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# Channel-Adaptive Sensing Strategy for Cognitive Radio Ad Hoc Networks

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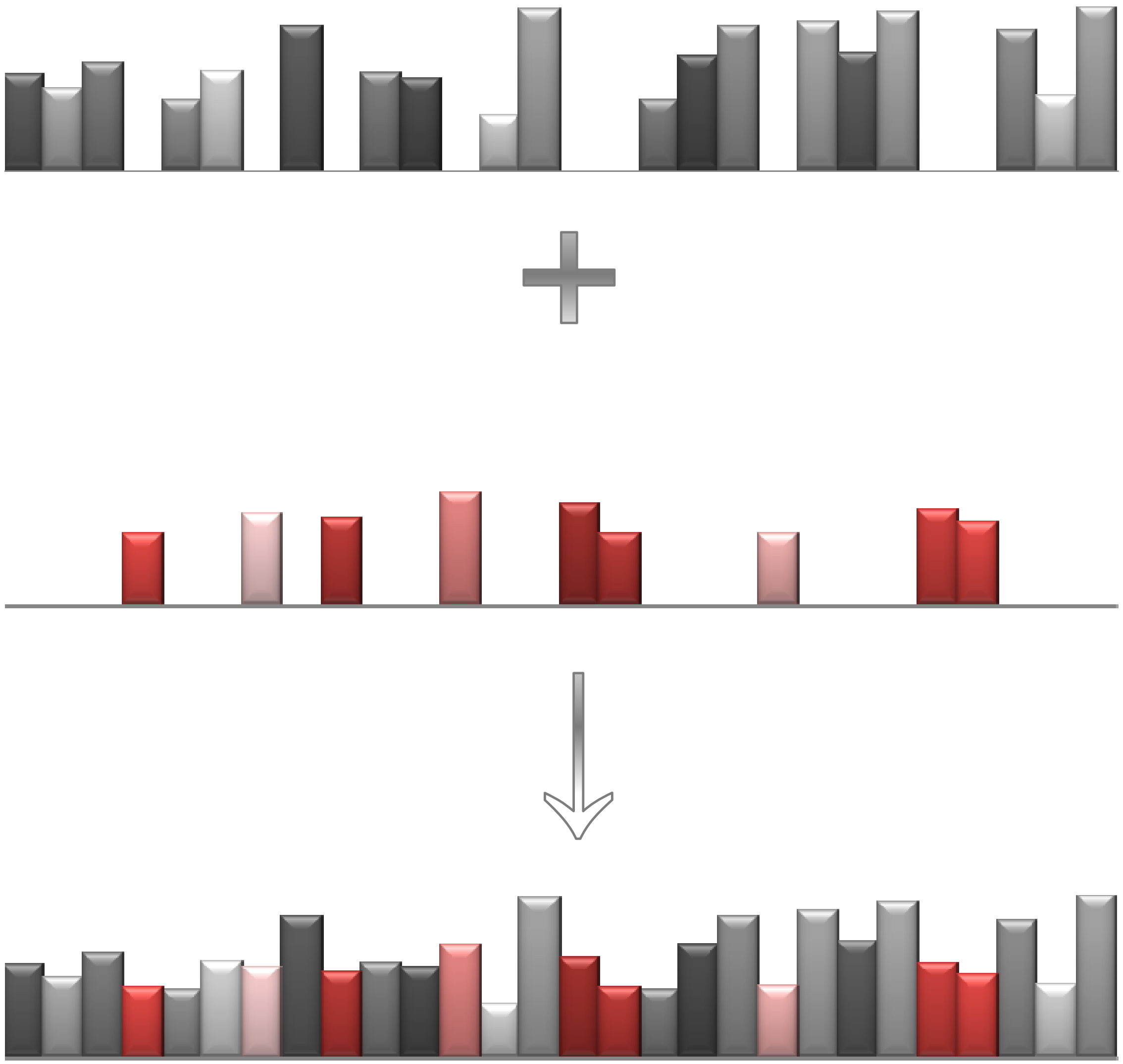
# Outline

- Introduction
- Related Work
- Observations and Goals
- Channel-Adaptive Sensing Strategy
- Numerical Results
- Conclusions and Future Work

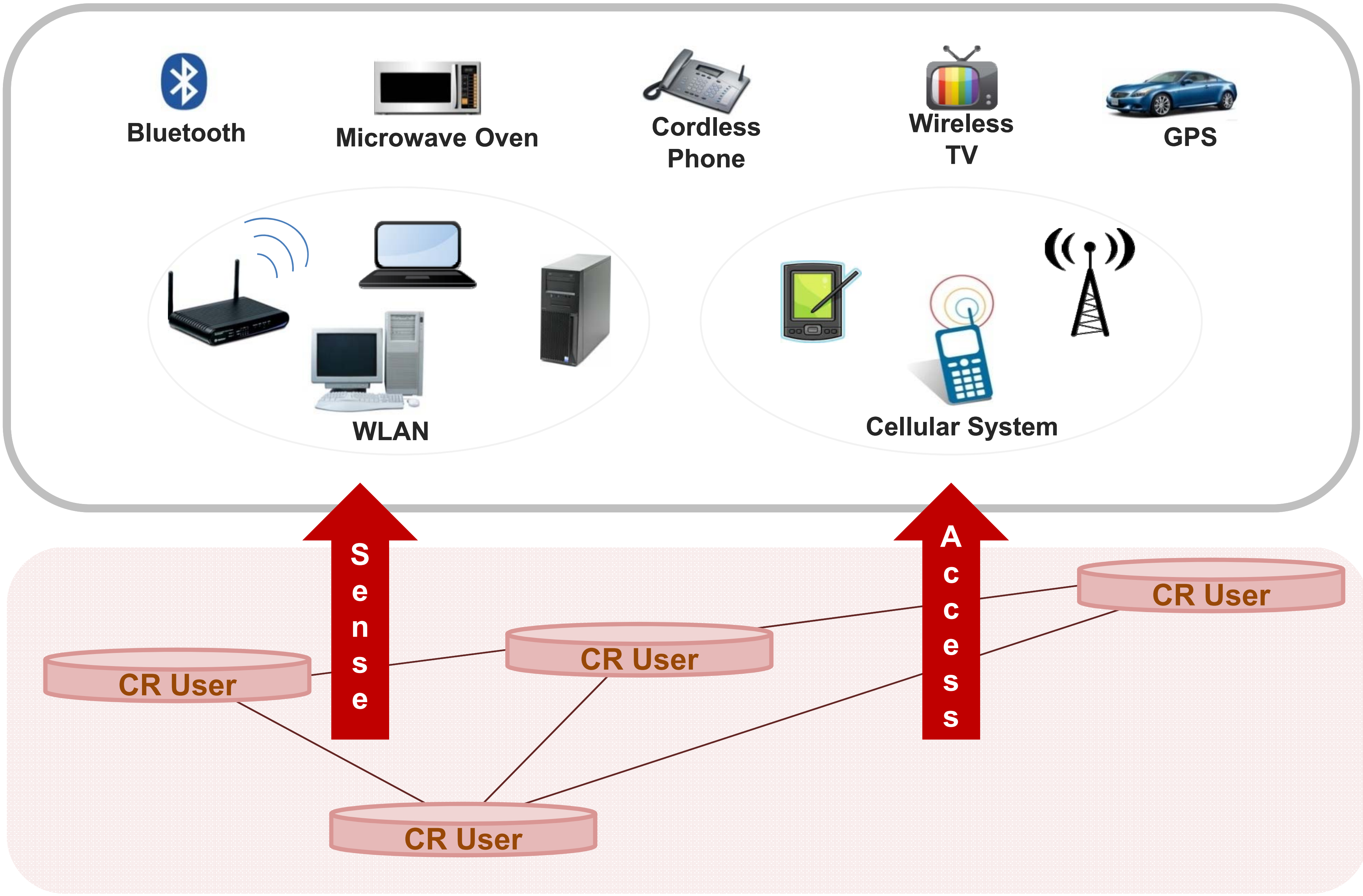
# Introduction: Cognitive Radio (CR)



Primary Users (PU)

Secondary Users (SU)

# Introduction: Cognitive Radio (CR)



# Introduction: CR MAC

## Problem

- Each SU has **limited sensing capability**.
- Neighboring SUs experience **similar spectrum opportunities**.

## Objective

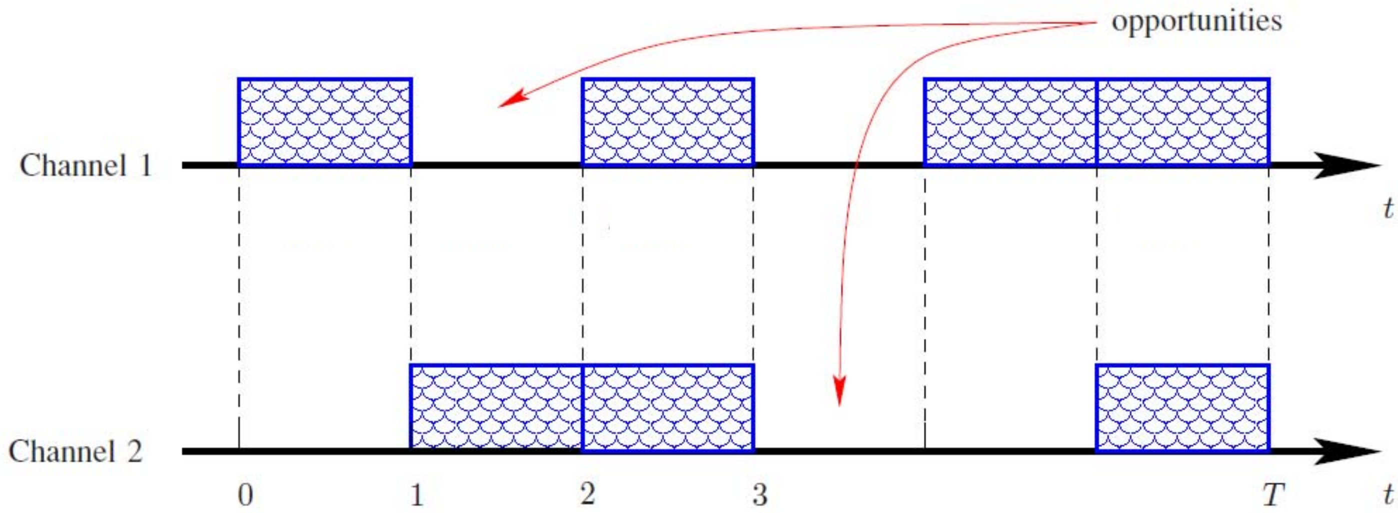
To **maintain high throughput**, SUs need to:

- Sense and access the channels that are not used heavily by PUs.
- Avoid collisions with other SUs.

## Our solution

- Randomize sensing decisions and increase the individual throughput by exploiting **spatially-variant channel conditions** on different SU links.

# 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)** 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

# Randomized Sensing Strategies

- The **conventional reward** choice is given by the channel bandwidth

$$R^{mn}(t) = B_n,$$

which is often normalized to one.

- When the myopic policy employs this reward ➔ SUs sense the channel that is **most likely to be idle**.
- As neighboring SUs learn the PU traffic through sensing, they will make similar sensing decisions ➔ **SU congestion**.
- Different SUs should seek spectrum opportunities on **different channels** ➔ a **randomized** sensing policy is required.
- Previously proposed randomized strategies **retain this reward.**

# Related Work

- Randomize sensing decisions.
- Employ user negotiation.
- Sacrifice individual throughput to compensate for possible SU collisions.
- Fail to exploit the underlying wireless channel.
- Provide limited throughput improvement.
- Policies compared in this paper:
  - Myopic policy: **Q. Zhao, L. Tong, A. Swami & Y. Chen, *JSAC* 07.**
  - Randomized strategy: **K. Liu & Q. Zhao, *ISSSTA* 08.**
  - Myopic with Collision Avoidance (CA): **Y. Lee, *Electron. Lett.* 10.**

**J. Jia, Q. Zhang & X. Shen, *JSAC* 08**
**H. Liu & B. Krishnamachari, *CCNC* 08**
**H. Liu, B. Krishnamachari & Q. Zhao, *ICC* 08**
**L. Lai, H. El Gamal, H. Jiang & H.V. Poor, *IEEE Trans. Mobile Comput.* 11**

# Observations and Goals

## Observations

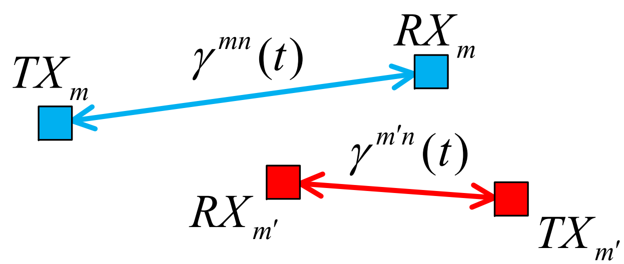
- In a wireless environment, **the powers of SU links vary** over space and frequencies due to channel fading.
- **Adapting the reward** to the channel state information (**CSI**) can improve the individual throughput.
- With different SU sensing preferences, **competition among SUs** can be readily resolved.

## Goals

- Increase network **throughput**.
- Improve **fairness** among users.
- Reduce **power** consumption.

# Channel-Adaptive Sensing Strategy

- For the SU pair $m$ at time slot $t$, let $\gamma^{mn}(t)$ denote the received signal-to-noise ratio (SNR) of the $n^{th}$ channel.



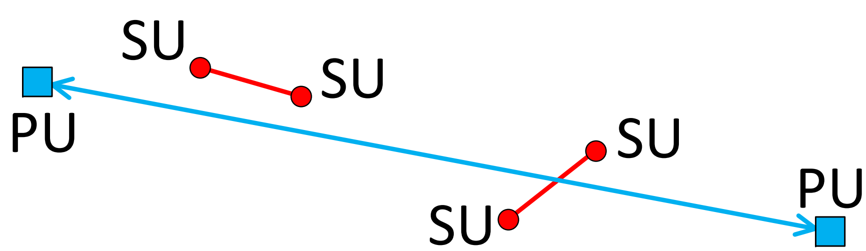

- In the proposed CSI-aided sensing policy, the **reward is given by the channel capacity**:

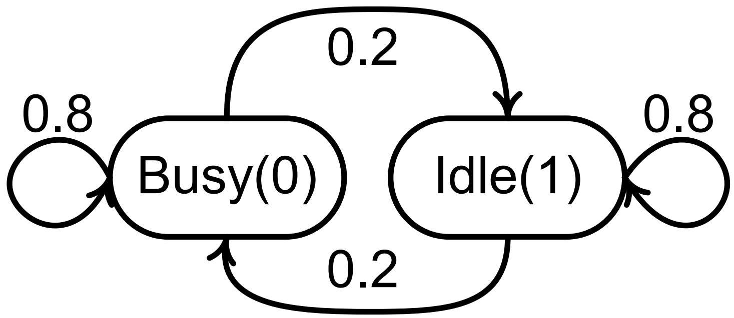
$$R_{\text{cap}}^{mn}(t) = C^{mn}(t) = B_n \log_2(1+\gamma^{mn}(t)).$$

- This reward is a function of the **instantaneous CSI** and varies over SU locations and over channels, randomizing the sensing decisions and improving the individual throughput.

# Simulation Setup

- We consider a CR network with **20 SU pairs** and **40 channels** with the **same bandwidth** $B=1$ **evolving independently**.
- Assume the transmission range of PUs is much larger than that of SUs, and thus **all SUs are affected by the same set of PUs.**
- The **transition matrix** of the channel state is the **same for all channels and all SUs**.

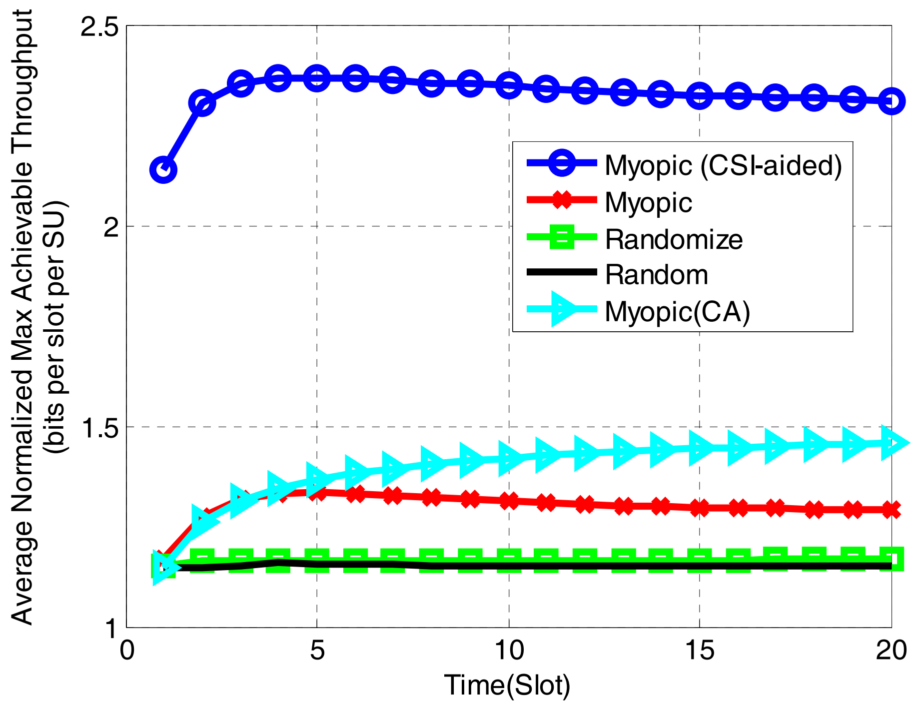



- $\gamma^{mn}(t)$ is **fixed over the duration of one time slot**.
- MAC: If multiple SU pairs choose to sense the same channel, and if that channel is idle, **only one SU can access successfully**. **(J. Chen, S.T. Sheu & C.A. Yang, *PIMRC* 03)**

# Ideal CSI-aided policy, perfect CSI

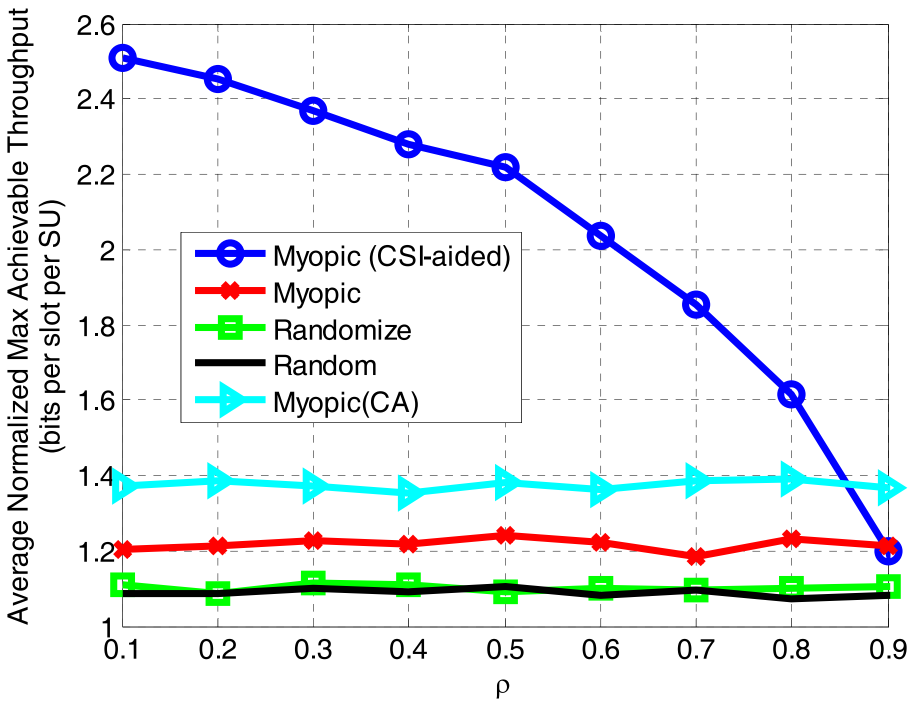
- Throughput vs. time, i.i.d. Rayleigh fading, average $\mathrm{SNR} = 10\mathrm{dB}$, $f_{dm} = 40\mathrm{Hz}$.
- All policies employ channel capacity as the **accumulated reward**.
- The gain of the CSI-aided policy is at least 0.8 bits/slot/user.
- This gain is due to **channel adaptation prior to sensing.**



# Robustness to Spatial Correlation

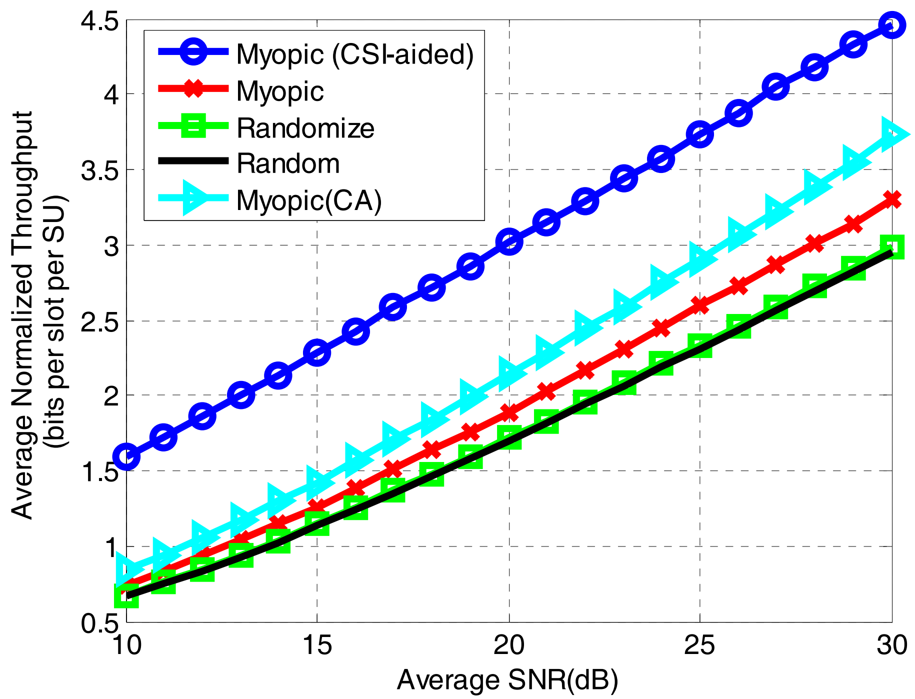
- Might be **easier to adapt to shadow fading** than to multipath fading.
- However, **shadow fading is correlated** in space and frequency, reducing multiuser diversity gain.
- Average $\mathrm{SNR} = 10\mathrm{dB},\ \sigma_{\gamma_{\mathrm{dB}}} = 5\mathrm{dB},$ perfect CSI, 40 Tx, 1 Rx.
- Correlated shadow fading model in: **(Ghasemi & E.S. Sousa, *IEEE Commun. Lett.* 07).**
- Throughput degrades as $\rho$ increases.
- In **ad hoc networks**, spatial correlation is below 0.3, so **multiuser diversity gain is mostly preserved.**

**(P. Agrawal & N. Patwari, *IEEE Trans. Wireless Commun.* 09)**



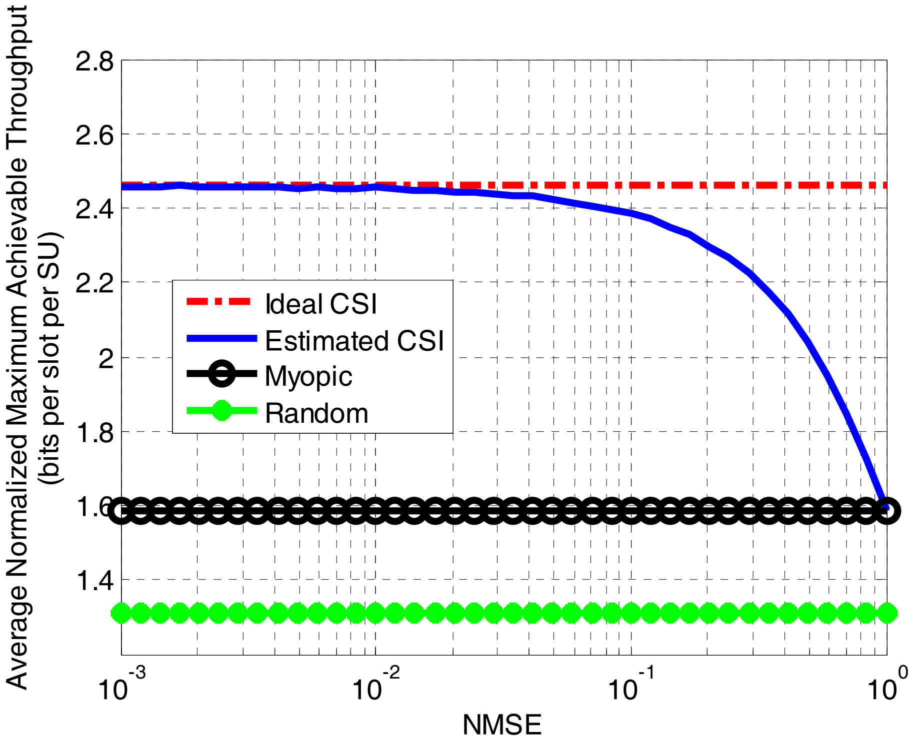
# Adaptive Modulation

- Assume continuous rate QAM adaptation with fixed transmission power: $R_{\mathrm{AM}}^{mn}(t) = B_n k^{mn}(t)$, where $k^{mn}(t)$ is the maximum spectral efficiency that the system can support under a certain BER constraint $(10^{-3})$. **(S.T. Chung & A.J. Goldsmith, *IEEE Trans. Commun.* 01)**
- **CSI-aided policy** outperforms myopic by **8dB** and myopic (CA) by at least **5dB** in realistic SNR range.

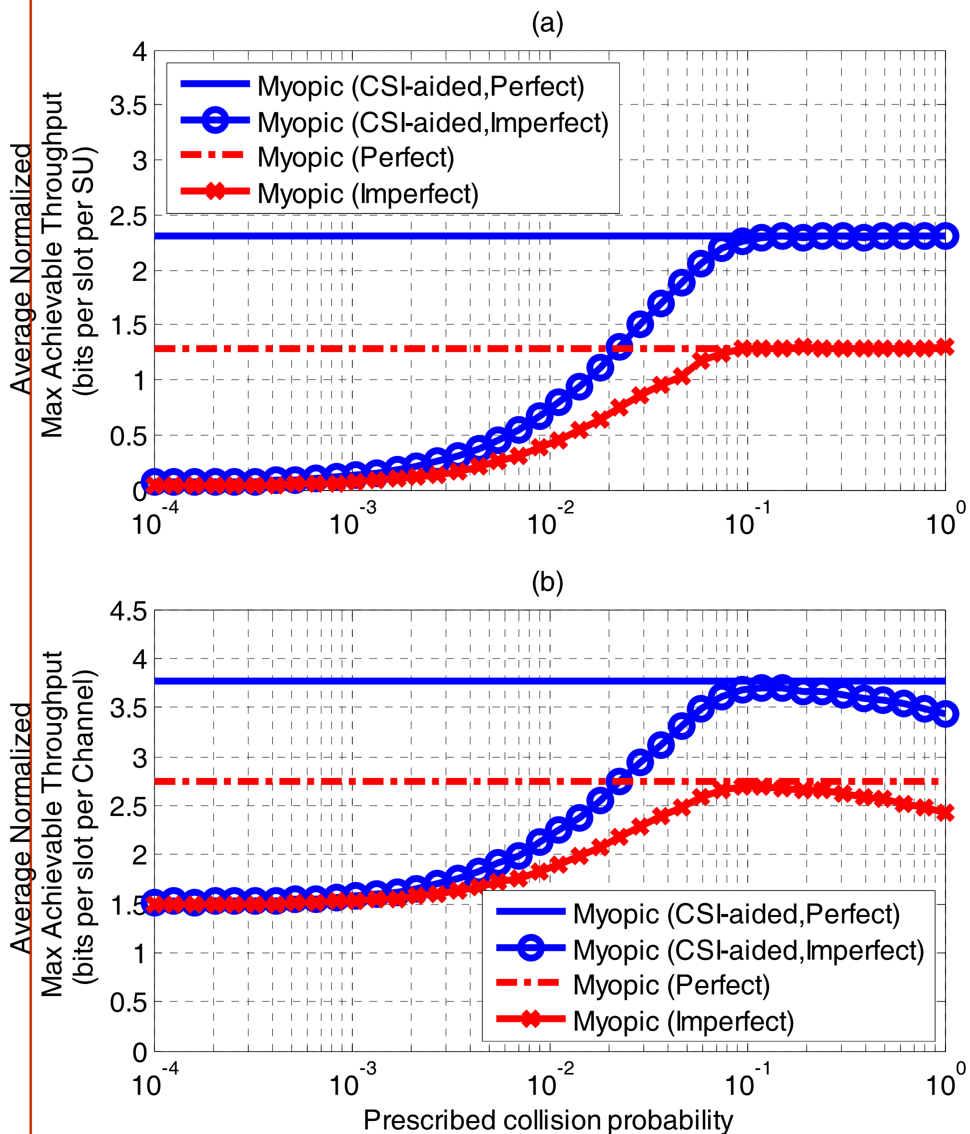


# Robustness to CSI Mismatch

- Channel gain is required prior to sensing – employ **pilots.**
  (A. Tajer & X. Wang, *IEEE Trans. Mobile Comput.* 10; A.Duel-Hallen, *Proc. IEEE* 07)
- **CSI mismatch**: $R(\hat{\gamma}) = \int_0^{\infty} R(\gamma) f(\gamma \mid \hat{\gamma}) d\gamma.$
- For Rayleigh fading, $f(\gamma \mid \hat{\gamma})$ was derived in :
  (D.L. Goeckel, *IEEE Trans. Commun.* 99).
- Approximates the ideal CSI case when **NMSE < 0.1**.
- Throughput of the CSI-aided policy **degrades gracefully** to that of the conventional myopic policy as the CSI mismatch increases.



# Performance with Sensing Error




- **Energy detection**. The **belief vector** is updated according to the sensing result and the sensor reliability information. **(S. Chen & L. Tong, *Milcom* 10)**
- i.i.d Rayleigh fading, SNR=10dB.
- SU network throughput **reaches the ideal case,** but PU throughput is reduced as $p_m$ grows.
- The **optimal value** of $p_m$ is 0.1.
- CSI-aided strategy **maintains 1 bit gain** over the conventional myopic policy for $p_m \geq 0.1$.

# Conclusions and Future Work

## Conclusions

- We proposed to **adapt the reward to the SU link CSI** in the CR ad hoc network sensing strategy design.
- This method **improves the SU throughput** and provides **multi-user diversity** by randomizing sensing decisions.
- CSI-aided strategy achieves a **throughput gain** of about 1 bit/slot/user or at least 5dB over other sensing strategies.

## Future Work

- Combine CSI-aware sensing with a **multiuser MAC** approach.
- Pilot-based methods for **CSI estimation** prior to sensing.
- Impact of **realistic spatial and frequency correlation**.
- Combine CSI-aided sensing with **PU traffic** statistics tracking.

# Thank you!