Optimal Sensing-Transmission Structure for Dynamic Spectrum Access

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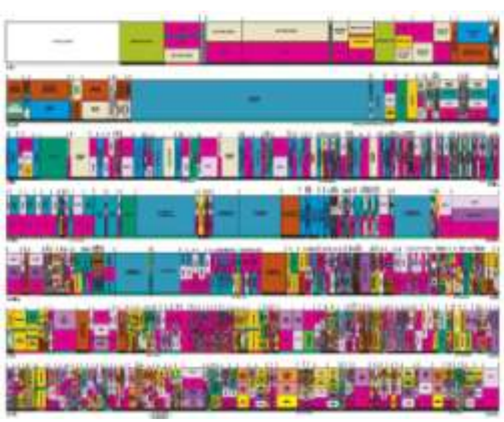
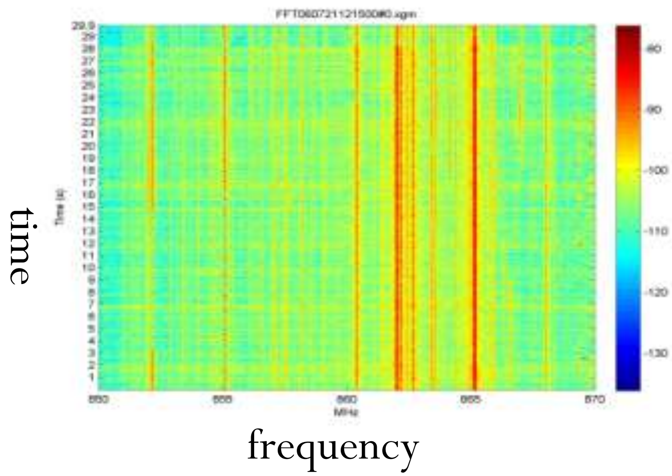
Spectrum Is Precious

- Spectrum: expensive resource
  - Demand: fast growing wireless applications and users
  - Supply: Limited, heavily regulated
    - Ex: US FCC TV band auction 62MHz BW: ~20 billions revenue



…, But It Is Underutilized

- Measurements results
  - A majority of spectrum is not utilized most of the time



Measurement result on public safety bands
Howard County, MD (JHU/APL)

- Limiting factor: spectrum access rather than physical scarcity of spectrum (FCC)
- More flexible spectrum access schemes/policy needed

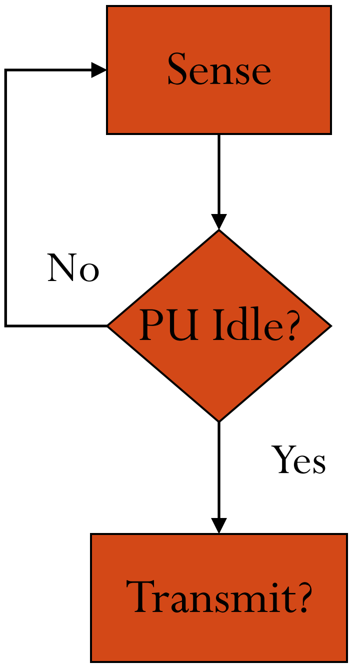
Dynamic Spectrum Access

- Dynamic spectrum access
  - Secondary users (SU) access primary users' (PU) spectrum
    - Different access priorities
  - Made possible by cognitive radio technology
    - Awareness of environment
  - Improve spectrum efficiency

- Challenges:
  - PU protection:
    - Interruption to the PU: minimum, controllable
  - PU may not cooperate
  - ……

Listen-Before-Talk (LBT)

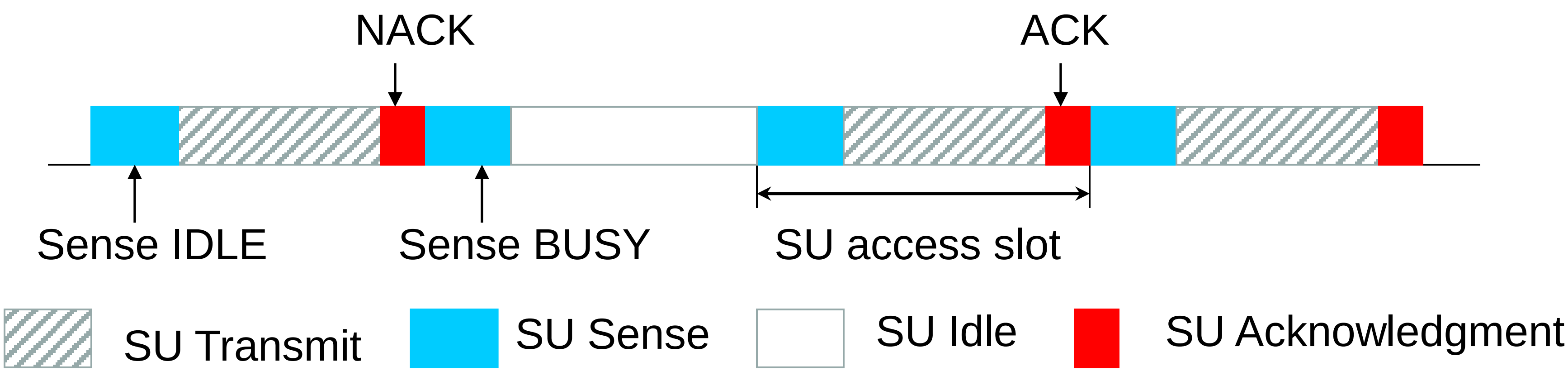
- Basic idea: SU transmits only if PU is detected to be inactive



- Simple
  - Requires no PU cooperation
  - Requires little infrastructure and planning
- Widely used: 802.11, 802.22
- Trade-off: PU protection vs SU access

Sensing-Transmission Structure: Related Work

- Periodic sensing

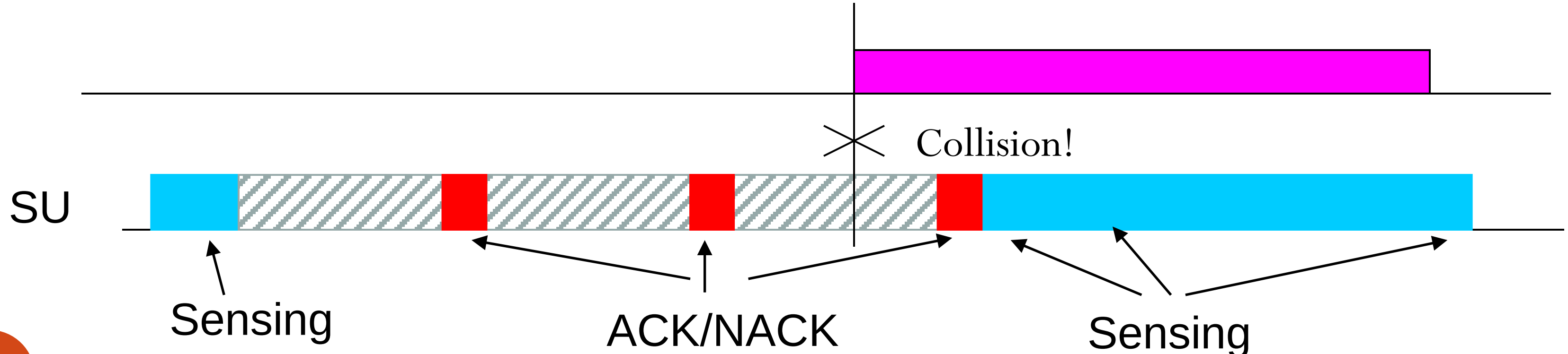


- Optimality not justified

One shoe does not fit all

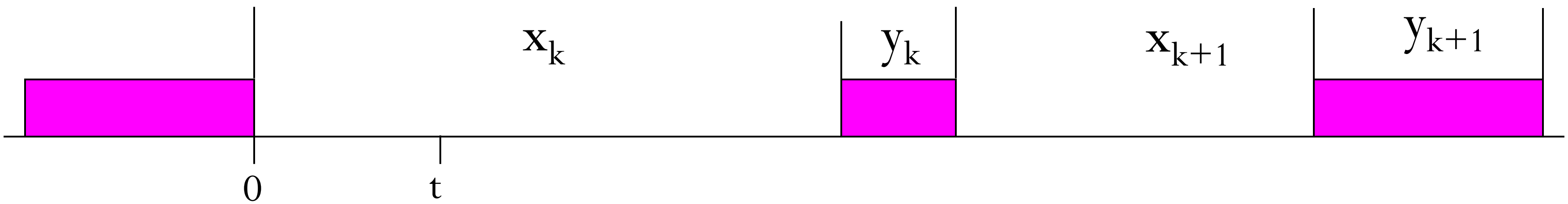
Our Approach

- General sensing-transmission structure
  - Not limited to periodic sensing
  - Dynamic sensing-transmission scheduling
  - Important when sensing overhead is large
- Exploit PU traffic characteristic
  - General PU traffic pattern
- Exploit SU-Receiver ACK/NACK
  - Infer collisions with the PU (even imperfect)



System Model: PU Model

- PU activities: semi-Markov renewal process
  - Transmit at will
  - Sojourn time of idle/busy state: $f_X(\cdot)/f_Y(\cdot)$



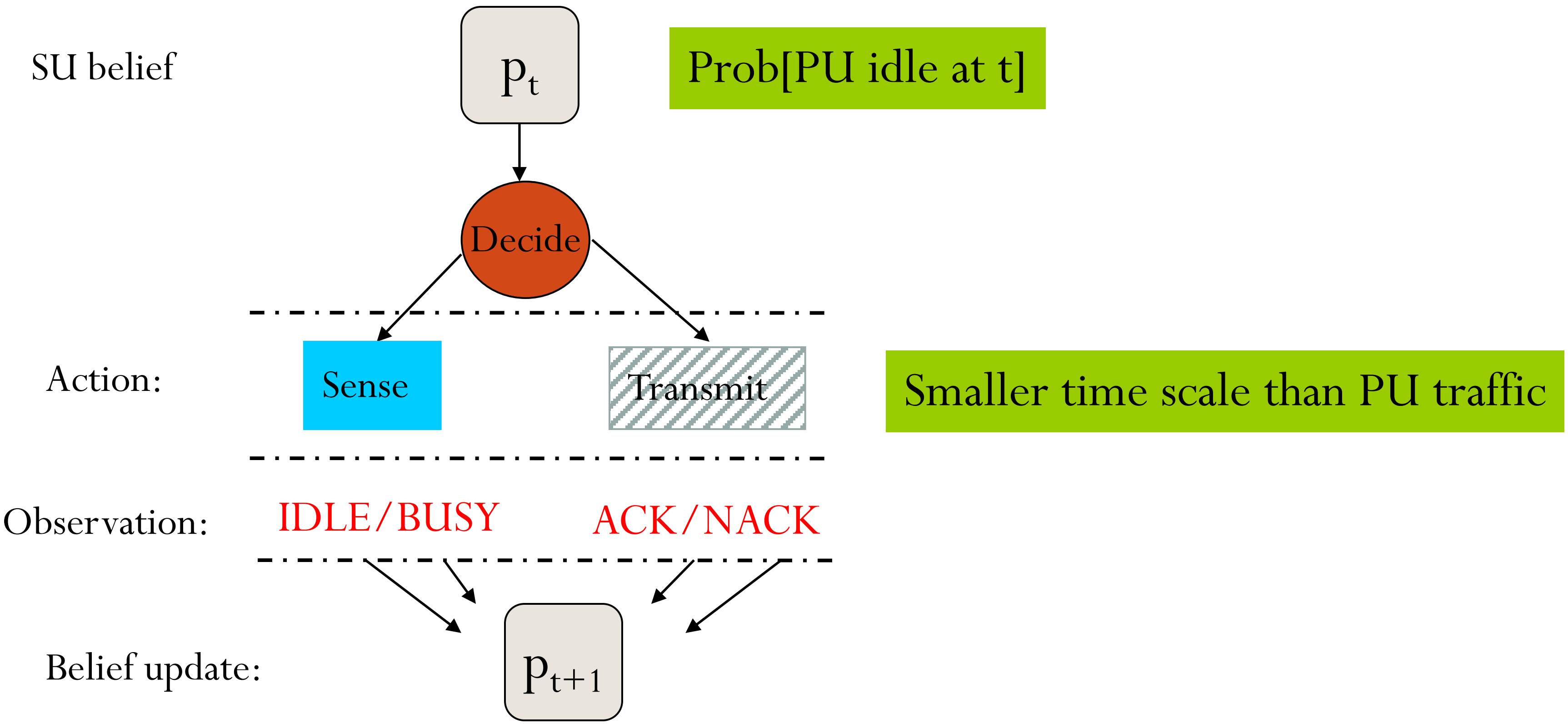
t : time elapsed since the PU's most recent state transition from BUSY to IDLE

g_t^T: Given the PU is idle at time t, the probability of that PU will remains idle for K_T

$$g_t^T = \frac{1 - F_X(t + K_T)}{1 - F_X(t)}$$

$F_X(.)$: CDF of PU idle time

System Model: SU Access



System Model: Noisy Observation

- Sensing error
  - p_f: false alarm probability
  - p_d: detection probability
- SU receiver ACK/NACK
  - γ_0: SU NACK rate without PU
  - γ_1: SU NACK rate with PU interference
  - $0 \leq \gamma_0 \leq \gamma_1 \leq 1$
  - γ_1: Captured effect vs. PU state inference
- Belief update
  - Bayesian rule
  - More certain about PU state

Scheduling: Decision Process Approach

- Immediate reward (utility)
  - Sensing: $r_t(p_t,0) = 0$
  - Transmission: $r_t(p_t,1) = b_t(p_t) - c_t(p_t)$

Benefit

$$[p_t g_t^T(1-\gamma_0) + (1-p_t g_t^T)(1-\gamma_1)]RK_T$$

Captured effect

Collision Cost

$$(1-p_t g_t^T)CK_T$$

Prob[PU returns during SU transmission]

- Objective: maximize expected SU utility per time unit

Optimal policy: $\pi^* = \text{argmax}_\pi E_\pi[\sum r_t(p_t,a_t) \mid p_0 = p]$

π: sensing-transmission scheduling policy
A sequence of mappings from belief space to action space

Finding the Optimal Policy

- V(t,p): maximum SU utility at time t
  - L(t,p): Listen at time t, and then follow optimal scheduling
  - M(t,p): transMit at time t, and then follow optimal scheduling

$$L(t,p) = \sum_{i \in \{\text{Idle},\text{Busy}\}} \Pr[o^S_{t+K_S} = i] V(t + K_S, p_{t+K_S}(i))$$

$$M(t,p) = r_t(p_t, 1) + \sum_{j \in \{\text{ACK},\text{NACK}\}} \Pr[o^T_{t+K_T} = j] V(t + K_T, p_{t+K_T}(j))$$

Immediate reward of transmission

Expected future reward

$$\boxed{V(t,p) = \max_{\text{Sense, Transmit}} \{L(t,p), M(t,p)\}}$$

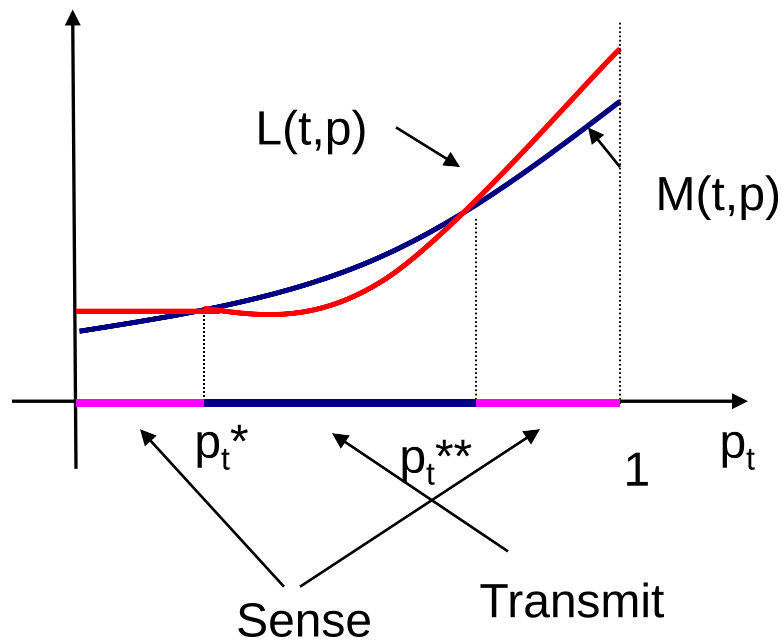
Bellman Equation

Structure of Optimal Policy

L(t,p): convex increasing in p

M(t,p): convex increasing in p

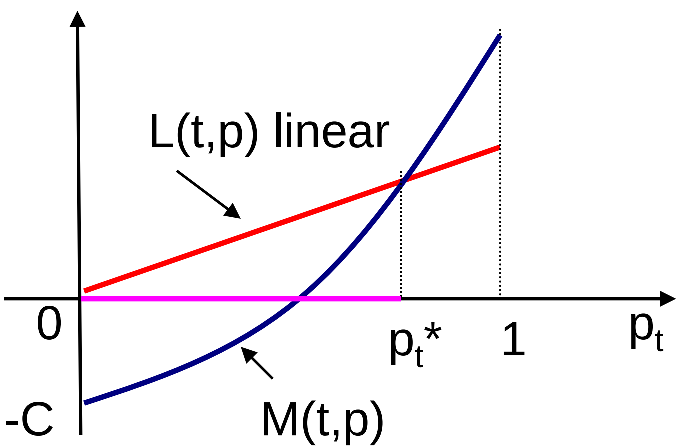
- Threshold-based policy is optimal
  - Threshold depends on time
  - P_f, P_d, γ_0, γ_1, R, C
  - PU idle time distribution
- Simplify the scheduler design
  - Offline computation
    - Backward induction
  - Online comparison



At most two thresholds

Optimal Policy: A Simple Example

- Perfect sensing without ACK/NACK
  - $p_f = 0$
  - $p_d = 1$
- Value function

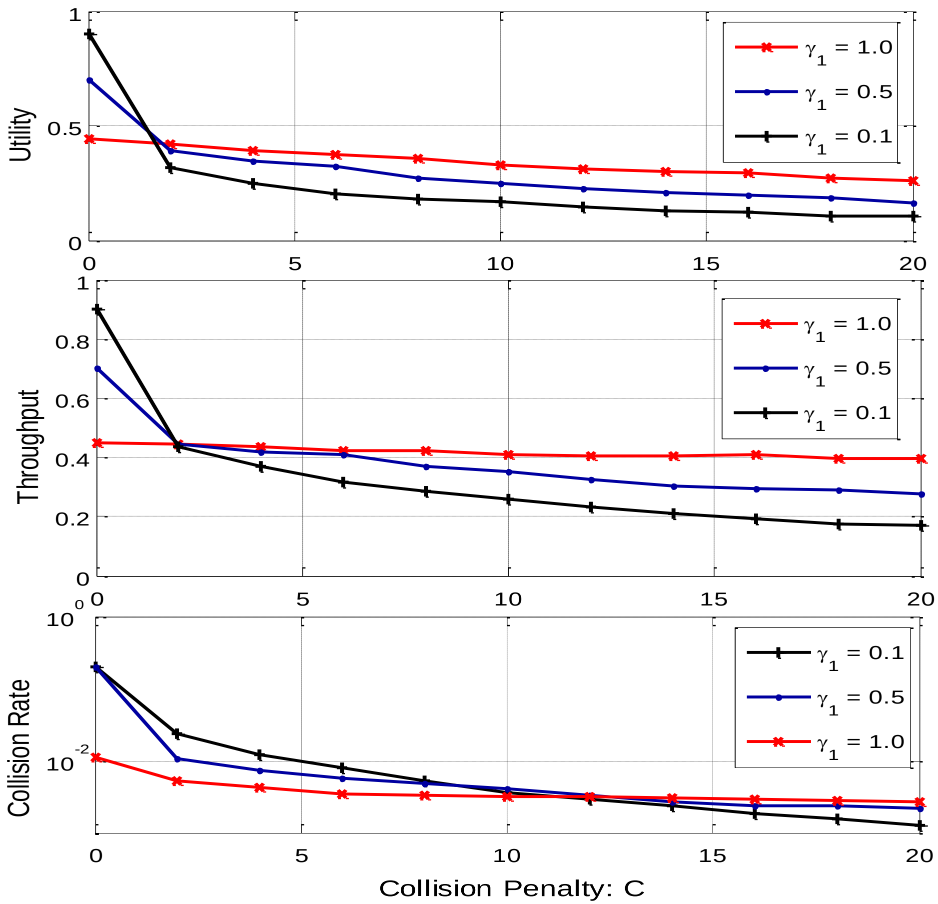


Optimal policy: threshold-based

$$a^*(t) = \begin{cases} 1 \text{ (Transmit)}, & \text{if } p_t > p_t^* \\ 0 \text{ (Sense)}, & \text{otherwise} \end{cases}$$

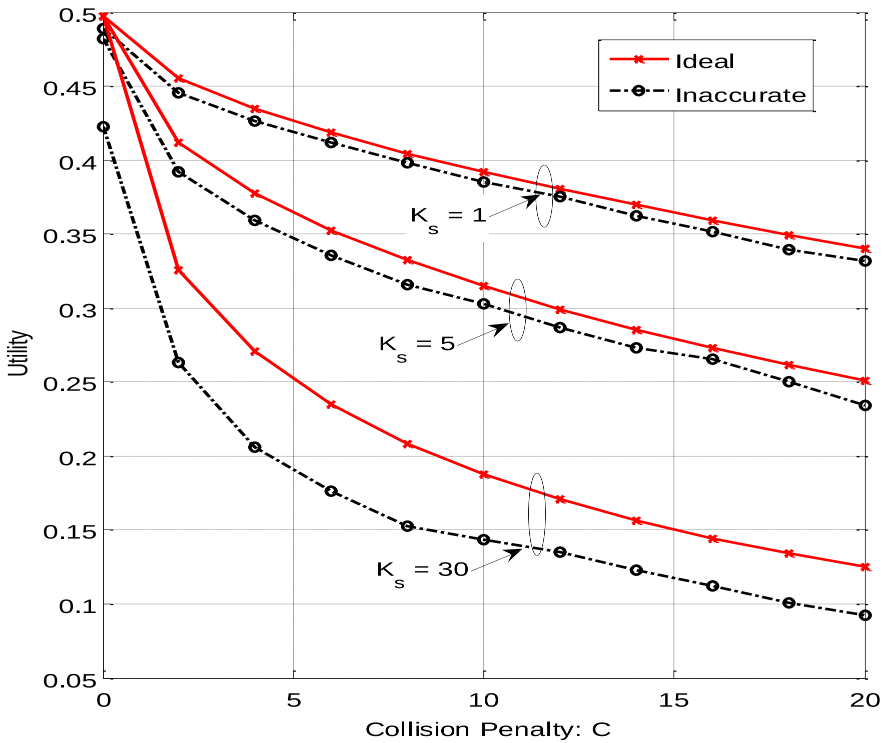
Simulation Results

- Simulation settings:
  - Uniformly dist. PU idle time
  - SU ACK/NACK
    - $\gamma_0 = 0.1$
    - γ_1: 0.1, 0.5, 1.0
- Observations:
  - Larger C, less PU collision
  - Larger C, smaller SU throughput



Perfect sensing with ACK/NACK

Error in Detecting the Beginning of Idle Time



Impact of inaccurate synchronization

- Inaccuracy in detecting the beginning of the PU idle time
  - Random delay over $[1, 3K_S]$
  - Small performance degradation
  - Longer sensing time: larger performance loss

Conclusion

- Sensing-transmission structure: important
  - Periodic LBT: not necessarily optimal
  - Tradeoff between learning and utilization of spectrum holes
- SU Utility:
  - Packet reward vs. collision cost
  - Tradeoff between PU protection and SU access
- ACK/NACK message from SU-Rx
  - Achieve more reliable observations of PU state
  - Detect collision with the PU
- Benchmark

Thank you!