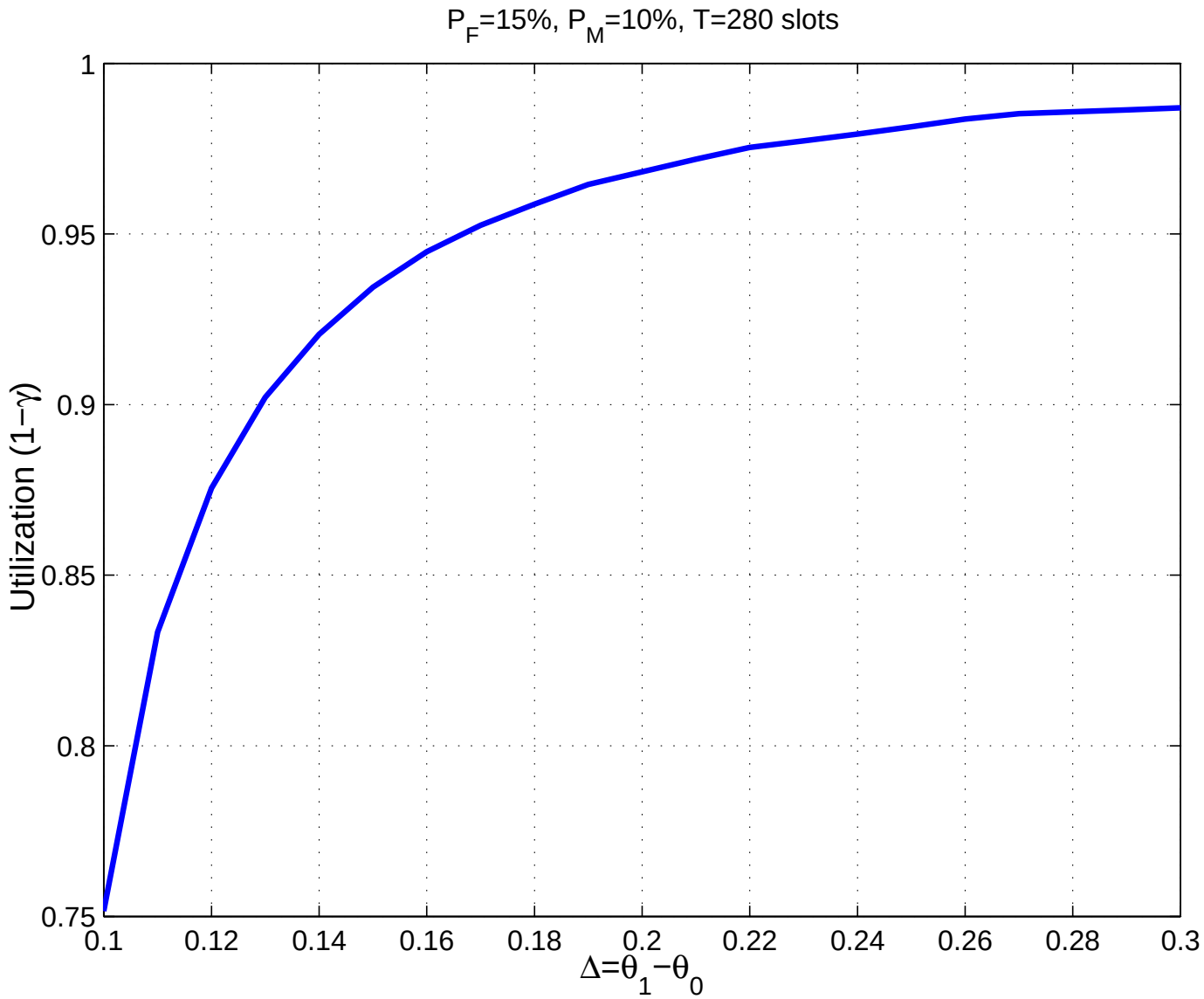
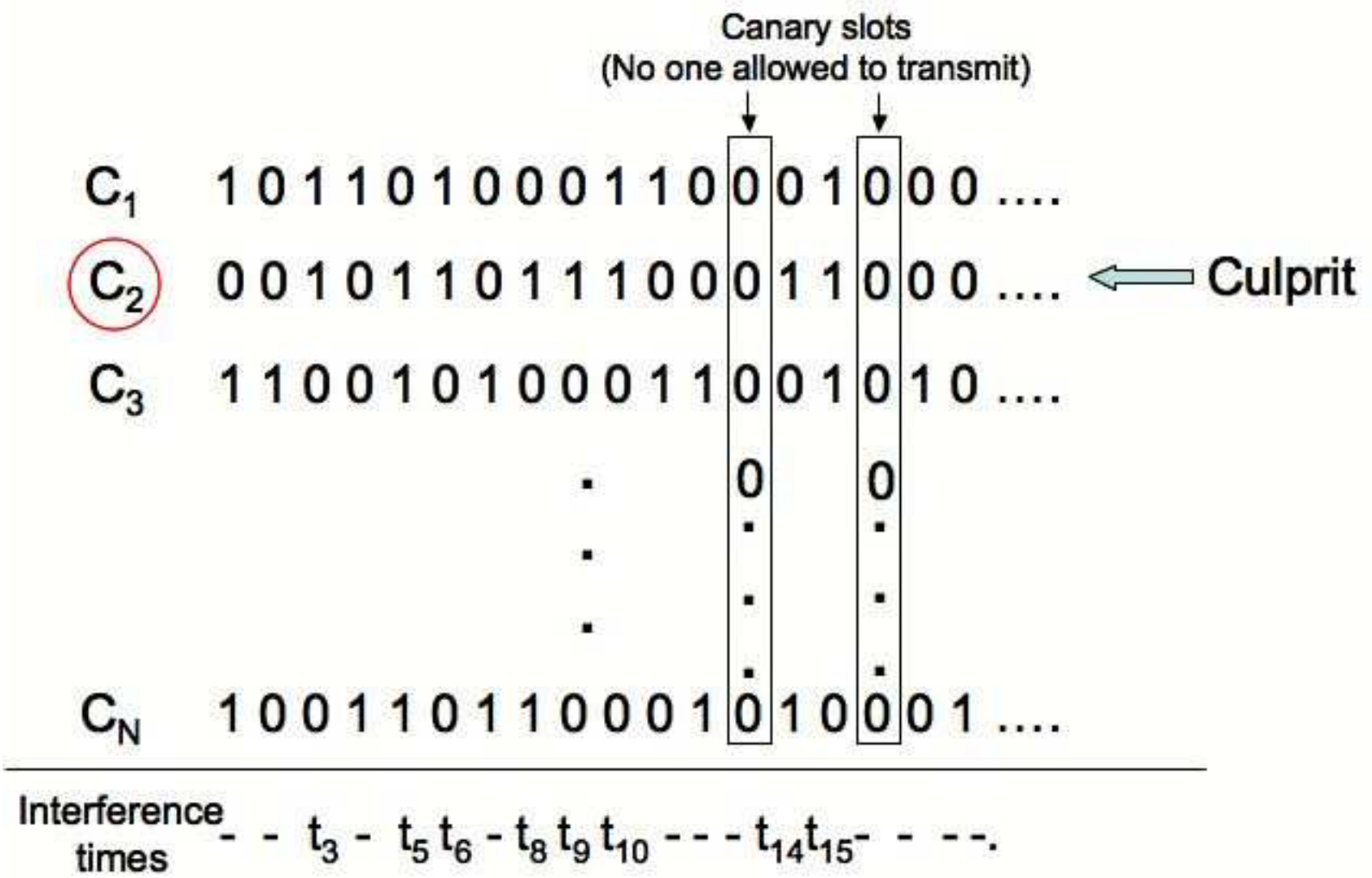


Identity through superimposed codes



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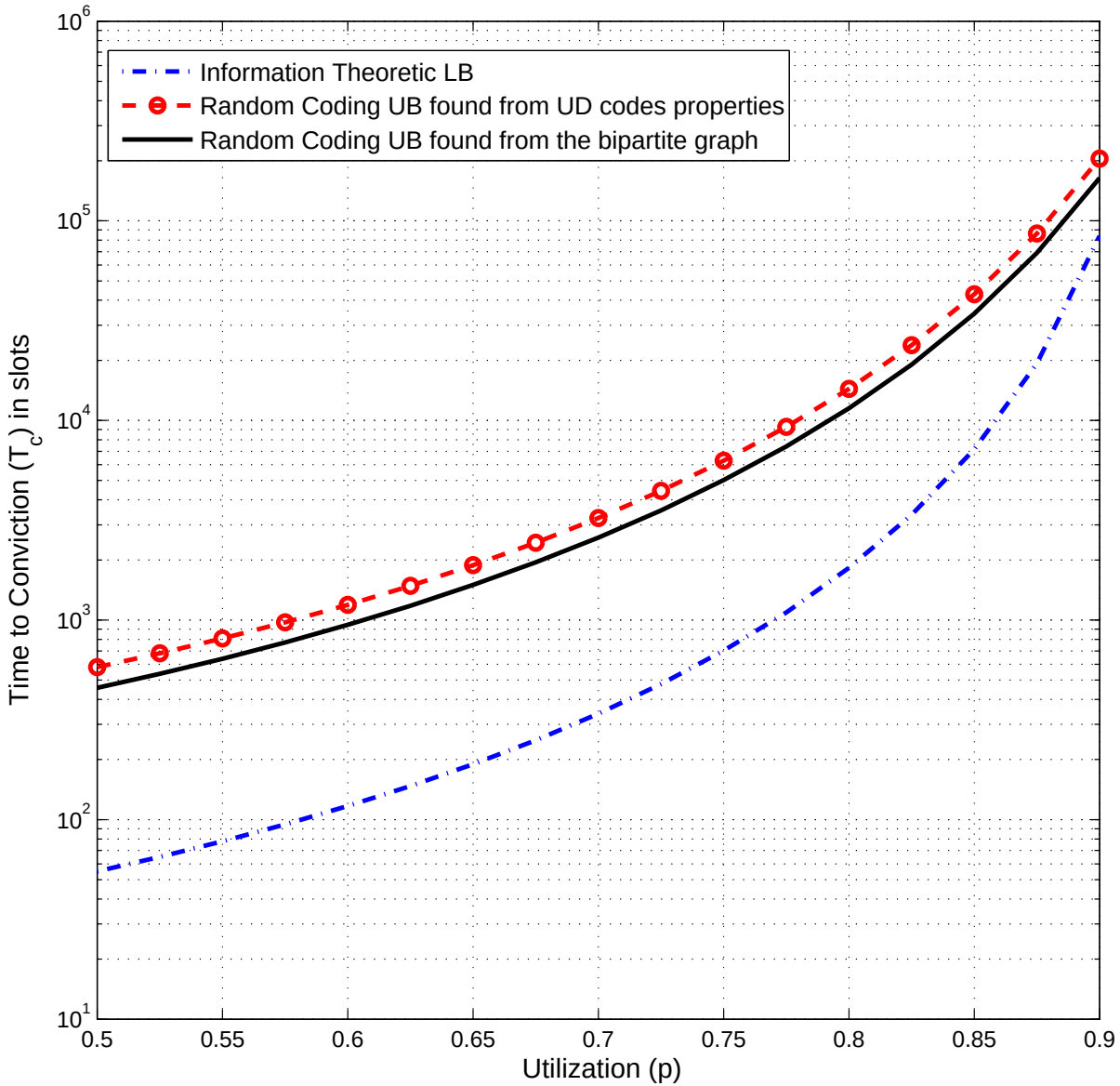

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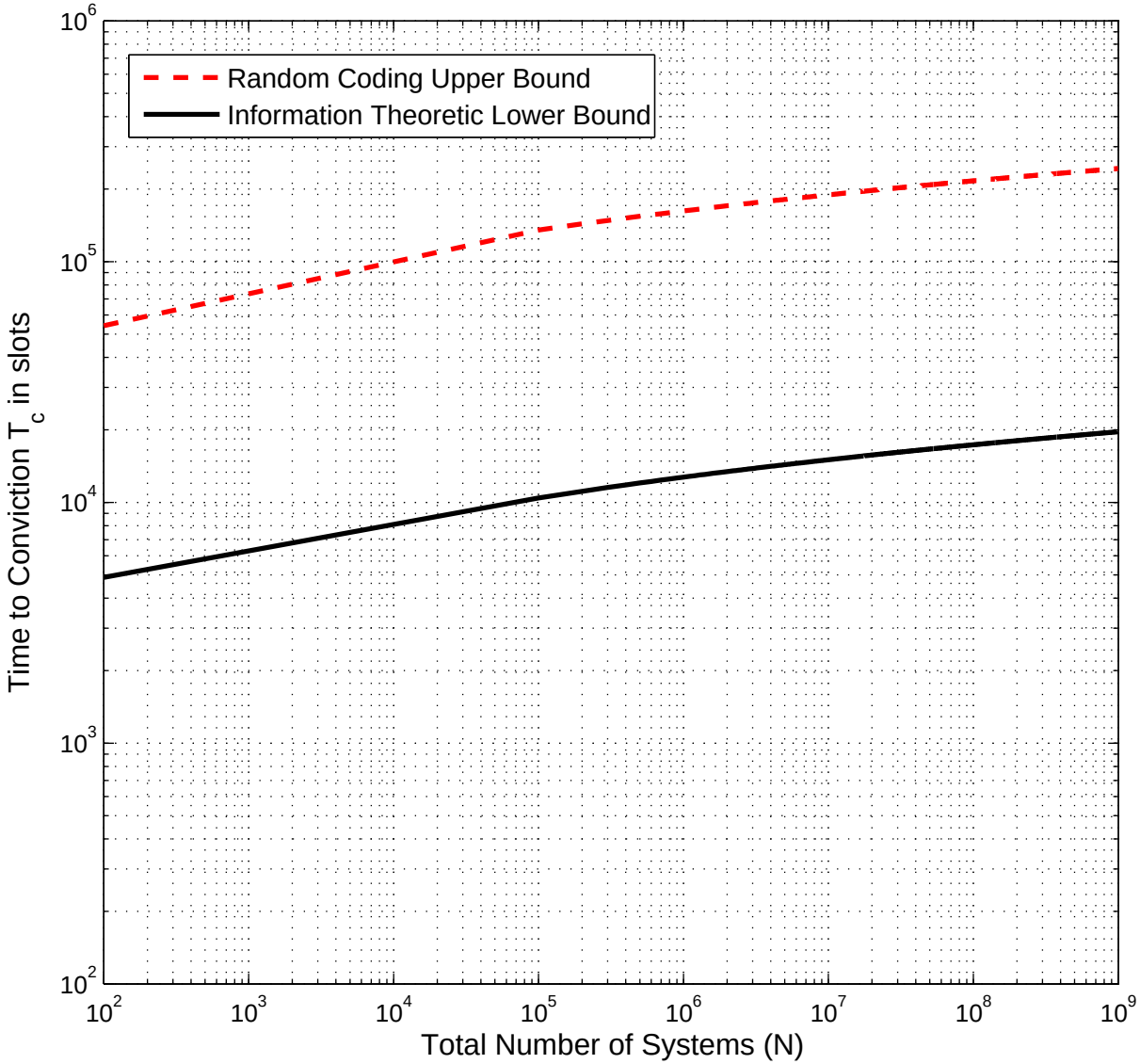

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Decouple sensor network and communication network

	Interference management is primary's responsibility	Interference management not primary's responsibility
Secondary has permission	**Markets**	**Spectrum Monitors**
Secondary must take care	**Denials**	**Opportunistic**

- Purely opportunistic use is harder than it looks.
- Cooperation is just another word for "infrastructure"

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- Purely opportunistic use is harder than it looks.
- Cooperation is just another word for "infrastructure"
- Dedicated sensor-network infrastructure
  - Assume network nodes know where they are
  - Assume large spatial extent beyond primary user scale
  - Construct primary usage map on slower time-scale

Decouple sensor network and communication network

	Interference management is primary's responsibility	Interference management not primary's responsibility
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- Coordinate secondary radios by giving explicit permission.

“Disneyland” vs “Yosemite”

- Owner controls access to preserve QoS
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“Spectrum tour guide” can coordinate users without owning bands.

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  - But big players got bigger — used the new technology to *cut costs* and further exploit economies of scale.

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- Cheap devices will win out over more expensive ones.