Cognitive Access Control Strategies with Periodic Channel Sensing for Continuous-Time Markovian Channels

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Joint work with
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Outline for The Talk

- Introduction
- Primary and Secondary System
- Optimal Access Policies
- Conclusion

Background

- Spectrum scarcity and the emerging of a lot of new wireless equipments
- Use certain portions, others are unutilized.
- Low level of the utility of the allocated channels

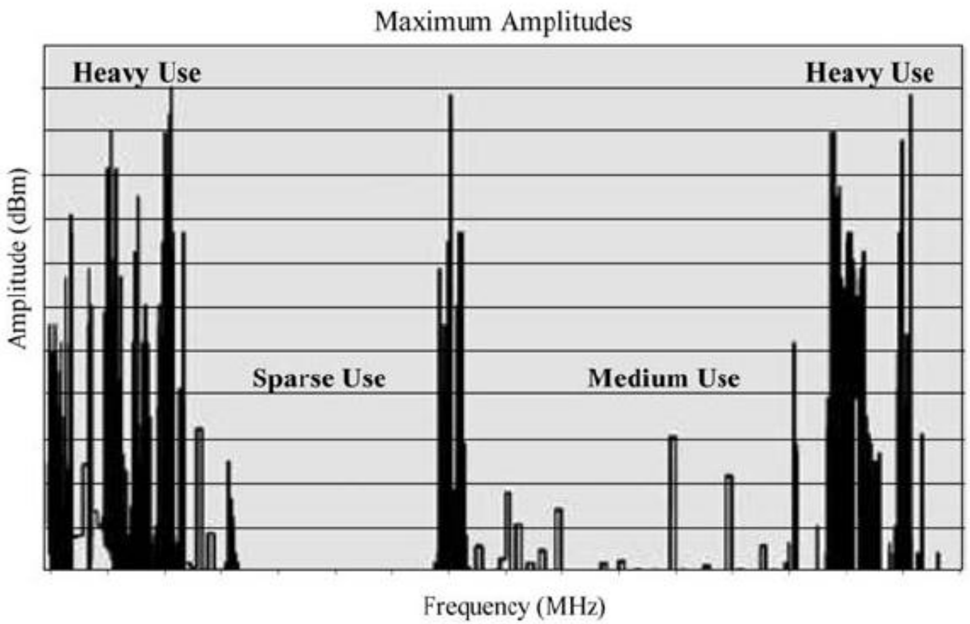

Fig 1. Spectrum Utilization (FCC)

Background

- Cognitive radio aims to explore the opportunity to access the licensed spectrum resource, so that the spectrum resource can be utilized more sufficiently.
- Primary Uesr (PU), Secondary User (SU)

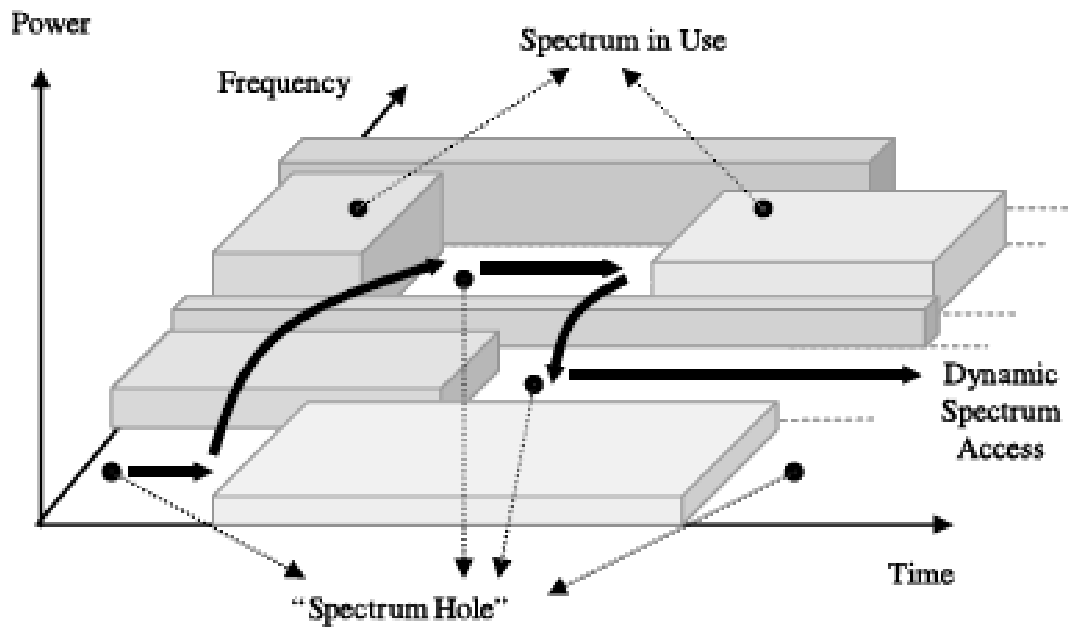

Fig 2. Spectrum hole [I. Akyildiz Comnet' 06]

Related work

- **Slotted structure**
  - [Zhao&Tong&Swami NFDSAN'05] shows first sensing and then transmitting under the constraints.
  - [Q. Zhao&Sadler SP'07] concerns about a hierarchical network.
  - [Chen *et al*. ACSSC'06], [Q. Zhao *et al*. JSAC'07] consider all users use slotted structure and formulate the problem as a POMDP.
  - [Q. Zhao *et al*. WC'06], [Ahmad *et al*. IT'08] show that optimal policy is myopic under certain conditions.

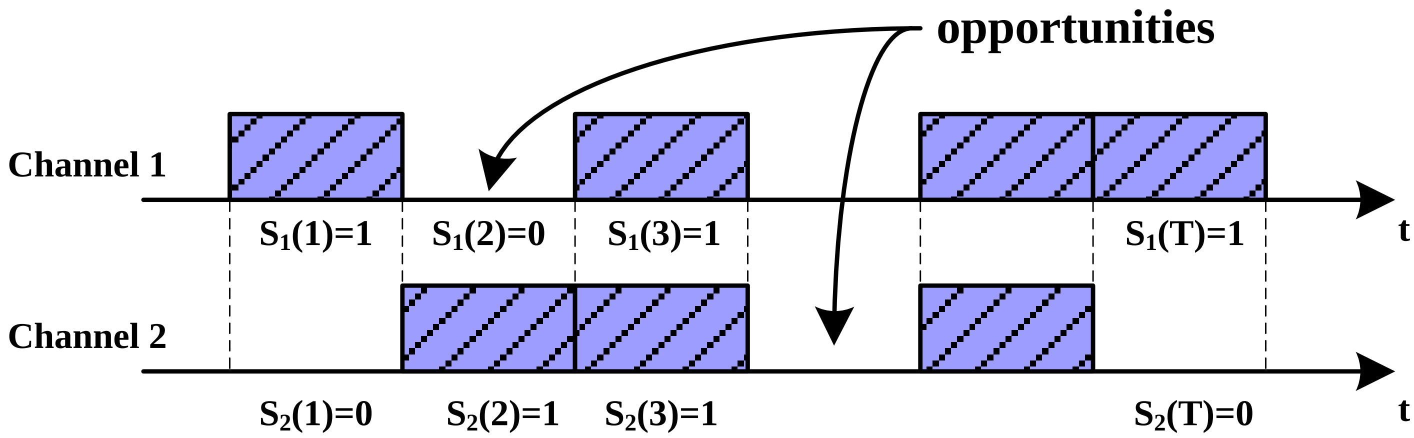

Fig 3. Slotted Cognitive Systems

Related Work

- **Unslotted structure**
  - [Zhao et al. SP'08] releases the constraint of slotted structure of PU, and imposes a periodic sensing structure to simplify the problem from a constrained POMDP to a CMDP with a finite number of states, and the resulting optimal access policy was obtained by a LP.

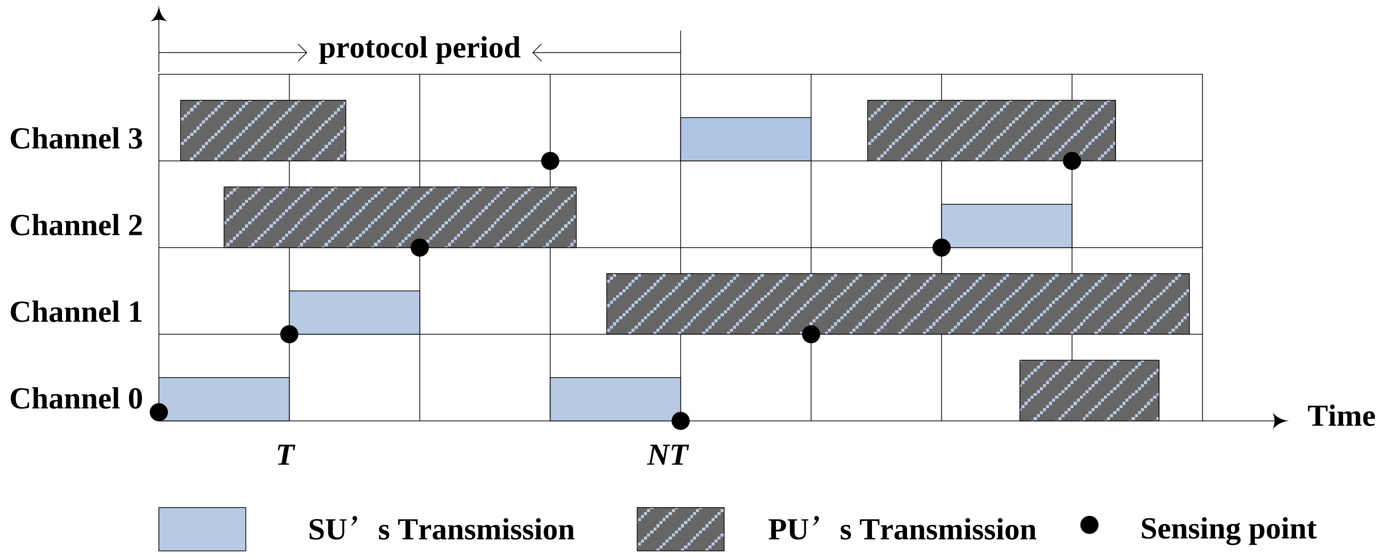

Fig 4. Optimal access via periodic sensing cognitive systems

Related Work

- **Unslotted structure**
  - [Huang *et al.* INFOCOM'08] and [Huang *et al.* INFOCOM'09] investigated the fundamental limit and structure of cognitive access of a single continuous-time Markovian channel, where the authors consider the optimal transmission policy with arbitrarily small sensing and transmission periods. The optimal transmission is probabilistic. For the single channel case, one of our access strategies (called PS-MA) reduces asymptotically to the access policy considered in [Huang *et al.* INFOCOM'08], as the duration of the transmission period approaches to zero.
  - [Zhao *et al.* WCNC'07] and [Akbar&Tranter SoutheastCon'07] independently introduced periodic sensing strategies with memoryless transmissions while [Akbar&Tranter SoutheastCon'07] does not consider constraints on collisions and [Zhao *et al.* WCNC'07] provides a lower bound version.

Related Work

- **Multiple secondary user cases**
  - [Wang *et al.* INFOCOM'10] proposes an ALOHA style protocol for a system similar to one considered here, but is in general suboptimal.
  - [Chen&Tong ITA'10] substantially generalization of the results in this talk to the multiuser setting.
  - [Liu&Zhao ITA'10] and [Anandkumar *et al.* INFOCOM'10] study the multiple secondary users for systems where primary and secondary users are both slotted. These results are very different from the ones considered in this paper in the models assumed and techniques used.

Our work

Our work

- Extend the work [Zhao et al. SP'08], where the framework of periodic sensing is adopted for multi-channel DSA under the continuous time Markovian traffic model.
- The optimality of a simple memoryless access policy with periodic channel sensing is established under tight constraints.
- The extension of the simple memoryless access policy to multi-secondary user case.

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Primary and secondary system

- **System Assumption**
  - N independent PU channels, 1 SU
  - PUs follow continuous time Markov chain, '0' channel idle and '1' channel busy; SU slotted protocol
  - λ_i^{-1} and μ_i^{-1} are holding times for idle and busy states respectively
  - The SU employs slotted transmissions with slot duration T.
  - At the beginning of each slot, the SU chooses one of the *N channels to sense and makes a decision to* transmit in one of the *N channels or not to transmit at all.*

Primary and secondary system

- **Sensing Scheme and Access**

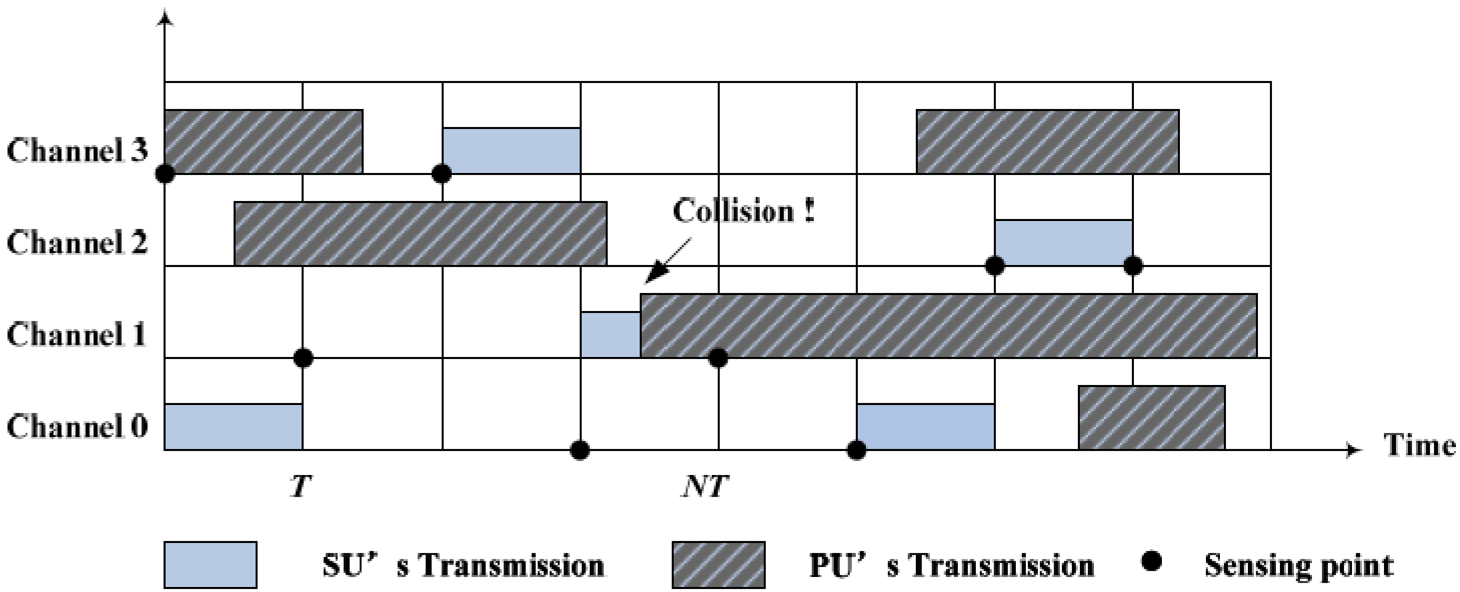

Fig 5. Illustration of a general admissible access protocol. The transmissions are in general probabilistic. Collisions may happen over channels that are sensed idle.

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Optimal Access Problem

- **System Throughput and Constraints**
  - $J(\pi) = \lim_{K \to \infty} \frac{1}{K} \sum_{k=1}^{K} E_\pi(R_k^\pi)$ the average throughput
  - $C_i(\pi)$ the collision for the *i*th primary user. It is defined to be the

f
t
f

$$C_i = \frac{1}{1 - v_i(0)e^{-\lambda_i T}} \lim_{n \to \infty} \frac{\mathbb{E}\left(\sum_{t=1}^{n} 1_{\{\text{collide PU } i \text{ in slot } t\}}\right)}{n}$$

- **Optimization problem formulation**

$$\max_{\pi \in \mathscr{P}} J(\pi) \quad \text{subject to } C_i(\pi) \le \gamma_i, \quad i = 0, \ldots, N-1,$$

- **Challenges:** The general constrained POMDP problem with average criteria is intractable in general.

Single SU Cognitive Access

- **Upper bound**

FO-OSA (optimal spectrum access with full observation)

π^{FO}

- **Lower bound**

PS-MA (periodic sensing with memoryless access)

π^{MA}

- **The main result in this talk it that establish a threshold condition on collision constraints such that**

$$J(\pi^{\mathrm{MA}}) = J(\pi^{\mathrm{FO}})$$

FO-OSA π^{FO}

- **Immediate reward**

$$g(x,i) = \begin{cases} \exp(-\lambda_i T), & x_i = 0; \\ 0, & x_i = 1, \end{cases}$$

It is the probability of collision-free transmission by the SU on channel i conditioned on full channel state information x.

It is also the average successful transmission by the SU when $X(k) = x$ and SU chooses to use channel i.

FO-OSA π^{FO}

- **Solution**

It is easy to show that the optimal performance can be achieved by stationary policies. Let the conditional transmission probability vector $\beta(x) \triangleq (\beta_i(x))$. The optimal solution corresponding to FO-OSA can be obtained by the following linear program.

$$\max_{\beta \in [0,1]^{N \times 2^N}} \sum_{x \in \{0,1\}^N} f(x) \sum_{i=0}^{N-1} g(x,i)\beta_i(x)$$

Stationary distribution of the primary user state vector X

subject to

$$\sum_{x \in \{0,1\}^N} \frac{f(x)(1 - g(x,i))\beta_i(x)}{1 - v_i(0)\exp(-\lambda_i T)} \leq \gamma_i, \qquad \forall i$$

$$\beta_i(x) \geq 0,$$

$$v_i(0) = \frac{\mu_i}{\lambda_i + \mu_i}, \qquad v_i(1) = \frac{\lambda_i}{\lambda_i + \mu_i}$$

PS-MA π^{MA}

■ Solution

Throughput of PS-MA

$$J(\pi^{\text{MA}}) = \frac{1}{N}\sum_{i=0}^{N-1} v_i(0)\beta_i^{\text{MA}}$$

$$\boxed{g(x,i) = \begin{cases} \exp(-\lambda_i T), & x_i = 0; \\ 0, & x_i = 1, \end{cases}}$$

PU&SU trans

Constraints

$$\frac{1}{N}v_q(0)\beta_q^{\text{MA}} \text{X} \frac{1-e^{-\lambda_q T}}{1-v_q(0)e^{-\lambda_q T}} \le \gamma_q$$

PU trans

The transmission probability is given by

$$\begin{aligned} \beta_q^{\text{MA}} &= \boxed{\phi_q \triangleq \frac{1-v_q(0)\exp(-\lambda_q T)}{1-\exp(-\lambda_q T)}, \quad q = 0,\cdots,N-1} \\ &= \min\left(\frac{\gamma_q N \phi_q}{v_q(0)}, 1\right), \end{aligned}$$

PS-MA π^{MA}

- **Solution**

As a function of collision constraints γ_i , the throughput of PS-MA is

$$\boxed{J(\pi^{\mathrm{MA}}) = \sum_{i=0}^{N-1} W_i(\gamma_i^{\mathrm{MA}} 1_{[\gamma_i > \gamma_i^{\mathrm{MA}}]} + \gamma_i 1_{[\gamma_i \le \gamma_i^{\mathrm{MA}}]})}$$

where

$$\phi_i \equiv \frac{1 - v_i(0)\exp(-\lambda_i T)}{1 - \exp(-\lambda_i T)}, \quad W_i \equiv \phi_i \exp(-\lambda_i T), \quad \gamma_i^{\mathrm{MA}} \equiv \frac{v_i(0)}{N\phi_i}$$

$$\beta_q^{\mathrm{MA}} = \min(\frac{\gamma_q N \phi_q}{v_q(0)}, 1)$$

FO-OSA π^{FO}

Analysis of the LP solution

When the constraints are tight, i.e., $\gamma_i \in [0, \gamma_i^{\text{FO}}], \forall i$, we have

$$J(\pi^{\text{FO}}) = \sum_{i=0}^{N-1} W_i \gamma_i$$

Here

$$S_i^k \equiv \{x | x \in \{0,1\}^N,\ x_i = 0,\ x \text{ contains total } k \text{ zeros}\},$$

$$F_i^k \equiv \sum_{x \in S_i^k} f(x), \quad \gamma_i^{\text{FO}} \equiv \frac{1}{\phi_i} \sum_{j=1}^{N} \frac{F_i^j}{j}.$$

$$\phi_i \equiv \frac{1 - v_i(0)\exp(-\lambda_i T)}{1 - \exp(-\lambda_i T)}, \quad W_i \equiv \phi_i \exp(-\lambda_i T).$$

FO-OSA π^{FO}

Analysis of the LP solution

The general solution can be estimated as

$$J(\pi^{\text{FO}}) \le \min(U, \sum_{i=0}^{N-1} W_i \gamma_i)$$

Here

$$U \equiv v_{(0)}(0)\exp(-\lambda_{(0)}T) + \sum_{i=1}^{N-1}(\prod_{j=0}^{i-1} v_{(j)}(1))v_{(i)}(0)\exp(-\lambda_{(i)}T)$$

FO-OSA and PS-MA

- **Performance gap**

$$J(\pi^{\mathrm{FO}}) - J(\pi^{\mathrm{MA}}) = \begin{cases} 0, & \gamma_i \in [0, \gamma_i^{\mathrm{MA}}], \forall i; \\ \sum_{i=0}^{N-1} W_i(\gamma_i - \gamma_i^{\mathrm{MA}}) 1_{[\gamma_i > \gamma_i^{\mathrm{MA}}]}, & \gamma_i \in [0, \gamma_i^{\mathrm{FO}}], \forall i. \end{cases}$$

FO-OSA and PS-MA

- **Performance gap**

In general

$$J(\pi^{\mathrm{FO}}) - J(\pi^{\mathrm{MA}}) \leq \min(\Delta U, \Delta W),$$

where

$$\Delta U = U - \sum_{i=0}^{N-1} W_i(\gamma_i^{\mathrm{MA}} 1_{[\gamma_i > \gamma_i^{\mathrm{MA}}]} + \gamma_i 1_{[\gamma_i \leq \gamma_i^{\mathrm{MA}}]}),$$

$$\Delta W \equiv \sum_{i=0}^{N-1} W_i(\gamma_i - \gamma_i^{\mathrm{MA}}) 1_{[\gamma_i > \gamma_i^{\mathrm{MA}}]},$$

Multi-SUs Cognitive Access

- **K-user Orthogonal PS-MA** $\pi_K^{\mathrm{MA-O}}$

For $K \le N$, each SU senses all channels periodically with its own sensing phase. When the channel is busy, it goes to the next channel in the next slot. Otherwise, it transmits with a probability adjusted to accommodate the presence of other SUs. For the special case N=K, is the same as FO-OSA.

Transmission probability $\beta_{i,K}^{\mathrm{MA-O}} = \min\{\frac{\gamma_i N \phi_i}{K v_i(0)}, 1\}$

Throughput $J(\pi_K^{\mathrm{MA-O}}) = \frac{K}{N} \sum_{i=0}^{N-1} v_i(0) \exp(-\lambda_i T) \beta_{i,K}^{\mathrm{MA-O}}$

Multi-SUs Cognitive Access

- **K-user random access (CSMA type)** $\pi_{i,K}^{\mathrm{MA-CSMA}}$

Each SU randomly chooses, with equal probability, a channel to sense. If the channel is busy, it will not transmit. Otherwise, it will continue to sense until a random backoff time. If no one transmits at the end of the backoff time, it will transmit with certain probability computed to ensure the collision constraint on that channel be satisfied.

Transmission probability

T

where $P_K(j) = C(K, j)(\frac{1}{N})^j(\frac{N-1}{N})^{K-j}$ means the probability that one particular channel can be selected by $0 \leq j \leq K$ SUs simultaneously when there are N channels.

$$J(\pi_{i,K}^{\mathrm{MA-CSMA}}) = \sum_{i=0}^{N-1}\sum_{j=1}^{K} P_K(j)(1-(1-\beta_{i,K}^{\mathrm{MA-CSMA}})^j)v_i(0)\exp(-\lambda_i T)$$

It can be seen that asymptotically, it achieves the FO-OSA performance as the number of users increases.

Numerical results

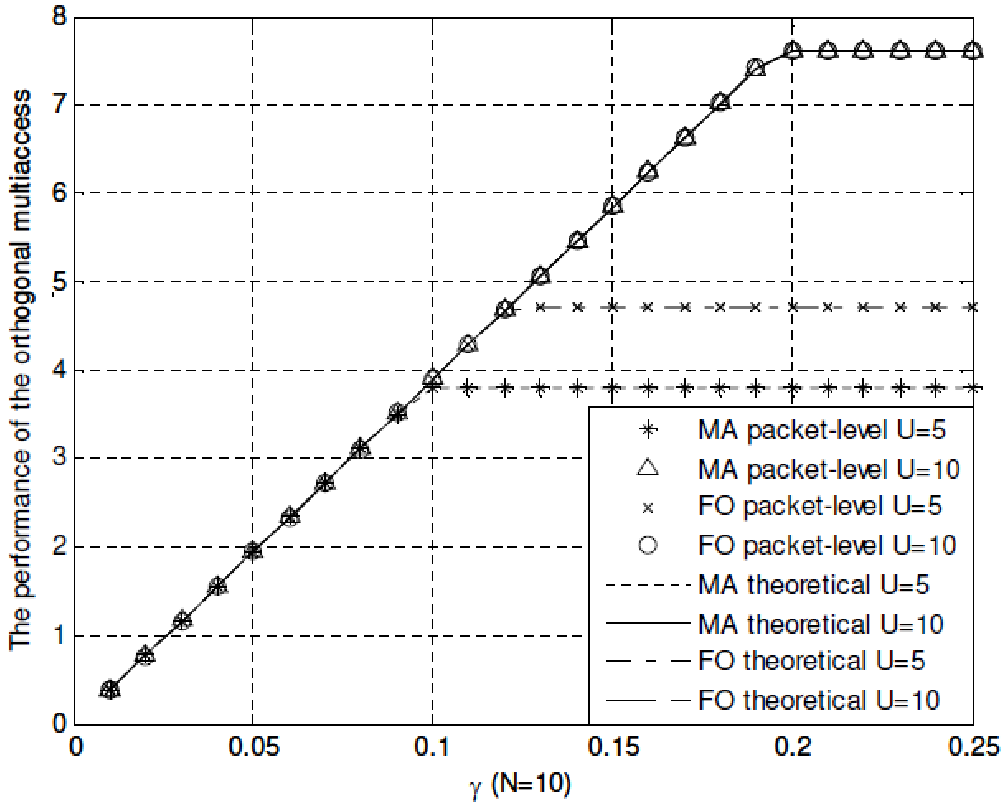

Fig. 6 The performances of the random access orthogonalized PS-MA and FO-OSA policies in homogeneous networks. The parameters are setting as
N = 10; U = 5, 10; λ^{-1} = 4.20 ms; μ^{-1} = 1.00 ms

Numerical results

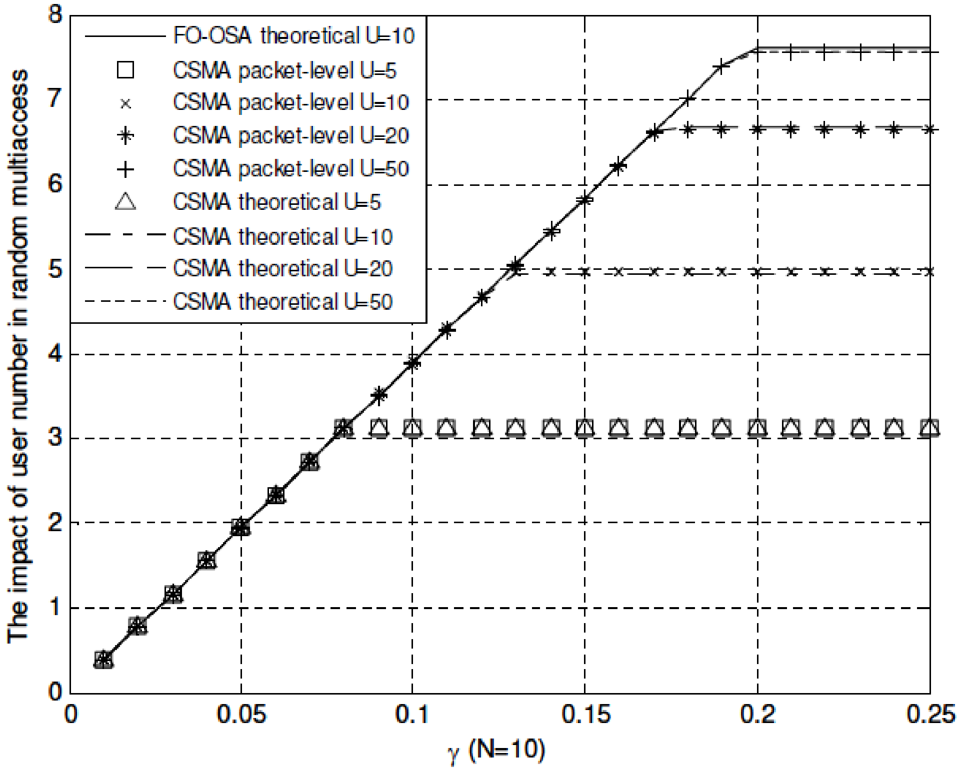

Fig 7. The performances of random access policies CSMA. The parameters are setting as N = 10; U = 5, 10, 20, 50; λ^{-1} = 4.20 ms; μ^{-1} = 1.00 ms

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Conclusion

- Introduce simple stationary feedback access control strategies for the secondary user providing lower and upper bounds to the optimal periodic sensing scheme with multiple primary users.
- Under tight constraints, a simple control strategy has been shown to be optimal.
- Numerical results show the optimal multi-secondary user access design is possible.
- Next step is to explore more practical setting with sensing cost.

Related publication

Xin Li, Qianchuan Zhao, Xiaohong Guan, Lang Tong, "Optimal Cognitive Access of Markovian Channels under Tight Collision Constraints," *IEEE Journal on Selected Areas in Communications (IEEE JSAC)*, 29(4):746-756, 2011