

# Opportunistic Scheduling with Utility Guarantees in Cognitive Radio Networks

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**Cognitive Radio Network Motivation:** Existing static allocation of radio spectrum considered inefficient ("white spaces" seen) **Possible solution:** Improve the utilization of the spectrum by allowing radios to access available spectrum dynamically

Key enabler: Cognitive Radio: Has the ability to adjust its operating point dynamically

Main challenges:

1. potentially oblivious primary users
2. imperfect "channel state info"
3. network dynamics (mobility, traffic)
4. distributed solutions desirable

**Our contribution:** We design a throughput optimal control algorithm for cognitive radio networks that overcomes these challenges and provides explicit performance guarantees.

## Network Model

M primary users (PU), N secondary users (SU). PU static, each has a unique channel that are orthogonal in frequency or space.

SU mobile, have no licensed channel. The set of channels they can access time-varying depending on mobility.

$H(t)$ : 0/1 channel accessibility matrix

## Interference model

$S_m(t)$ : actual state for channel  $m$  (0=busy, 1=idle)  
Allow at most one transmission per channel per slot.  
Additionally, interference sets  $I_{nm}$  (set of channels SU  $n$  interferes with when it uses channel  $m$ ). Together, these determine conditions for successful SU transmission

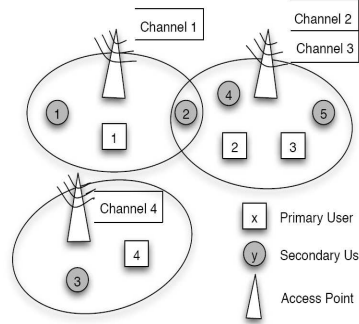
## Channel State Information model

probability  $P_m(t) = E\{S_m(t)|S(t-1)\}$  known at slot  $t$ .  
This is obtained by sensing the channels or knowledge of PU traffic statistics or combination etc.  
This models scenarios with imperfect channel state information

## Queueing Dynamics

Secondary user  $n$  maintains queue  $U_n(t)$ . Flow control decision  $R_n(t)$  denotes how many new packets to admit at SU  $n$ .  
Transmission decisions  $\mu_{nm}(t)$  denote which SU transmits on which channel. These are subject to network model constraints

## Example Network



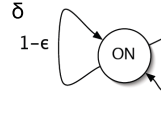
$$H(t) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

$h_{ij}(t) = 1$  if SU  $i$  can access channel  $j$  in slot  $t$

**Mobility model:**  $H(t)$  evolves according to a finite state ergodic Markov Chain, transition probabilities not known

$I_{21} = \{1, 2\}$  Important special case  $I_{nm} = \{m\}$  for all  $n, m$

2 state Markov chain example. Assume know  $\epsilon, \delta$



$$E\{S(t)|S(t-1) = ON\} = 1 - \epsilon$$

$$E\{S(t)|S(t-1) = OFF\} = \delta$$

$$U_n(t+1) = \max[U_n(t) - \sum_{m=1}^M \mu_{nm}(t)S_m(t), 0] + R_n(t)$$

**Goal:** Maximize SU throughput subject to maximum time average rate of collisions  $\rho_m$  with any PU  $m$

In principle, can solve if know all parameters. However, in practice, several unknowns (like mobility pattern,  $\Lambda$ , traffic dynamics).

Our Approach: **Lyapunov Optimization technique** (unifies stability and utility optimization). Main idea: Convert time average constraints into queueing stability problems using virtual queues. Then, use Lyapunov Stability argument to design an optimal control algorithm.

Define virtual collision queues:  $X_m(t+1) = \max[X_m(t) - \rho_m, 0] + C_m(t)$

If this queue is stable, the constraint on the maximum time average rate of collisions met

## Cognitive Network Control Algorithm (CNC)

"cross-layer" algorithm decoupled into 2 components. ( $V \geq 0$ )

**Flow control:** Each SU chooses the number of packets to admit  $R^{CNC}$  as the solution to:

$$\text{Minimize: } R_n(t)[U_n(t) - V\theta_n]$$

$$\text{Subject to: } 0 \leq R_n(t) \leq A_n(t)$$

-simple threshold policy, implemented separately as each SU

## Scheduling transmissions of SU:

Choose a resource allocation  $\mu^{CNC}$  that maximizes:

$$\sum_{n,m} \mu_{nm}(t) [U_n(t)P_m(t) - \sum_{k=1}^M X_k(t)(1 - P_k(t))I_{nm}^k]$$

subject to network constraints  
-a generalized Maximum Weight Match problem

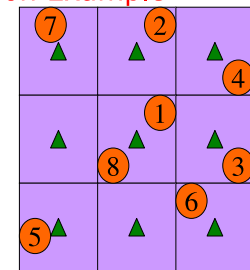
## CNC Performance Theorem

**Strong reliability bound:** The worst case number of collisions suffered by any primary user  $m$  is no more than  $\rho_m T + X_{max}$  over any finite interval  $T$  (where  $X_{max}$  is a constant)  
- deterministic guarantee

**Bounded worst case SU queue backlog:** The worst case queue backlog is upper bounded by a finite constant  $U_{max}$  for all secondary users  
-  $U_{max}$  linear in  $V$

**Utility-Delay tradeoff:** The average SU throughput achieved by CNC is within  $O(1/V)$  of the optimal value

Cell partitioned network with 9 static PU, 8 mobile SU, moving according to a Random Walk



## Observations:

- All collision constraints met
- The achieved throughput is very close to the input rate for small values of the input rate
- The achieved throughput saturates at a value depending on  $V$ , being very close to the network capacity for large  $V$

