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

- 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.

Spectrum usage of an active FTP session in a WLAN (ACSP at Cornell).
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:
    $$ S(t) \triangleq [S_1(t), \ldots, S_N(t)] \in \{0 \ (\text{busy}), \ 1 \ (\text{idle})\}^N. $$
  - 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 $L = 1$):
  \[ H_0 : \text{channel is idle} \quad \text{vs.} \quad H_1 : \text{channel is busy} \]

- Two Types of sensing errors:
  - false alarm ($\epsilon$): $H_0 \to H_1$ (overlook)
  - miss detection ($\delta$): $H_1 \to H_0$ (misidentification)

- Which point ($\epsilon, \delta$) 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) $\Rightarrow$ overlooked opportunity
  - miss detection (busy sensed as idle) $\Rightarrow$ collision

- When and how much to trust the sensor?

For $L = 1$, tx prob. $= \begin{cases} p_0 & \text{if idle} \\ p_1 & \text{if busy} \end{cases}$

- $p_0 < 1 : \text{conservative}$
- $p_1 > 0 : \text{aggressive}$

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

\[ \Lambda(t) \rightarrow \text{slot } t \rightarrow \Lambda(t+1) \]

<table>
<thead>
<tr>
<th>Decision Making</th>
<th>Data Transmission</th>
<th>Ack. ( K(t) )</th>
</tr>
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<tbody>
<tr>
<td>( \Lambda(t) )</td>
<td>(Obtain reward if channel idle / Incur collision if channel busy)</td>
<td>(tx succeeds or not)</td>
</tr>
</tbody>
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\[ \text{Sensing policy } \pi_s \]
- deterministic: \( \Lambda(t) \rightarrow \) a set \( A(t) \) of \( L \) channels to be sensed in slot \( t \).
- randomized: \( \Lambda(t) \rightarrow \) PMF of \( A(t) \).

\[ \text{Spectrum sensor } \pi_\delta: \Lambda(t) \rightarrow \) a decision rule \( \Delta(t) \) used for occupancy detection:
\[
\{\Delta(t), \text{channel measurements}\} \rightarrow \Theta(t) = \{\Theta_n(t)\}_{n \in A(t)} \in \{0(\text{busy}), 1(\text{idle})\}^L.
\]

\[ \text{Access policy } \pi_c \]
- deterministic: \( \{\Lambda(t), \Theta(t)\} \rightarrow \Phi(t) \in \{0(\text{no access}), 1(\text{access})\}^L. \)
- randomized: \( \{\Lambda(t), \Theta(t)\} \rightarrow \) tx probabilities.

\[ \{\pi_\delta^*, \pi_s^*, \pi_c^*\} = \arg \max_{\pi_\delta, \pi_s, \pi_c} \mathbb{E}\left[\sum_{t=1}^{T} R(t)\right] \quad \text{s.t. collision prob. } P_n(t) \leq \zeta, \quad \forall n \in A(t) \quad (\ast) \]
The Separation Principle for Single-Channel Sensing

**Theorem:** \( \pi_\delta \) and \( \pi_c \) can be decoupled from \( \pi_s \) without losing optimality

- Choose \( \pi_\delta \) and \( \pi_c \) to max. immediate reward \( R(t) \) and ensure constraint \( P_n(t) = \zeta \).
  \[ \Rightarrow \text{A static optimization problem.} \]
  \[ \Rightarrow \text{Explicit optimal design of spectrum sensor:} \]
  optimal Neyman-Pearson (NP) detector with prob. of missing (PM) \( \delta = \zeta \).

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

\[ \frac{1 - \delta}{1 - \zeta} \]

\[ \frac{\delta \cdot \zeta}{1 - \zeta} \]

\[ \frac{1 - \delta}{1 - \zeta} \]

\[ \frac{\delta \cdot \zeta}{1 - \zeta} \]
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:
  - $\mathcal{H}_0 : S_A(t) = [1, 1, \ldots, 1]$
  - $\mathcal{H}_1 : S_A(t) = [0, 1, \ldots, 1]$
  - $\ldots$
  - $\mathcal{H}_{2^L-1} : S_A(t) = [0, 0, \ldots, 0]$.

- Decision rule: $\{\{Y_n\}_{n=1}^L\} \rightarrow \{\mathcal{H}_0, \ldots, \mathcal{H}_{2^L-1}\}$ 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: $\mathcal{H}_0 : S_n(t) = 1$, $\mathcal{H}_1 : S_n(t) = 0$, $n \in A(t)$.

- Decision rule $\Delta_n(t) : \{Y_n\} \rightarrow \{\mathcal{H}_0, \mathcal{H}_1\}$ 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**

- **Sensing Outcomes:** $\Theta_1, \Theta_2, \ldots, \Theta_L$
- **Access Decision-Maker:** $\{f_n(\Theta)\}_{n \in A(t)}$
- **Tx. probability** $f_n(\Theta) \triangleq \Pr\{\Phi_n = 1|\Theta\}$ governs access decision $\Phi_n, \forall n \in A(t)$.
- **Access decision** jointly exploits sensing outcomes from all sensed channels: $\Theta = \{\Theta_n\}_{n \in A(t)}$.
- **# of tx. probabilities to be designed** $= 2^L$ (possible sensing outcomes) $\times L$ (chosen channels).

**Independent access decision-making**

- **Sensing Outcomes:** $\Theta_1, \Theta_2, \ldots, \Theta_L$
- **Access Decision-Makers:** $\{f_1(\Theta_1), f_2(\Theta_2), \ldots, f_L(\Theta_L)\}$
- **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

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

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.
  
    \[ Y_n \xrightarrow{\text{NP detector for channel } n} \Theta_n \]

  - Access policy: trust the sensing outcome.
    \[ \Theta_n \xrightarrow{\text{Access decision-maker for channel } n} \Phi_n = \Theta_n \]

- 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 = ζ.

\[ Y_1 \rightarrow \cdots \rightarrow \text{NP detector for channel } n \rightarrow \Theta_n \]
\[ Y_L \rightarrow \Theta_n \]

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

\[ \Theta_n \rightarrow \text{Access decision-maker for channel } n \rightarrow \Phi_n = \Theta_n \]

- Exploits all channel measurements \( \{Y_n\}_{n \in A(t)} \) 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 \( \Lambda(t) \).

- 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 = ζ.

\[
Y_n \xrightarrow{\text{NP detector for channel } n} \Theta_n
\]

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

\[
\Theta_1 \cdots \Theta_L \xrightarrow{\text{Access decision-maker for channel } n} \Phi_n \sim f_n(\Theta)
\]

- Exploits all sensing outcomes \( \Theta = \{\Theta_n\}_{n \in A(t)} \) in making access decision for each chosen channel.

- **Locally optimal** when channels evolve independently.

- Reduces to the SP approach when channels evolve independently.
Performance 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]).
