Joint PHY-MAC Design for Opportunistic Spectrum Access with Multi-Channel Sensing

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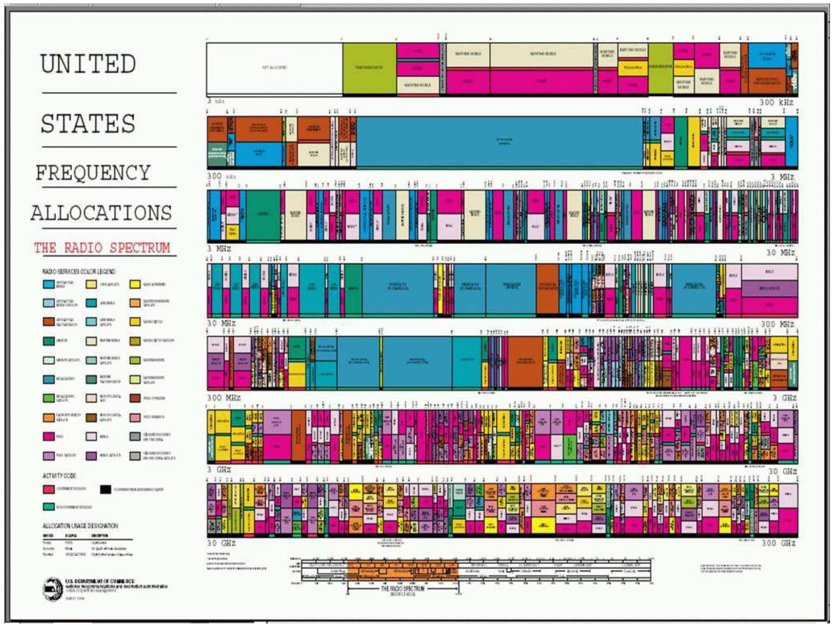
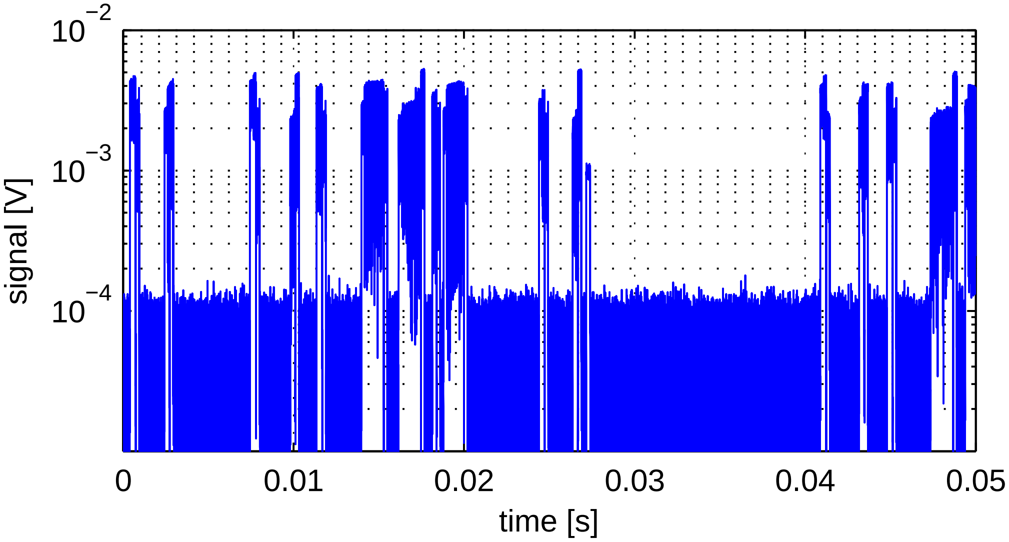
Spectrum Scarcity vs. Spectrum Opportunity

Overly Crowded Spectrum



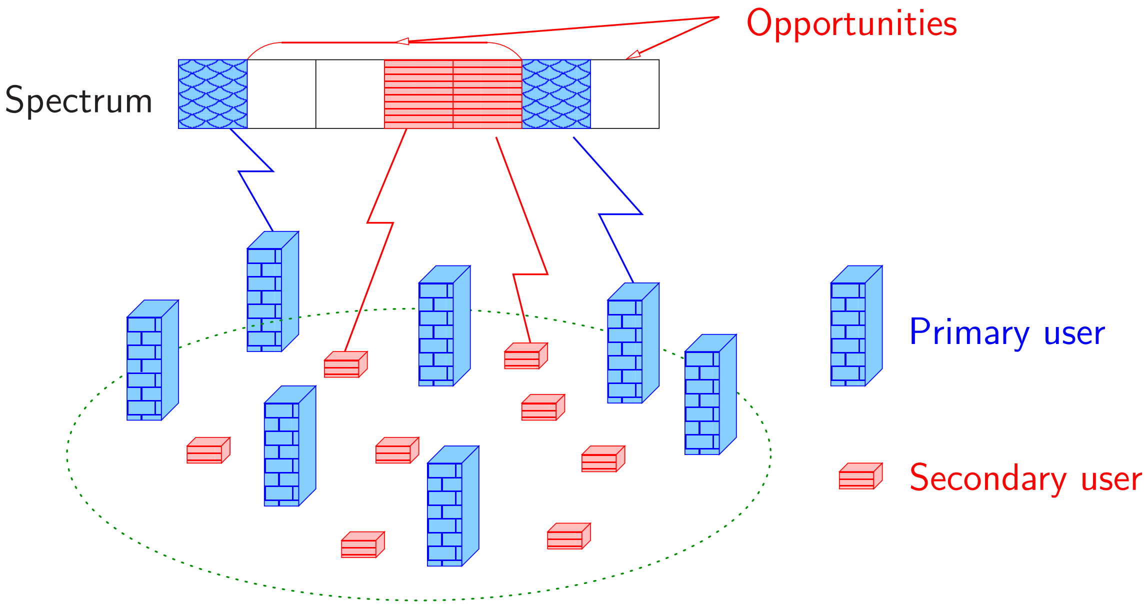
Pervasive Spectrum Opportunities



Spectrum usage of an active FTP session in a WLAN (ACSP at Cornell).

- Almost all usable radio frequencies have already been licensed.
- At any given time and location, a large portion of licensed spectrum lies unused.
  - □ Over 62% white space exists in the spectrum under 3GHz.
  - □ About 75% idle time during an active FTP session in WLAN.
  - □ Up to 90% idle time during voice-over-IP applications such as Skype.

Opportunistic Spectrum Access (OSA)



Basic idea:

Allow secondary users to exploit spectrum opportunities.

Design objective:

Maximize secondary users' throughput while limiting their interference to primary users (licensees).

Three basic design components:

- **Spectrum sensor**: opportunity identification (PHY)
- **Sensing policy**: where in the spectrum to sense (MAC)
- **Access policy**: whether to tx given sensing errors may occur (MAC)

A decision-theoretic framework for joint PHY-MAC design.

Main Results

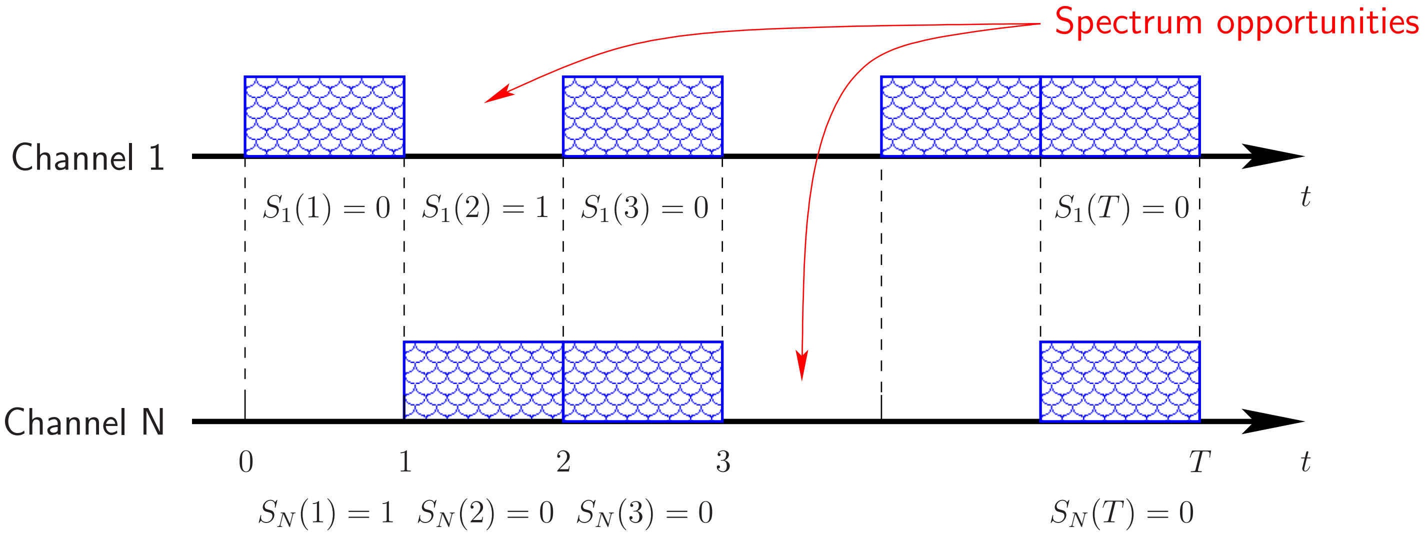
- A decision-theoretic framework based on partially observable Markov decision process (POMDP)
  - ☐ jointly optimizes the three basic design components
  - ☐ captures fundamental design tradeoffs

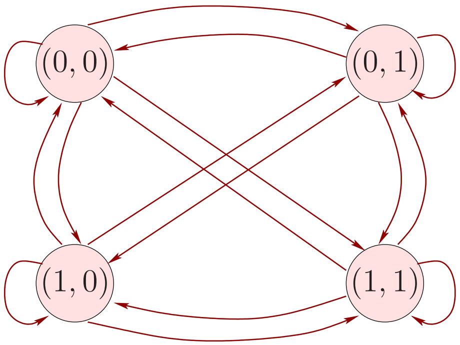
    Spectrum sensor: false alarm vs. miss detection

    Access Policy: overlooked opportunity vs. collision

    Sensing Policy: gaining access vs. gaining information
- Structural policies for the joint design
  - ☐ Separation principle for single-channel sensing and its extension to multi-channel sensing
  - ☐ Explicit optimal sensor design and closed-form optimal access policy.
  - ☐ Sensing design reduced from a constrained POMDP to an unconstrained one.
- Quantitative characterization of the interaction between PHY and MAC
  - ☐ Impact of the operating characteristics of spectrum sensor on MAC
  - ☐ Exploiting MAC information at PHY for improved sensor performance.

Network Model

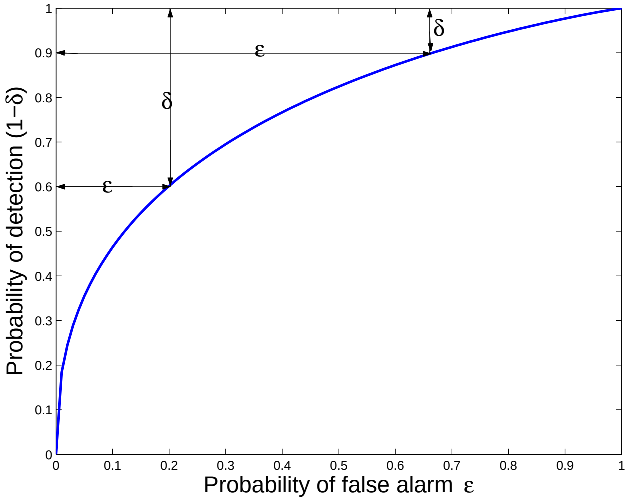




- A spectrum of N channels, each with bandwidth B_n.
- A slotted primary network
  - Markovian spectrum usage with 2^N states: $\mathbf{S}(t) \stackrel{\Delta}{=} [S_1(t), \ldots, S_N(t)] \in \{0 \text{ (busy)}, 1 \text{ (idle)}\}^N$.
  - Known transition probabilities.
- An ad hoc secondary network without dedicated control channel
  - Independent users, each can sense and access L channels in each slot.
  - User obtains a reward $R(t) = B_n$ for each successful access of idle channels.
  - User collides with primary users if access a busy channel.

Basic Components and Design Tradeoffs

Spectrum Sensor: false alarm vs. miss detection



- Binary hypotheses test (for $L = 1$):

$$\mathcal{H}_0 : \text{channel is idle} \quad \text{vs.} \quad \mathcal{H}_1 : \text{channel is busy}$$

- Two Types of sensing errors:
  - false alarm (ϵ): $\mathcal{H}_0 \to \mathcal{H}_1$ (overlook)
  - miss detection (δ): $\mathcal{H}_1 \to \mathcal{H}_0$ (misidentification)
- Which point (ϵ, δ) on the ROC curve should the sensor operate? (decision rule)

Access Policy: overlooked opportunity vs. collision

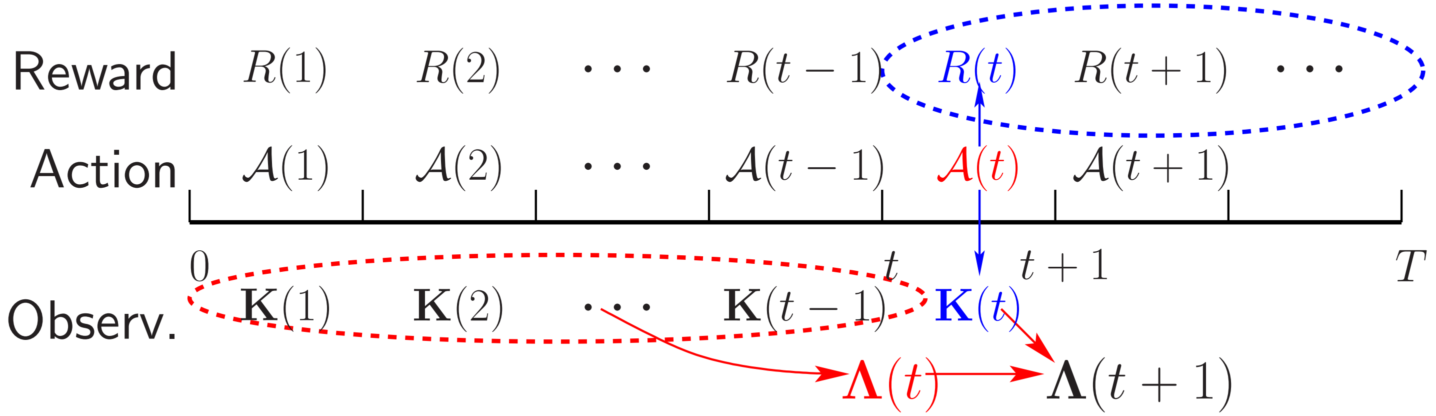
- Consequences of trusting sensing outcome:
  - false alarm (idle sensed as busy) $\Longrightarrow$ overlooked opportunity
  - miss detection (busy sensed as idle) $\Longrightarrow$ collision
- When and how much to trust the sensor?

$$\text{For } L = 1, \text{ tx prob. } = \begin{cases} p_0 & \text{if idle} \\ p_1 & \text{if busy} \end{cases} \qquad \begin{array}{l} p_0 < 1 \;:\; \text{conservative} \\ p_1 > 0 \;:\; \text{aggressive} \end{array} \quad \Longleftrightarrow \quad \text{sensor } \{\epsilon, \delta\}$$

Joint design of access policy at MAC and spectrum sensor at PHY

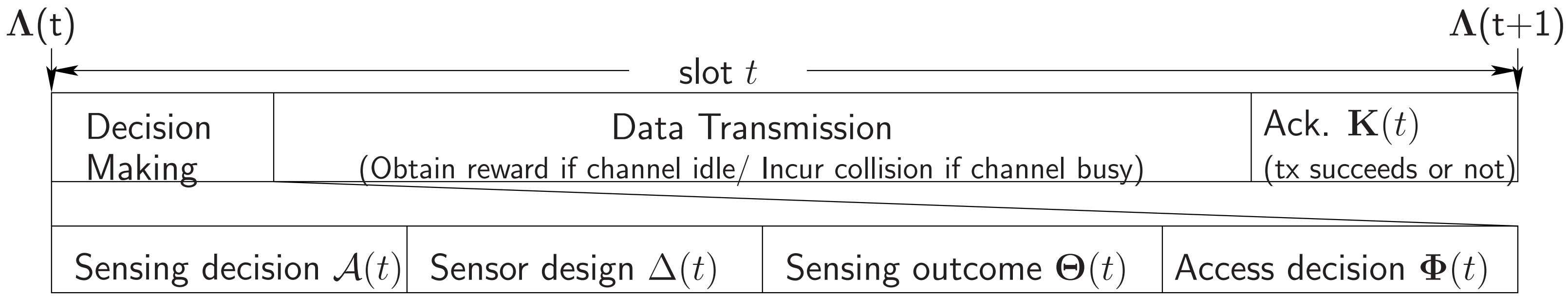
Basic Components and Design Tradeoffs

Sensing Policy: gaining access vs. gaining information



- Each observation $\mathbf{K}(t) \in \{0(\text{unsuccessful}), 1(\text{successful access})\}^L$ provides partial information on the spectrum usage state.
- Sensing action $\mathcal{A}(t)$ should be based on the conditional distribution $\mathbf{\Lambda}(t)$ that exploits the entire decision and observation history.
- $\mathcal{A}(t)$ results in immediate reward $R(t)$ and observation $\mathbf{K}(t)$ that affects future reward.
- Optimal $\mathcal{A}(t)$ achieves the best tradeoff between gaining immediate reward and gaining spectrum information.

A Constrained POMDP Formulation



$\mathbf{\Lambda}$(t) $\mathbf{\Lambda}$(t+1)

slot t

Decision Making

Data Transmission

(Obtain reward if channel idle/ Incur collision if channel busy)

Ack. $\mathbf{K}(t)$

(tx succeeds or not)

Sensing decision $\mathcal{A}(t)$

Sensor design $\Delta(t)$

Sensing outcome $\mathbf{\Theta}(t)$

Access decision $\mathbf{\Phi}(t)$

- **Belief vector** $\mathbf{\Lambda}(t) = \{\Lambda_{\mathbf{s}}(t)\}_{\mathbf{s}\in\{0,1\}^N}$, where $\Lambda_{\mathbf{s}}(t)$ is the conditional probability that the spectrum is in state $\mathbf{s}$: $\{\mathbf{\Lambda}(t), \mathcal{A}(t), \mathbf{K}(t)\} \rightarrow \mathbf{\Lambda}(t+1)$
- **Sensing policy** π_s
  - deterministic: $\mathbf{\Lambda}(t) \rightarrow$ a set $\mathcal{A}(t)$ of L channels to be sensed in slot t.
  - randomized: $\mathbf{\Lambda}(t) \rightarrow$ PMF of $\mathcal{A}(t)$.
- **Spectrum sensor** π_δ: $\mathbf{\Lambda}(t) \rightarrow$ a decision rule $\Delta(t)$ used for occupancy detection:

$$\{\Delta(t), \text{channel measurements}\} \rightarrow \mathbf{\Theta}(t) = \{\Theta_n(t)\}_{n\in\mathcal{A}(t)} \in \{0(\text{busy}), 1(\text{idle})\}^L.$$

- **Access policy** π_c
  - deterministic: $\{\mathbf{\Lambda}(t), \mathbf{\Theta}(t)\} \rightarrow \mathbf{\Phi}(t) \in \{0(\text{no access}), 1(\text{access})\}^L$.
  - randomized: $\{\mathbf{\Lambda}(t), \mathbf{\Theta}(t)\} \rightarrow$ tx probabilities.
- **Objective:**

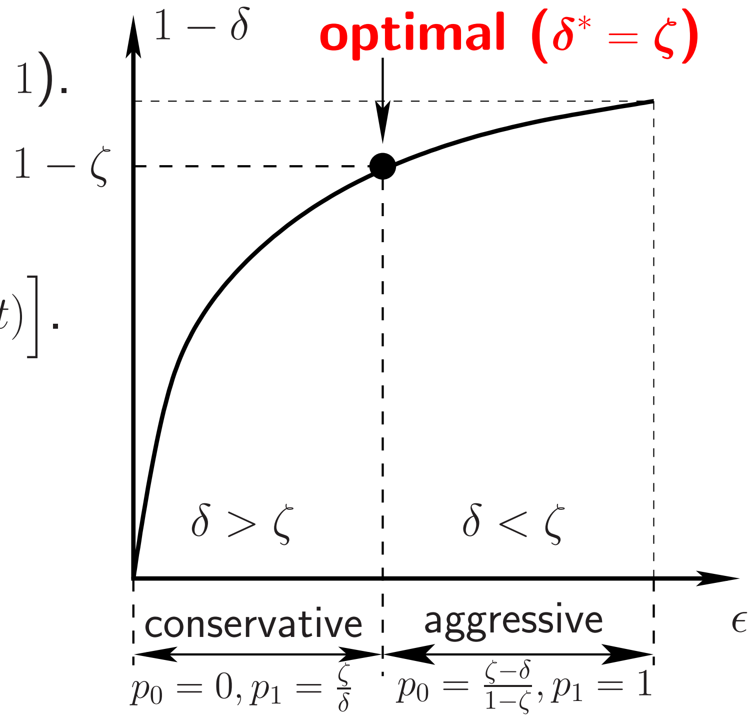
$$\{\pi_\delta^*, \pi_s^*, \pi_c^*\} = \arg\max_{\pi_\delta,\pi_s,\pi_c} \mathbb{E}[\sum_{t=1}^{T} R(t)] \quad \text{s.t. collision prob. } P_n(t) \le \zeta, \quad \forall n \in \mathcal{A}(t) \qquad (*)$$

The Separation Principle for Single-Channel Sensing

Theorem: π_δ and π_c can be decoupled from π_s without losing optimality

- ☐ Choose π_δ and π_c to max. immediate reward $R(t)$ and ensure constraint $P_n(t) = \zeta$.
  - $\Longrightarrow$ A static optimization problem.
  - $\Longrightarrow$ Explicit optimal design of spectrum sensor:
    optimal Neyman-Pearson (NP) detector with prob. of missing (PM) $\delta = \zeta$.
  - $\Longrightarrow$ Closed-form optimal access policy:
    trust sensing outcome (tx prob. $p_0 = 0, p_1 = 1$).

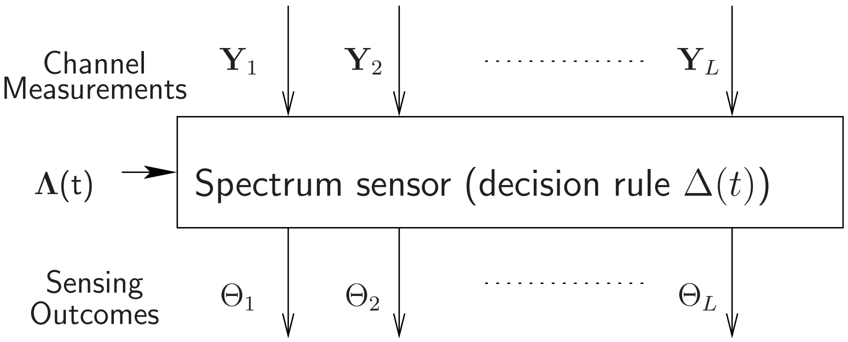
- ☐ Choose π_s to maximize total reward $\mathbb{E}\left[\sum_{t=1}^{T} R(t)\right]$.
  - $\Longrightarrow$ An unconstrained POMDP.
  - $\Longrightarrow$ Deterministic sensing policy.



Two Spectrum Sensor Structures for Multi-Channel Sensing

Goal: dynamically choose decision rules $\Delta(t)$ for spectrum opp. identification.

Joint opportunity identification

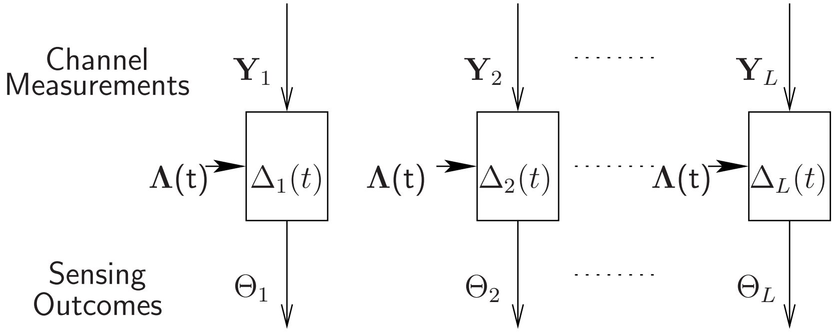


- Perform a 2^L-ary hypothesis test:

$$\begin{aligned}\mathcal{H}_0 :&\ \mathbf{S}_{\mathcal{A}}(t) = [1,1,\ldots,1],\\ \mathcal{H}_1 :&\ \mathbf{S}_{\mathcal{A}}(t) = [0,1,\ldots,1],\\ &\cdots\\ \mathcal{H}_{2^L-1} :&\ \mathbf{S}_{\mathcal{A}}(t) = [0,0,\ldots,0].\end{aligned}$$

- Decision rule: $\{\{\mathbf{Y}_n\}_{n=1}^{L}\} \rightarrow \{\mathcal{H}_0,\ldots,\mathcal{H}_{2^L-1}\}$ jointly exploits channel measurements.
- Performance is specified by a set of $2^L \times (2^L - 1)$ error probabilities.

Independent opportunity identification



- Performs L independent hypothesis tests:

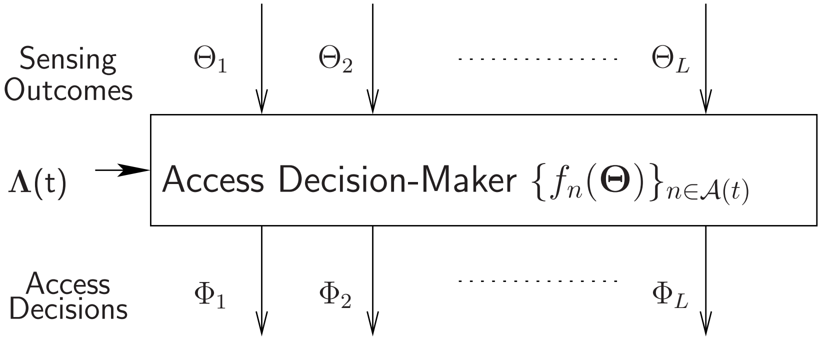
$$\begin{aligned}\mathcal{H}_0 :&\ S_n(t) = 1,\\ \mathcal{H}_1 :&\ S_n(t) = 0, \qquad n \in \mathcal{A}(t).\end{aligned}$$

- Decision rule $\Delta_n(t) : \{\mathbf{Y}_n\} \rightarrow \{\mathcal{H}_0, \mathcal{H}_1\}$ ignores correlation among channel measurements.
- Performance is specified by L pairs of false alarm and miss detection rates.
- Less complex than joint identification.

Two Access Policy Structures for Multi-Channel Sensing

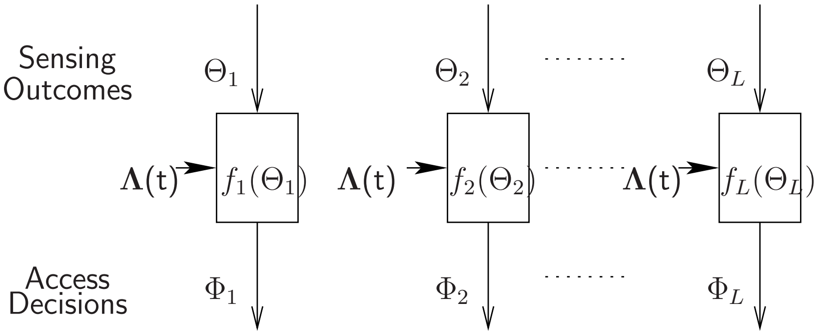
Goal: dynamically choose access decisions or transmission probabilities.

Joint access decision-making



- Tx. probability $f_n(\boldsymbol{\Theta}) \triangleq \Pr\{\Phi_n = 1|\boldsymbol{\Theta}\}$ governs access decision $\Phi_n, \forall n \in \mathcal{A}(t)$.
- Access decision jointly exploits sensing outcomes from all sensed channels: $\boldsymbol{\Theta} = \{\Theta_n\}_{n\in\mathcal{A}(t)}$.
- $\#$ of tx. probabilities to be designed $= 2^L$ (possible sensing outcomes) $\times$ L (chosen channels).

Independent access decision-making



- Tx. probability $f_n(\Theta_n) \triangleq \Pr\{\Phi_n = 1|\Theta_n\}$ independent of sensing outcomes from other channels.
- Access decision ignores correlation among sensing outcomes.
- $\#$ of tx. probabilities to be designed $= 2L$ (chosen channels).
- Less complex than joint identification.

Extension of the Separation Principle

$$\{\pi_\delta^*, \pi_s^*, \pi_c^*\} = \arg\max_{\pi_\delta, \pi_s, \pi_c} \mathbb{E}[\sum_{t=1}^{T} R(t)] \quad \text{s.t. collision prob. } P_n(t) \leq \zeta, \quad \forall n \in \mathcal{A}(t) \qquad (*)$$

Joint sensor & joint access structure

- Provides globally optimal solution.
- Requires randomized policies for optimality.
- Optimal but computationally prohibitive.

Independent sensor & independent access structure

- The **separation principle** holds.
- Optimal solution under this structure (the SP approach):
  - Spectrum sensor: optimal NP detector with PM $= \zeta$.

$\mathbf{Y}_n$ → NP detector for channel n → Θ_n

  - Access policy: trust the sensing outcome.

Θ_n → Access decision-maker for channel n → $\Phi_n = \Theta_n$

- Caveat: ignores correlation among channel occupancies.

Exploiting Correlation: The PHY Layer Approach

Joint sensor & independent access structure

- ☐ Sensor: optimal NP detector, using all channel measurements, with PM $= \zeta$.

$\mathbf{Y}_1$ ⋮ $\mathbf{Y}_L$ → NP detector for channel n → Θ_n

- ☐ Access policy: trust the sensing outcome (using one sensing outcome).

Θ_n → Access decision-maker for channel n → $\Phi_n = \Theta_n$

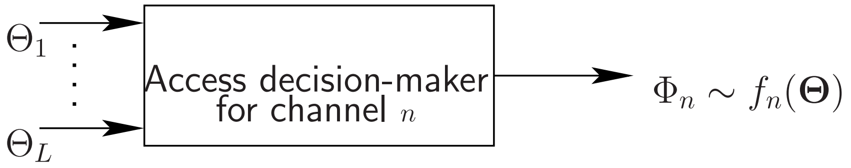
- Exploits all channel measurements $\{\mathbf{Y}_n\}_{n \in \mathcal{A}(t)}$ in occupancy detection for each chosen channel.
- Uses MAC layer information at PHY layer: the *a priori* joint distribution of channel measurements is obtained from the **belief vector** $\mathbf{\Lambda}(t)$.
- Locally optimal (maximizes instantaneous throughput).
- Reduces to the SP approach when channels evolve independently.

Exploiting Correlation: The MAC Layer Approach

Independent sensor & joint access structure

- ☐ Sensor: optimal NP detector, using single channel measurements, with PM $= \zeta$.

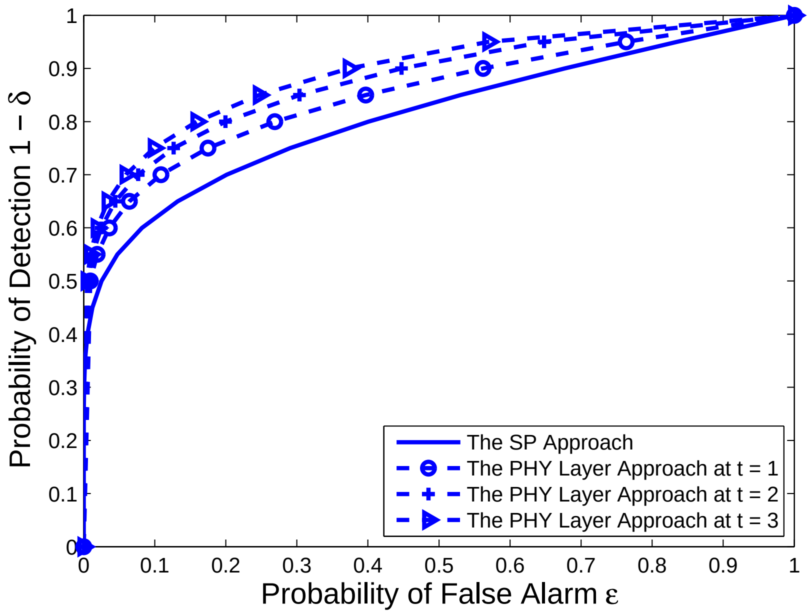
- ☐ Access policy: myopic tx probabilities $f_n(\mathbf{\Theta})$ (maximizes the instantaneous throughput) obtained via linear programming.



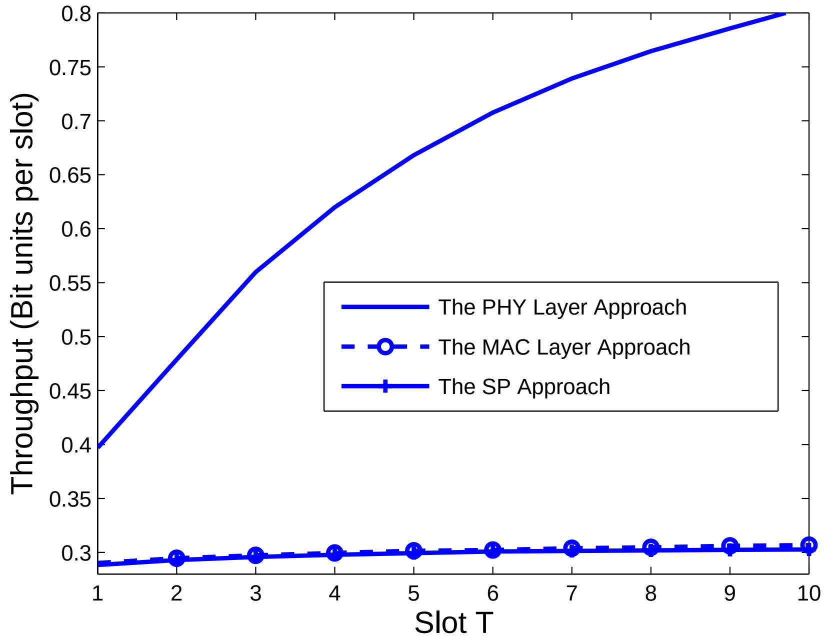
- Exploits all sensing outcomes $\mathbf{\Theta} = \{\Theta_n\}_{n \in \mathcal{A}(t)}$ in making access decision for each chosen channel.
- Locally optimal when channels evolve independently.
- Reduces to the SP approach when channels evolve independently.

Performance Comparison

ROC of spectrum sensor



Normalized Throughput



- Performance of the PHY layer spectrum sensor is improved by exploiting the MAC layer sensing and access decisions (characterized by the belief vector).
- Exploitation of channel correlation at the PHY layer is more effective than that at the MAC layer.

Conclusions

- Optimal OSA with multi-channel sensing formulated as a constrained POMDP.
- **Separation Principle**
  - ☐ holds for $L = 1$; extends to $L > 1$ under the independent sensor $\&$ independent access structure.
  - ☐ leads to explicit optimal sensor design and closed-form optimal access policy.
  - ☐ reduces sensing design from a constrained POMDP to an unconstrained one.
- **Exploiting Channel Correlation**
  - ☐ PHY layer approach: improved sensor performance by exploiting MAC information (belief vector).
  - ☐ MAC layer approach: infers channel correlation from sensing outcomes.

Limitations

- Known transition probabilities of the underlying Markov process (robustness to model mismatch can be found in [1]).
- Interaction among secondary users not taken into account (exploited in [2]).

[1] Y. Chen, Q. Zhao, and A. Swami, "Joint Design and Separation Principle for Opportunistic Spectrum Access," in *Proc. of IEEE Asilomar Conference, Nov. 2006.*

[2] Y. Chen, Q. Zhao, and K. Liu, "Distributed Spectrum Sharing Among Competing Secondary Users," submitted to 45th Annual Allerton Conference on Communication, Control, and Computing, 2007.