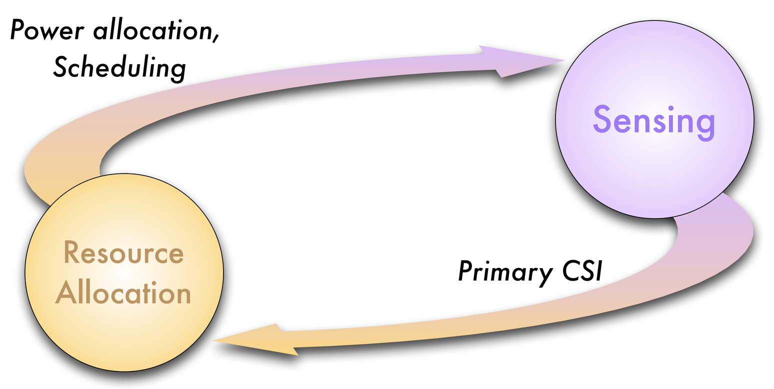

Soft-Decision Sequential Sensing for Optimization of Interweave Cognitive Radio Networks

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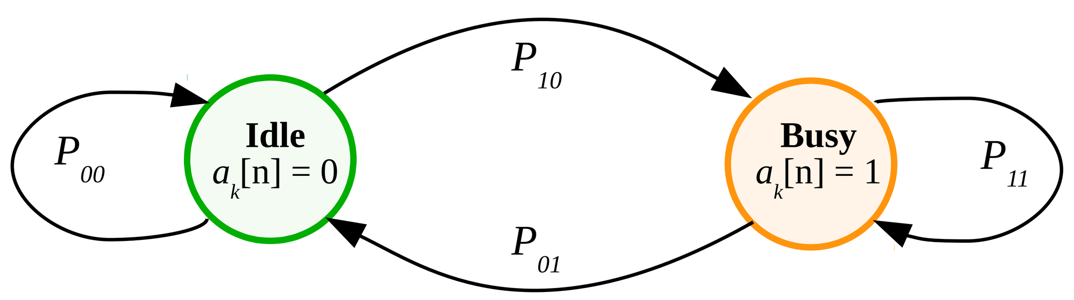
ABSTRACT

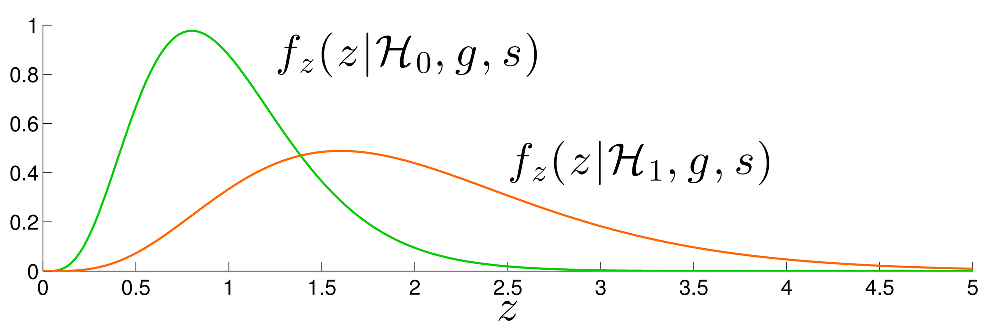
When the capability of a Cognitive Radio (CR) to sense the spectrum is limited, control and resource allocation schemes should optimize not only transmitting resources, but also sensing resources. In this paper, the cost of such sensing resources is incorporated into the optimization, with the aim of **dynamically adapting** the power (energy) devoted to sense each channel. More precisely, the tradeoff among: **throughput, power devoted to sense, power devoted to transmit, and probability of interference** is optimized. A soft-decision Bayesian sequential sensing scheme is used to exploit the time-correlation of the primary occupancy. The joint design leverages tools of **Dynamic Programming (DP)** to solve the sequential sensing problem and relies on reinforcement learning to develop a stochastic solution.

SYSTEM MODEL

- M Secondary Users (SUs), orthogonal access
- K channels, 1 Primary User (PU) per channel
- Long-term constraints on: QoS, probability of interference (*Lagrange multipliers*, [5])
- Perfect Secondary CSI (fast fading)
- Primary CSI imperfect, costly to acquire [2]
- PU behavior is modeled by a Markov chain [1]:



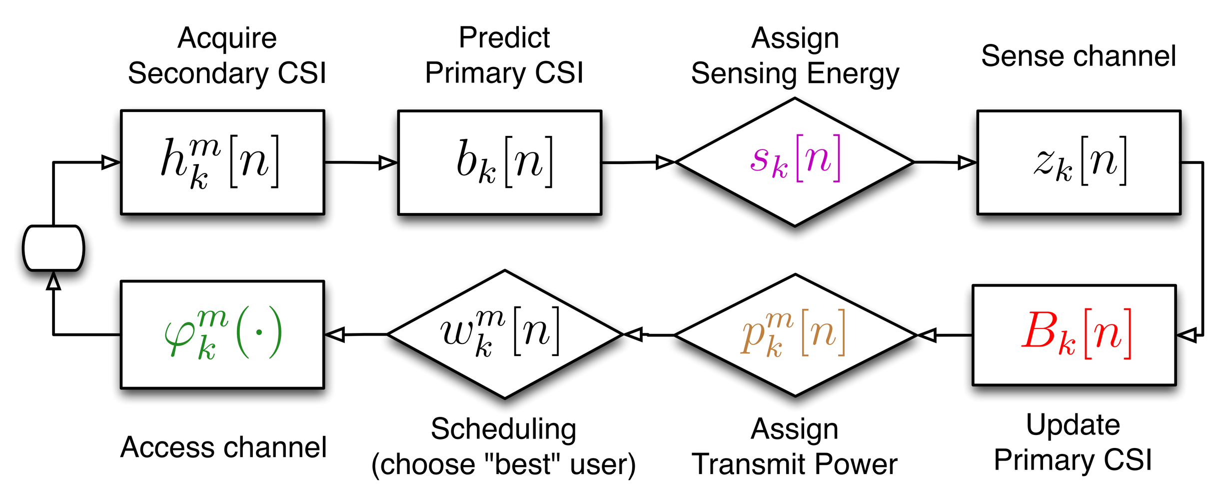
- Analog measurements used to update the **belief** on PU presence. EXAMPLE - energy detection:



$$B_k[n] = \frac{b_k[n] f_z(z|\mathcal{H}_1, g, s)}{b_k[n] f_z(z|\mathcal{H}_1, g, s) + (1 - b_k[n]) f_z(z|\mathcal{H}_0, g, s)}$$

Note: the proposed technique works **independently of the class** of spectrum sensor used

SYSTEM OPERATION



PROBLEM FORMULATION

Short-term utility for user m at channel k:

$$\varphi_k^m(h_k^m[n], B_k[n], p_k^m[n]) := \beta^m C_k^m(h_k^m[n] p_k^m[n]) - \pi^m p_k^m[n] - \theta_k B_k[n]$$

Long-term (average) system utlity:

$$\bar{U} := \sum_{n=0}^{\infty} \gamma^n \mathbb{E}\Big[\sum_k \big(-\xi_k s_k[n] + \sum_m w_k^m[n] \varphi_k^m(h_k^m[n], B_k[n], p_k^m[n])\big)\Big]$$

Optimal joint design:

$$\mathrm{P}^* := \max_{\{w_k^m[n], p_k^m[n], s_k[n]\}_{\forall n}} \bar{U}$$

$$\text{s. to}: \; w_k^m[n] \in \{0,1\}, \; \sum_m w_k^m[n] \le 1, \; p_k^m[n] \ge 0 \text{ and } s_k[n] \ge 0.$$

This is an infinite-horizon **POMDP** because $s_k[n]$ has (through $B_k[n]$ and $b_k[n+1]$) an impact on $B_k[n+1]$.

ALGORITHMIC APPROACH

The problem can be separated channel-wise. In addition, we split the original problem into 2 sub-problems without loss of optimality.

OPTIMAL POWER AND ACCESS

1. Optimize power for each user separately
2. Choose the "best" user to access the channel
3. If no user has utility > 0, leave the channel silent

Instantaneous per-channel *expected* utility (as a function of $B_k[n]$ and thus valid for *any* sensing scheme) [6]:

$$\mathcal{R}_k(\mathbf{h}_k[n], B_k[n]) = \Big[\max_{m,p} \{\varphi_k^m(h_k^m[n], B_k[n], p)\}\Big]_+$$

OPTIMAL SENSING

Leveraging the optimal RA, the joint optimization can be rewritten as an unconstrained POMDP [3]:

$$\mathrm{P}_{\mathrm{DP}}^* := \max_{\{s_k[n] \ge 0\}} \sum_{n=0}^{\infty} \gamma^n \sum_k \mathbb{E}[\mathcal{R}_k(\mathbf{h}_k[n], B_k[n]) - \xi_k s_k[n]]$$

Myopic Policy (ignore impact of $s_k[n]$ on the future):

$$s_k^{\mathrm{M}}[n] = \arg\max_{s \ge 0} \bar{\mathcal{R}}_k(b_k[n], \mathbf{h}_k[n], s), \quad \text{where}$$

$$\bar{\mathcal{R}}_k(b_k[n], \mathbf{h}, s) := \mathbb{E}_z\left[\mathcal{R}_k(\mathbf{h}, B_k[n]) \middle| b_k[n], \mathbf{h}, g_k, s\right] - \xi_k s$$

Optimal Policy:

$$s_k^*[n] = \arg\max_{s \ge 0} \bar{\mathcal{R}}_k(b_k[n], \mathbf{h}_k[n], s) + \sum_{n'=n+1}^{\infty} \gamma^{n'} \mathbb{E}[\bar{\mathcal{R}}_k[n'] | s]$$

$$s_k^*[n] = \arg\max_{s \ge 0} Q_k^*(b_k[n], \mathbf{h}_k[n], s)$$

OPTIMAL Q-FUNCTION

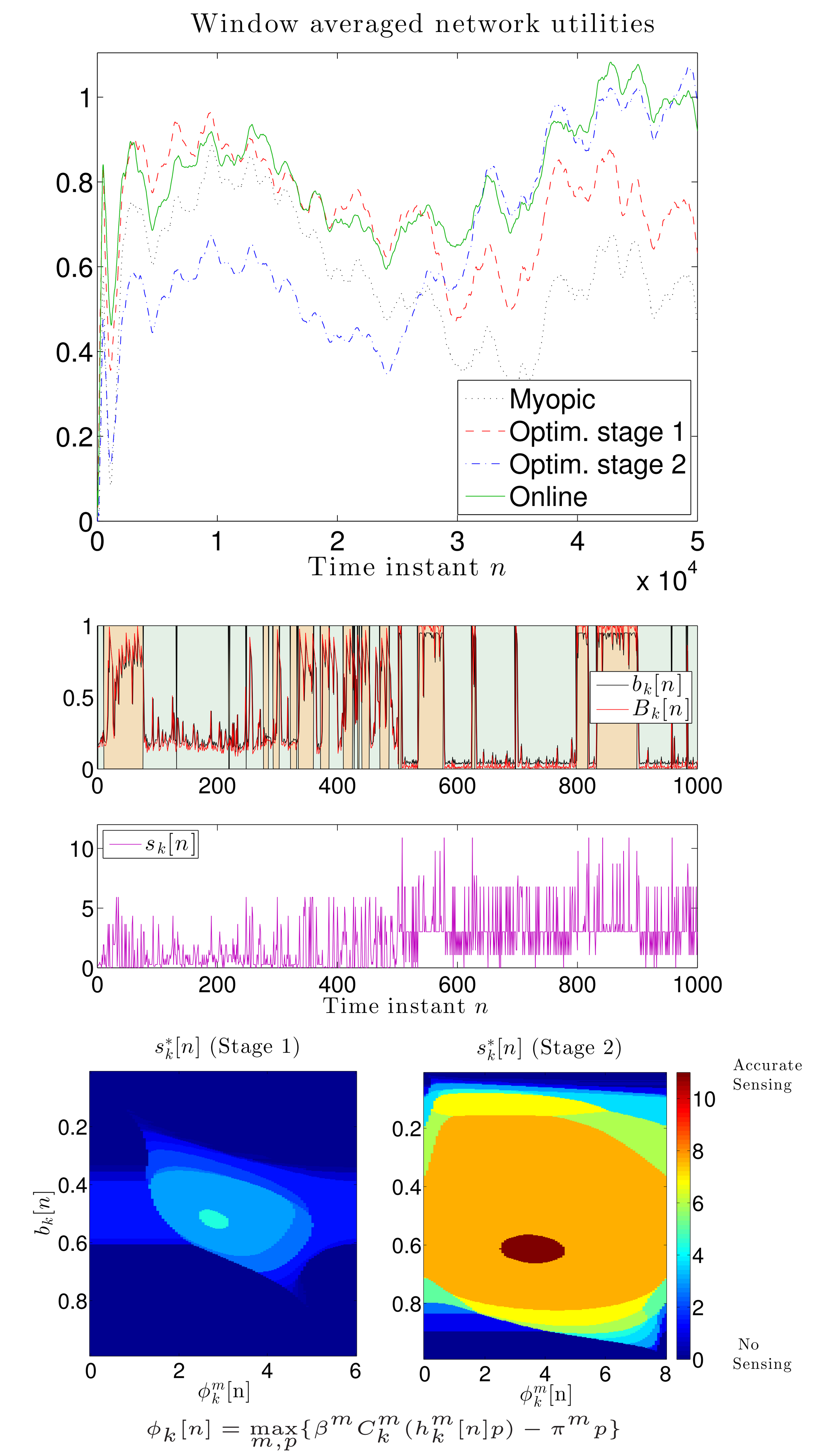
2 methods are proposed to estimate $Q_k^*(\cdot)$:

- Off-line (model-based) Q-iteration. Converges to $Q_k^*(\cdot)$. Requires knowledge about $f_h(h_k^m[n])$.
- Online (variant of Q-learning). Converges to a neighbourhood of $Q_k^*(\cdot)$. Does not require knowledge about $f_h(h_k^m[n])$. Robust to non-stationarities.

We develop a technique to reduce the dimensionality of the Q-function and reduce computational load.

RESULTS

(Model parameters change suddenly at 50% of simulation time)



NOTATION

k, m	channel index, user index	$p_k^m[n]$	nominal power of SU m on channel k
g_k	SNR from kth PU	$w_k^m[n]$	scheduling coefficients
$h_k^m[n]$	kth channel, mth SU fading coefficient	$s_k[n]$	energy spent in sensing channel k
$a_k[n]$	primary presence on channel k	θ_k	price of intefering PU k
$b_k[n]$	*pre-decision* belief (on $a_k[n]$)	π^m	price of transmitting user m
$B_k[n]$	*post-decision* belief (on $a_k[n]$)	ξ_k	price of sensing power on channel k
$z_k[n]$	measure from sensing channel k	β_k	(benefit) price of throughput
$C(\cdot)$	power-throughput (capacity) function	γ	exponential discount factor (< 1)

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