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CRN_IS9: Performance Analysis of Hybrid Cognitive Radio Systems with Imperfect Channel Knowledge

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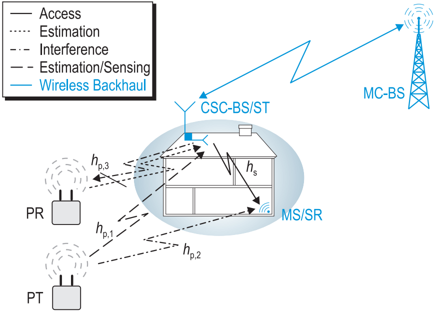
Hybrid Scenario



Hybrid System:

- A spectrum sensing and a power control mechanism is employed at the ST
- To accomplish this $\Rightarrow$ Knowledge of the channels $h_{p,1}$, $h_{p,3}$ is required at ST
- Further, to characterize the throughput at SR $\Rightarrow$ Knowledge of the channels $h_{p,2}$, h_s is required at ST

In a realistic scenario:

- Channel knowledge is not available at the ST, **Solution** needs to be estimated
- Without any knowledge of the primary system, direct estimation of channel is not possible

Hybrid Scenario

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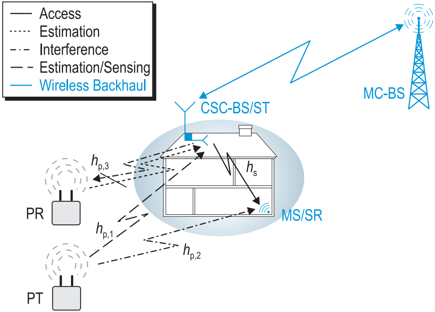


Contributions:

- We propose an analytical framework that facilitates a successful incorporation of the estimation of the involved channels
- We examine the impact of channel knowledge in terms of interference encountered
- We depict a estimation-sensing-throughput tradeoff that allow us to optimize the performance of the hybrid system

Signal Model

- Received signal at the ST

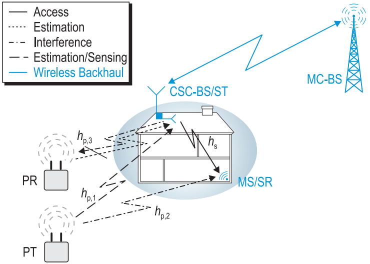
$$y_{\mathrm{ST}}[n] = \begin{cases} h_{\mathrm{p},1} \cdot x_{\mathrm{PT}}[n] + w[n] & : \mathcal{H}_1 \\ w[n] & : \mathcal{H}_0 \end{cases}$$

- Received signal at the PR

$$y_{\mathrm{PR}}[n] = \begin{cases} h_{\mathrm{p},3} \cdot x_{\mathrm{ST,cont}}[n] + w[n] & : \mathrm{P_d} \\ h_{\mathrm{p},3} \cdot x_{\mathrm{ST,full}}[n] + w[n] & : 1 - \mathrm{P_d} \end{cases}$$

- Received signal at the SR

$$y_{\mathrm{SR}}[n] = \begin{cases} h_{\mathrm{s}} \cdot x_{\mathrm{ST,full}}[n] + h_{\mathrm{p},2} \cdot x_{\mathrm{PT}}[n] + w[n] & : 1 - \mathrm{P_d} \\ h_{\mathrm{s}} \cdot x_{\mathrm{ST,full}}[n] + w[n] & : 1 - \mathrm{P_{fa}} \\ h_{\mathrm{s}} \cdot x_{\mathrm{ST,cont}}[n] + h_{\mathrm{p},2} \cdot x_{\mathrm{PT}}[n] + w[n] & : \mathrm{P_d} \\ h_{\mathrm{s}} \cdot x_{\mathrm{ST,cont}}[n] + w[n] & : \mathrm{P_{fa}} \end{cases}$$



Problem Description

- Existing models (Ideal Model)

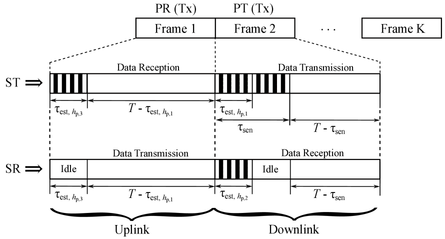
$$\text{Interference constraint} \begin{cases} \mathbb{P}(\mathcal{H}_1) \cdot \mathrm{P_d} \cdot |h_{\mathrm{p,3}}|^2 P_{\mathrm{Tx,ST,cont}} \le \theta_{\mathrm{I}} \\ \text{and } \mathbb{P}(\mathcal{H}_1) \cdot (1 - \mathrm{P_d}) \cdot |h_{\mathrm{p,3}}|^2 P_{\mathrm{Tx,ST,full}} \le \theta_{\mathrm{I}} \end{cases}$$

$$\text{Throughput at SR} \begin{cases} R_0(\tau_{\mathrm{sen}}) = & \frac{T-\tau_{\mathrm{sen}}}{T} \cdot \log_2\left(1 + |h_{\mathrm{s}}|^2 \frac{P_{\mathrm{Tx,ST,full}}}{\sigma_{\mathrm{w}}^2}\right)(1 - \mathrm{P_{fa}}) \cdot \mathbb{P}(\mathcal{H}_0), \\ R_1(\tau_{\mathrm{sen}}) = & \frac{T-\tau_{\mathrm{sen}}}{T} \log_2\left(1 + \frac{|h_{\mathrm{s}}|^2 P_{\mathrm{Tx,ST,full}}}{|h_{\mathrm{p,2}}|^2 \sigma_{\mathrm{s}}^2 + \sigma_{\mathrm{w}}^2}\right)(1 - \mathrm{P_d}) \cdot \mathbb{P}(\mathcal{H}_1), \\ R_2(\tau_{\mathrm{sen}}) = & \frac{T-\tau_{\mathrm{sen}}}{T} \cdot \log_2\left(1 + |h_{\mathrm{s}}|^2 \frac{P_{\mathrm{Tx,ST,cont}}}{\sigma_{\mathrm{w}}^2}\right) \mathrm{P_{fa}} \cdot \mathbb{P}(\mathcal{H}_0), \\ R_3(\tau_{\mathrm{sen}}) = & \frac{T-\tau_{\mathrm{sen}}}{T} \cdot \log_2\left(1 + \frac{|h_{\mathrm{s}}|^2 P_{\mathrm{Tx,ST,cont}}}{|h_{\mathrm{p,2}}|^2 \sigma_{\mathrm{s}}^2 + \sigma_{\mathrm{w}}^2}\right) \mathrm{P_d} \cdot \mathbb{P}(\mathcal{H}_1). \end{cases}$$

- Without the knowledge of received power (sensing channel, $h_{\mathrm{p,1}}$), the characterization of $\mathrm{P_d}$ at the ST is not possible
- Without the knowledge of the interference channel towards the PR ($h_{\mathrm{p,3}}$), the power control mechanism cannot be employed at the ST
- The knowledge of the access (h_{s}) and the interference channel ($h_{\mathrm{p,2}}$) to the SR, from the PT, is required at the ST for characterizing the SU throughput.

Proposed Approach

Proposed frame structure for the secondary system



- We consider the estimation of involved channels. In order to facilitate deployment received power estimation is proposed for the sensing and interference channel.
- Next, we characterize the variations due to channel estimation in the estimation parameters in terms of their pdfs.
- We further characterize the aforementioned variations, which include the interference received at PR and expected throughput at SR in terms of their cdf.
- We utilize these cdfs to obtain the expression estimation-sensing-throughput tradeoff.

Performance Characterization

Channel Estimation

- Sensing channel

$$F_{\hat{P}_{\mathrm{Rx,ST},h_{\mathrm{p},1}}}(x) = 1 - \Gamma\left(\frac{\tau_{\mathrm{est},\ h_{\mathrm{p},1}} f_{\mathrm{s}}}{2}, \frac{\tau_{\mathrm{est},\ h_{\mathrm{p},1}} f_{\mathrm{s}} x}{2 P_{\mathrm{Rx,ST},h_{\mathrm{p},1}}}\right)$$

- Access channel

$$F_{|\hat{h}_{\mathrm{s}}|^2}(x) \approx 1 - \Gamma\left(a, \frac{x}{b}\right)$$

- Interference channel

$$F_{\hat{P}_{\mathrm{Rx,SR},h_{\mathrm{p},2}}}(x) = 1 - \Gamma\left(\frac{\tau_{\mathrm{est},\ h_{\mathrm{p},2}} f_{\mathrm{s}}}{2}, \frac{\tau_{\mathrm{est},\ h_{\mathrm{p},2}} f_{\mathrm{s}} x}{2 P_{\mathrm{Rx,SR},h_{\mathrm{p},2}}}\right)$$

- Interference channel

$$F_{\hat{P}_{\mathrm{Rx,ST},h_{\mathrm{p},3}}}(x) = 1 - \Gamma\left(\frac{\tau_{\mathrm{est},\ h_{\mathrm{p},3}} f_{\mathrm{s}}}{2}, \frac{\tau_{\mathrm{est},\ h_{\mathrm{p},3}} f_{\mathrm{s}} x}{2 P_{\mathrm{Rx,ST},h_{\mathrm{p},3}}}\right)$$

Detection probability constraint

$$\mathbb{P}(\mathrm{P_d}(\hat{P}_{\mathrm{Rx,ST},h_{\mathrm{p},1}}) \leq \bar{\mathrm{P}}_{\mathrm{d}}) \leq \rho_{\mathrm{d}}$$

Interference constraint

$$\mathbb{P}(P_{\mathrm{Rx,PR}}(\mathrm{P_d}(\hat{P}_{\mathrm{Rx,ST},h_{\mathrm{p},1}}), \hat{P}_{\mathrm{Rx,ST},h_{\mathrm{p},3}}) \geq \theta_{\mathrm{I}}) \leq \rho_{\mathrm{cont}}$$

Expected secondary throughput

$$\begin{aligned}\mathbb{E}_{\Omega}\left[R_{\mathrm{s}}(\tau_{\mathrm{sen}})\right] = \frac{T - \tau_{\mathrm{est},\ h_{\mathrm{p},3}} - \tau_{\mathrm{sen}}}{T} \cdot &\Big[(1 - \mathrm{P_{fa}}) \cdot \mathbb{P}(\mathcal{H}_0) \cdot \mathbb{E}_{\mathrm{C}_0}[\mathrm{C}_0] + \\ &(1 - \mathbb{E}_{\mathrm{P_d}}[\mathrm{P_d}]) \cdot \mathbb{P}(\mathcal{H}_1) \cdot \mathbb{E}_{\mathrm{C}_1}[\mathrm{C}_1] + \\ &\mathrm{P_{fa}} \cdot \mathbb{P}(\mathcal{H}_0) \cdot \mathbb{E}_{\mathrm{C}_2}[\mathrm{C}_2] + \\ &\mathbb{E}_{\mathrm{P_d}}[\mathrm{P_d}] \cdot \mathbb{P}(\mathcal{H}_1) \cdot \mathbb{E}_{\mathrm{C}_3}[\mathrm{C}_3]\Big].\end{aligned}$$

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Performance Characterization

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- **Theorem**: The expected achievable SU throughput subject to an outage constraint on detection probability at the ST and an outage constraint on interference power at the PR given by

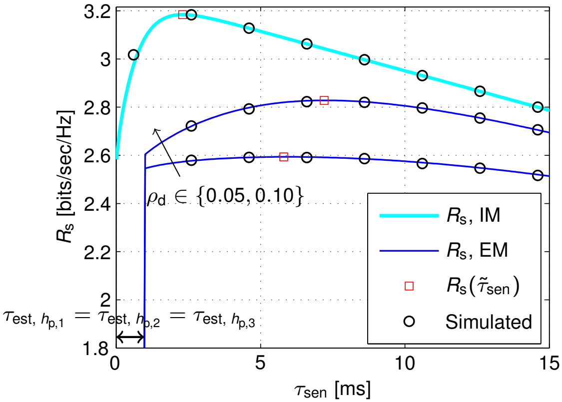
$$R_\mathrm{s}(\tilde{\tau}_\mathrm{sen}) = \max_{\tau_\mathrm{sen}, P_\mathrm{Tx,ST,cont}} \mathbb{E}_\Omega \left[R_\mathrm{s}(\tau_\mathrm{sen}) \right]$$
$$\text{s.t. } \mathbb{P}(\mathrm{P_d} \leq \bar{\mathrm{P}}_\mathrm{d}) \leq \rho_\mathrm{d}$$
$$\text{s.t. } \mathbb{P}(P_\mathrm{Rx,PR} \geq \theta_\mathrm{I}) \leq \rho_\mathrm{cont}$$

Numerical Analysis

Parameter	Definition	Value
f_s	Sampling Frequency	1 MHz
T	Frame Duration	100 ms
$\tau_{\mathrm{est},\,h_{\mathrm{p},1}}$	Estimation time for the channel $h_{\mathrm{p},1}$	1 ms
$\tau_{\mathrm{est},\,h_{\mathrm{p},2}}$	Estimation time for the channel $h_{\mathrm{p},2}$	1 ms
$\tau_{\mathrm{est},\,h_{\mathrm{p},3}}$	Estimation time for the channel $h_{\mathrm{p},3}$	1 ms
$\|h_{\mathrm{p},1}\|^2$	Power gain for channel $h_{\mathrm{p},1}$	-120 dB
$\|h_{\mathrm{p},2}\|^2$	Power gain for channel $h_{\mathrm{p},2}$	-120 dB
$\|h_{\mathrm{p},3}\|^2$	Power gain for channel $h_{\mathrm{p},3}$	-100 dB
$\|h_\mathrm{s}\|^2$	Power gain for channel h_s	-80 dB
θ_I	Interference threshold	-110 dBm
ρ_cont	Outage constraint on interference power at PR	0.1
ρ_d	Outage constraint on detection probability	0.1
σ_s^2	Transmit power at PT and PR	10 dBm
σ_w^2	Noise power at ST, SR and PR	-100 dBm
$\bar{\mathrm{P}}_\mathrm{d}$	Detection probability threshold	0.9
$\mathbb{P}(\mathcal{H}_0)$	Occurrence Probability for hypothesis $\mathcal{H}_0$	0.2
$P_{\mathrm{Tx,ST,full}}$	Transmit power at ST	0 dBm
N_s	Number of pilot symbols	10

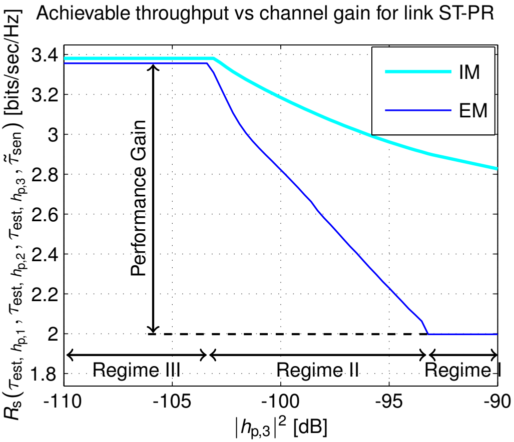
Numerical Analysis

Sensing-throughput tradeoff for $\tau_{\text{est},\, h_{\text{p},1}} = \tau_{\text{est},\, h_{\text{p},2}} = \tau_{\text{est},\, h_{\text{p},3}} = 1$ ms



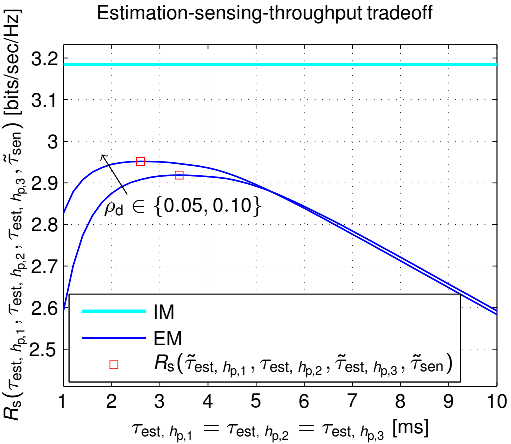
- As indicated by the margin between the IM and the EM, a certain performance degradation is witnessed due to the incorporation of channel estimation
- The sensing-throughput tradeoff yields a suitable sensing time $\tilde{\tau}_{\text{sen}}$ that achieves the maximum performance in terms of SU throughput $R_s(\tilde{\tau}_{\text{sen}})$

Numerical Analysis



- In Regime I, no benefits are attained from the US (power control) while operating in this regime, hence, the HS operates as an IS.
- In Regime III, which illustrates favorable channel conditions for the US, since the ST is limited by the transmit power, $P_{\text{Tx,ST,cont}} = P_{\text{Tx,ST,full}}$, the HS procure no further performance gains.

Numerical Analysis



- The estimation-sensing-throughput tradeoff corresponding to the EM.
- The performance degradation is sensitive to the outage constraint on the detection probability.

Summary

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- The performance of cognitive radio as hybrid systems is investigated from a deployment perspective.
- It is argued that channel knowledge is absolutely mandatory for the performance characterization.
- In view of this, an analytical framework that incorporates channel estimation and subsequently captures the effect of imperfect channel knowledge is established.
- More importantly, a fundamental tradeoff between the estimation, the sensing time and secondary throughput is determined.
- In future, it will be interesting to include the effect of channel fading on the performance of the hybrid systems.

Thank you for attention!