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Channel-Adaptive Spectrum Detection and Sensing Strategy for Cognitive Radio Ad Hoc Networks

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Introduction: Hardware Constrained CR

Overlaid CR (Cognitive Radio) Structure

- **SU**s (Secondary User) are required to **sense before accessing** the spectrum licensed to **PU**s (Primary Users).

Hardware Constraint

- Each SU has **limited sensing capability**.
- Sensing outcomes are **prone to errors**, especially under **low PU-to-SU SNR region**:
  - Miss detection (MD) ➔ Collision with PUs,
  - False alarm (FA) ➔ Missed spectrum opportunities.

Observations and Contribution

Observations

- Secondary network throughput degrades when **the received PU signal is weak at the SU sensor**.
- Neighboring SUs experience **similar spectrum opportunities ➔ SU congestion**.

Novel Contribution

- Adapt threshold to the **instantaneous received SNR of the PU signal at the SU sensor ➔** improved **sensor reliability**.
- This **CSI (Channel State Information)** is incorporated into the sensing strategy **➔ randomized sensing decisions** & **reduced SU congestion**.

Related Work

Resolve SU congestion

- **Randomized** policies, e.g. [2-3] - small gain vs. myopic strategy [1].
- **Reward adaptation to SU link CSI** [4] - diversity boosts CR network throughput.
- **Throughput of all strategies degrades for weak PU SNR at sensor**.

Improved sensing detectors

- **Threshold adaptation**, e.g. [5-7] - has not been incorporated into sensing strategy design.
- **Cooperative sensing**, e.g. [8] - requires many independent sensing decisions.

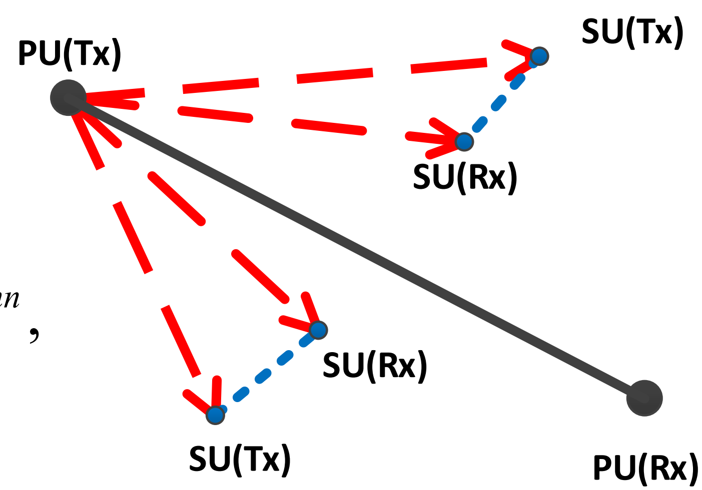
[1] Q. Zhao, L. Tong, A. Swami & Y. Chen, *JSAC* 07
[2] K. Liu & Q. Zhao, *ISSSTA* 08
[3] Y. Lee, *Electron. Lett.* 10
[4] Y. Lu & A. Duel-Hallen, *CCNC* 13
[5] F.T. Foukalas, et. al, *Optimization Lett.* 11
[6] X. Ling, et. al, *IEEE Wireless Commun. Lett.* 12
[7] Y. Lin et. al, *IEEE Trans. Mobile Comput.* 12
[8] Z. Quan, et. al, *IEEE Signal Process. Mag.* 08

Adaptive Sensing Threshold Control

- For the m^{th} SU pair on the n^{th} channel, $m = 1 \cdots M$, $n = 1 \cdots N$, the instantaneous **miss detection** and **false alarm** probabilities are [1]:

$$p_{\mathrm{MD}}^{mn}(t) = 1 - Q_\nu\left(\sqrt{2\nu\lambda^{mn}(t)}, \sqrt{\tau^{mn}(t)}\right), \quad p_{\mathrm{FA}}^{mn}(t) = \Gamma\left(\nu, \tau^{mn}(t)/2\right)\Big/\Gamma(\nu)$$

where $\lambda^{mn}(t)$ is the PU-to-SU SNR per sample, ν is the number of samples, $\tau^{mn}(t)$ is the detection threshold.



- Conventionally, the detection **threshold is fixed**, $\tau^{mn}(t) = \tau^{mn}$:

$$p_{\mathrm{MD}}^{mn} = 1 - \int_{\lambda^{mn}} Q_\nu\left(\sqrt{2\nu\lambda^{mn}}, \sqrt{\tau^{mn}}\right) f_{\lambda^{mn}}(\lambda^{mn})\, d\lambda^{mn},$$

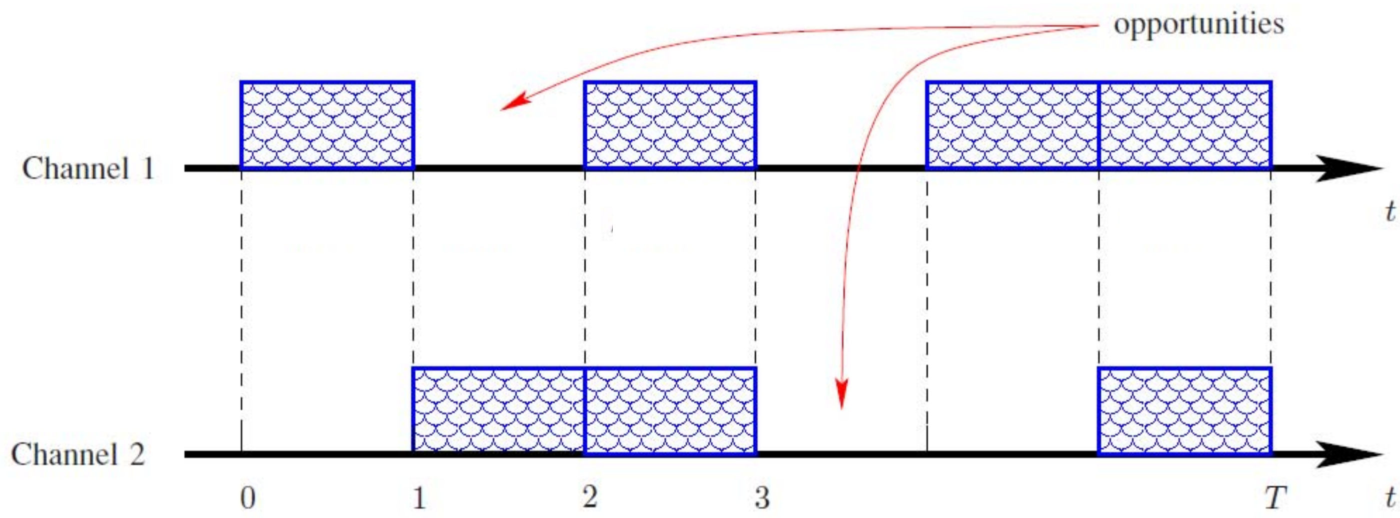
$$p_{\mathrm{FA}}^{mn} = \Gamma\left(\nu, \tau^{mn}/2\right)\Big/\Gamma(\nu).$$

- We propose to **adapt the threshold** to the instantaneous PU-to-SU CSI $\lambda^{mn}(t)$:

$$\tau^{mn}(t) = p_{\mathrm{MD}}^{mn\ -1}(p_{\mathrm{MD,Target}}).$$

[1] A. Ghasemi & E.S. Sousa, *DySPAN* 05

Myopic Sensing in a POMDP Framework



- The PU traffic is modeled as a **stationary Markov chain**.
- SUs can **learn** the particular realization of the MC through sensing and **predict the channel availability probabilities (belief vector)** $\theta^{mn}(t)$ accordingly.
- At each time slot, SU chooses to sense the channel with the **maximum expected reward** $E[R^{mn}(t)]$:

$$n_*^m(t) = \arg\max_n \theta^{mn}(t) R^{mn}(t).$$

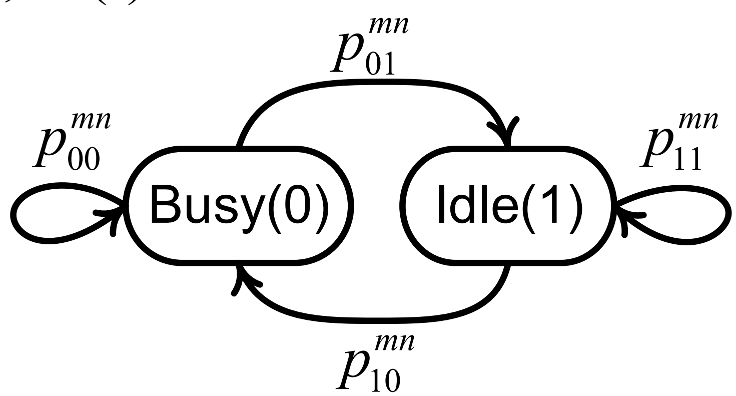
Q. Zhao, L. Tong, A. Swami & Y. Chen, *JSAC* 07

Use $p_{FA}^{mn}(t)$ to Update Belief

- The **belief vector** is updated according to the sensing result and the sensor reliability information [1], $\forall n = n_*^m(t), m = 1, \ldots, M$,

$$\theta_r^{mn}(t) = \begin{cases} \dfrac{\left(1 - p_{\mathrm{FA}}^{mn}\right)\theta^{mn}(t)}{\left(1 - p_{\mathrm{FA}}^{mn}\right)\theta^{mn}(t) + p_{\mathrm{MD}}^{mn}(1 - \theta^{mn}(t))}, a^m(t) = 1 \\ \dfrac{p_{\mathrm{FA}}^{mn}\theta^{mn}(t)}{p_{\mathrm{FA}}^{mn}\theta^{mn}(t) + (1 - p_{\mathrm{MD}}^{mn})(1 - \theta^{mn}(t))}, a^m(t) = 0 \end{cases}$$

$$\theta^{mn}(t+1) = \begin{cases} p_{11}^{mn}\theta_r^{mn}(t) + p_{01}^{mn}(1 - \theta_r^{mn}(t)), \text{if n} = n_*^m(t) \\ p_{11}^{mn}\theta^{mn}(t) + p_{01}^{mn}(1 - \theta^{mn}(t)), \text{if } n \neq n_*^m(t) \end{cases}$$



- We employ $p_{\mathrm{FA}}^{mn}(t)$ instead of the average p_{FA}^{mn} → **improved estimation of the current PU states.**

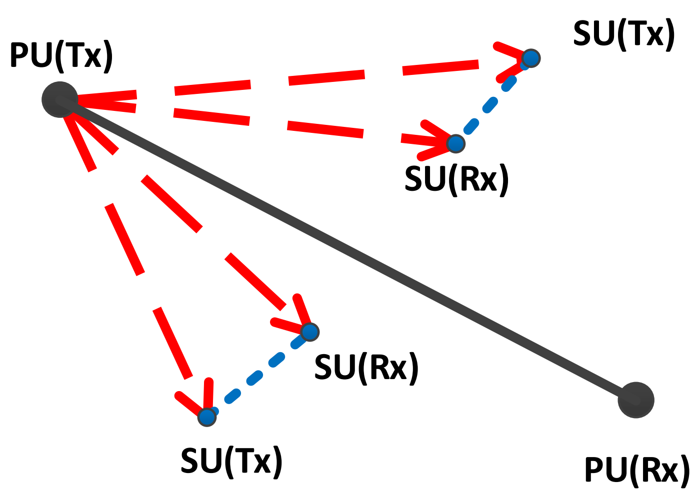
[1] S. Chen & L. Tong, *Milcom* 10

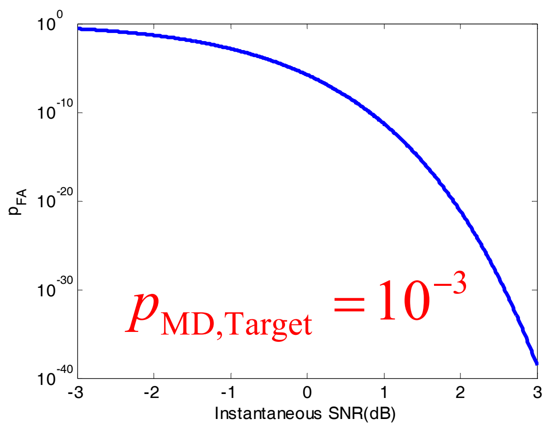
Reward Adaptation

- We **modify the reward** by **the sensing reliability**:

$$R_{\text{AT}}^{mn}(t) = (1 - p_{\text{FA}}^{mn}(t))R_{\text{FT}}^{mn}(t).$$

- Conventionally, $R_{\text{FT}}^{mn}(t) = B_n$; we proposed $R_{\text{FT}}^{mn}(t) = C^{mn}(t)$ in [1].
- $p_{\text{FA}}(\text{t})$ decreases with PU-to-SU CSI $\lambda(t)$.
- SUs **favor channels** with small $p_{\text{FA}}(\text{t})$, or **strong** $\lambda(t)$.
- **Fewer spectrum opportunities get wasted**.
- **Randomized sensing decisions** and reduced SU congestion.

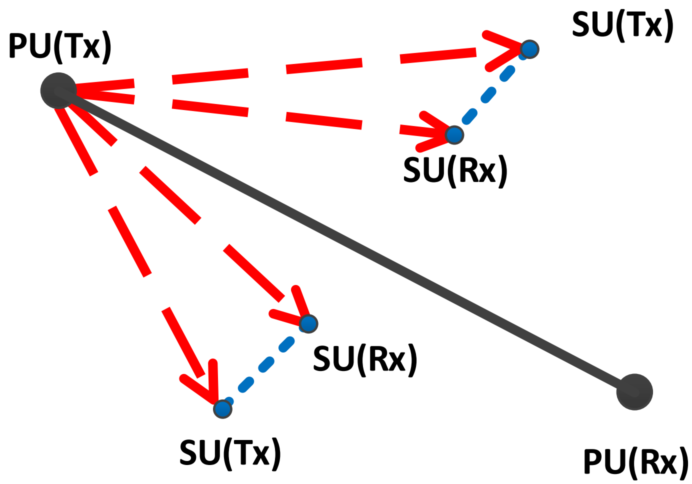


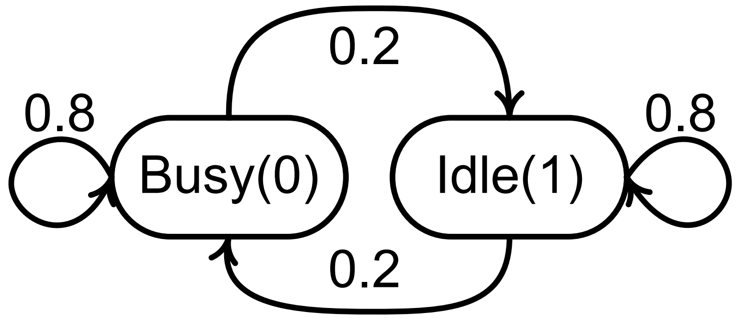


[1] Y. Lu & A. Duel-Hallen, *CCNC* 13

Simulation Setup

- **20** SU pairs and **40** channels with the **same bandwidth** $B = 1$.

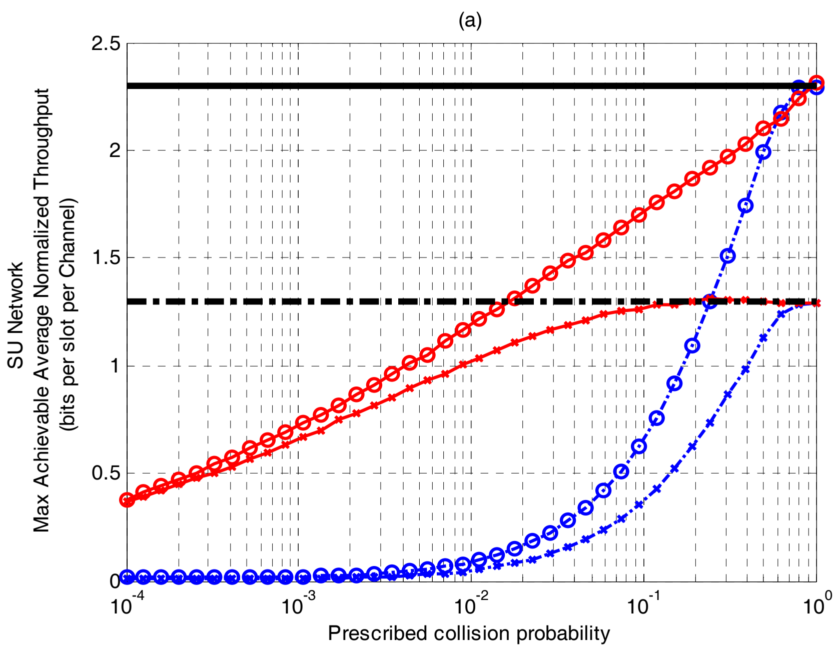


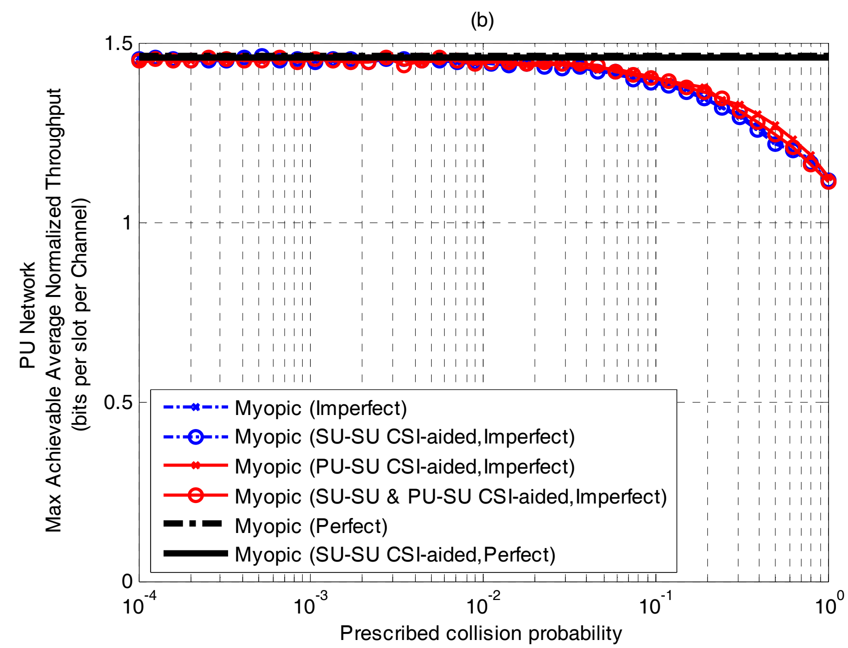


- All **SU-to-SU** and **PU-to-SU** links follow **i.i.d Rayleigh fading** with mean SNRs equal to 10dB and -10dB, respectively.
- **Overlay** structure: miss detection always leads to primary collision.

Adaptation to the PU-to-SU CSI

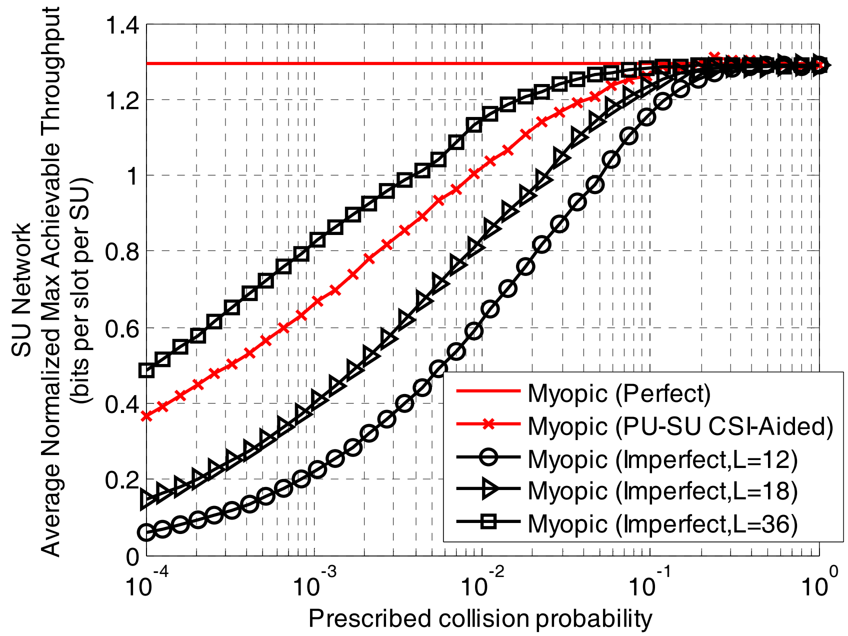
- More **reliable sensing results** and **reduced SU collisions.**
- Average PU-to-PU SNR=10dB, i.i.d Rayleigh fading.
- **0.4 to 1 bit throughput gain** relative to fixed threshold policies.





Comparison with Cooperative Sensing

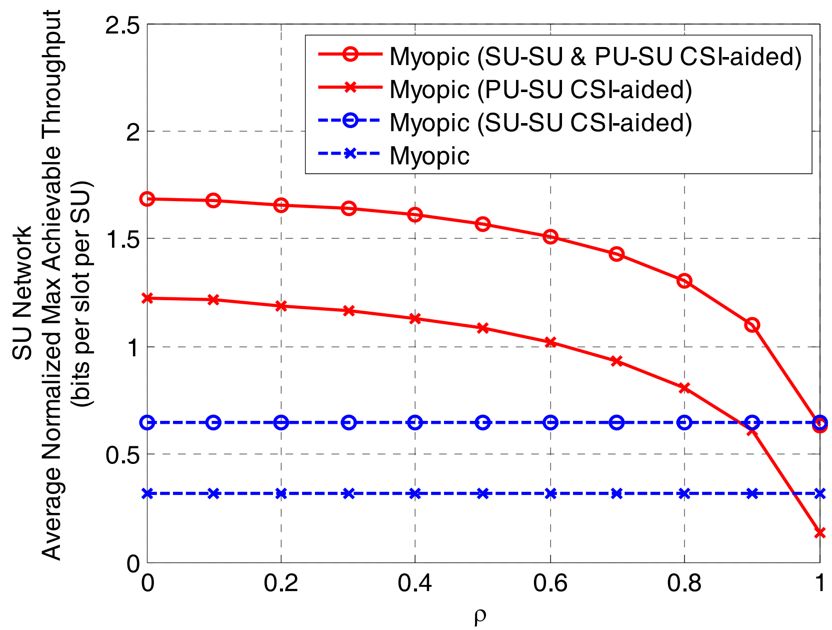
- $p_{\mathrm{MD,Target}} = 0.1.$
- **OR-rule** hard decision combining [1]: $P_{\mathrm{FA}} = 1-(1-p_{\mathrm{FA}})^{L}, \quad P_{\mathrm{MD}} = p_{\mathrm{MD}}^{L}.$
- **Need ≥ 30 independent sensing branches** with fixed threshold to match the performance of the proposed sensing strategy **at a single detector**.



[1] A. Ghasemi & E.S. Sousa, *DySPAN* 05

Impact of Correlated Shadow Fading

- **Easier to adapt to shadow fading** than to multipath fading.
- **Correlation** in space & frequency **reduces diversity**.
- **Spatial correlation** for adjacent SUs is ρ and $\rho_{mm'} = \rho^{|m-m'|}$ [1].
- $\mu_{\gamma_{dB}} = 10\text{dB},\ \mu_{\lambda_{dB}} = -10\text{dB}.$
- **Throughput degrades as ρ increases.**
- **Throughput gain is mostly preserved** in practical ad hoc networks with **ρ ≤ 0.3** [2].



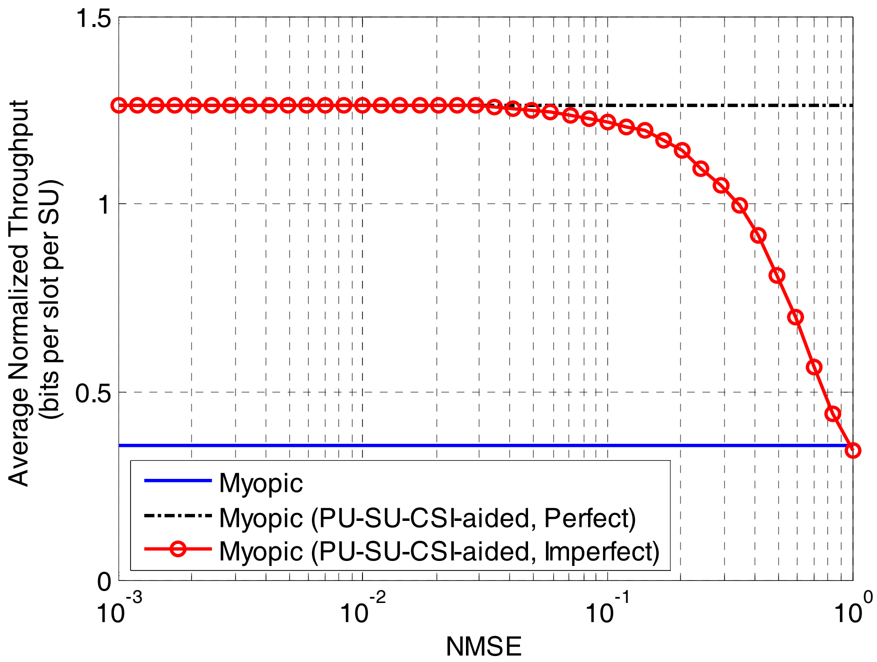
[1] M. Gudmundson, *Electron. Lett.* 91
[2] P. Agrawal & N. Patwari, IEEE Trans. *Wireless Commun.* 09

PU-to-SU CSI Error

- **PU-to-SU CSI estimation:**
  - Channel gain map [1]
  - "Silence" phase [2]
- **CSI mismatch**:

$$\hat{\tau}(t) = \hat{p}_{\mathrm{MD}}^{-1}(p_{\mathrm{MD,Target}}),$$

$$\hat{p}_{\mathrm{MD}}(t) = \int_0^{+\infty} p_{\mathrm{MD}}(t) f(\lambda \mid \hat{\lambda}) d\lambda.$$



- Approximates the ideal CSI case when **NMSE < 0.1**.
- **Degrades gracefully** to the conventional myopic strategy as the CSI mismatch increases.

[1] E. Dall'Anese, S. Kim & G.B. Giannakis, *IEEE Trans. Veh. Technol.* 11
[2] A. Jovicic & P. Viswanath, *IEEE Trans. Inf. Theory* 09

Conclusion and Future Work

Conclusion

- The **detection threshold is adapted** to the instantaneous PU signal SNR under an instantaneous p_{MD} constraint.
- **Instantaneous p_{FA} is incorporated** in the sensing strategy.
- Provide **0.4 to 1 bit gain** over fixed threshold strategies.
- Matches the throughput of conventional cooperative sensing with **30 independent diversity branches**.

Future Work

- **Estimation and prediction** of fading PU-to-SU channel.
- Joint CSI-aided sensing and **collision-avoidance MAC**.
- Test under **asynchronous model**.

Thank you!