Image Transmission over Cognitive Radio Systems with Channel and Sensing Uncertainty

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   - Interference Link Estimation
   - Cognitive Channel Model
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   - 16-HQAM Constellation
   - Bit Error Rate Analysis
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- Existing literature mainly focuses on the performance of spectrum sensing methods and the throughput of cognitive radio systems.
- There have been relatively limited number of studies on multimedia transmission in cognitive radio networks.
- Hence, in this work, we mainly analyze the performance of image transmissions based on HQAM modulation in cognitive radio systems subject to average/peak transmission power and average interference constraints under channel and sensing uncertainty.

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Channel Sensing

- We consider an underlay cognitive radio system in which the secondary transmitter communicates with the secondary receiver over a flat-fading channel.
- Before initiating data transmission, secondary transmitter first performs channel sensing of secondary link and estimates the interference link between the secondary transmitter and the primary receiver. The detection and false-alarm probabilities are defined as

$$P_{\text{d}} = \Pr\{\hat{\mathcal{H}}_1 | \mathcal{H}_1\} \qquad P_{\text{f}} = \Pr\{\hat{\mathcal{H}}_1 | \mathcal{H}_0\},$$

$\mathcal{H}_0$: the primary users are inactive, $\mathcal{H}_1$: the primary users are active,
$\hat{\mathcal{H}}_0$: the channel is detected as idle, $\hat{\mathcal{H}}_1$: the channel is detected as busy.

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Interference Link Estimation

- It is assumed that the secondary transmitter performs minimum mean square error (MMSE) estimation to estimate the interference link between the secondary transmitter and the primary receiver.
- At the secondary transmitter, the received signal y_e is written as

$$y_e = \sqrt{E_p} g p + n_e,$$

where p is pilot signal transmitted from primary receiver, E_p is the pilot transmit power level, $|p|^2 = 1$, and $n_e \sim \mathcal{CN}(0, \sigma_{n_e}^2)$ is the noise during estimation. g is assumed to be independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian random variable with mean zero and variance σ_g^2.

Interference Link Estimation

- $g = \hat{g} + \tilde{g}$, where $\hat{g}$ is the MMSE estimation of the interference link and $\tilde{g}$ is its estimation error. The MMSE estimate of the interference link is

$$\hat{g} = \frac{\sqrt{E_p \mathbb{E}\{|g|^2\}}}{E_p \mathbb{E}\{|g|^2\} + \sigma_{n_e}^2} p^* y_e = \frac{\sqrt{E_p \sigma_g^2}}{E_p \sigma_g^2 + \sigma_{n_e}^2} p^* y_e.$$

where $\sigma_e^2 = \frac{\sigma_{n_e}^2 \sigma_g^2}{E_p \sigma_g^2 + \sigma_{n_e}^2}$ since $\hat{g}$ and $\tilde{g}$ are uncorrelated.

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Cognitive Channel Model

- Following channel sensing of secondary link and estimating interference link, the secondary transmitter starts sending image data.
- Secondary users are assumed to transmit under both idle and busy sensing decisions. Under this assumption, the channel input-output relation is given by

$$y = \begin{cases} hx\sqrt{P_i(h,\hat{g})} + n & \text{primary user is inactive} \\ hx\sqrt{P_i(h,\hat{g})} + n + \omega & \text{primary user is active} \end{cases}.$$

x: transmitted signal, y: received signal,
n: circularly symmetric complex Gaussian noise, $n \sim \mathcal{CN}(0, \sigma_n^2)$.
ω: additive Gaussian disturbance, which includes any additional interference caused by the primary transmitter, $\omega \sim \mathcal{CN}(0, \sigma_\omega^2)$.
h: fading coefficient in the channel between the secondary transmitter and the secondary receiver, which follows Rayleigh distribution.
$P_i(h,\hat{g})$ denotes the instantaneous transmission power under the sensing decision $\hat{\mathcal{H}}_i$ for $i \in \{0,1\}$.

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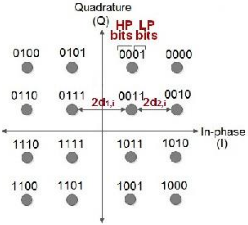
16-HQAM Constellation

- Secondary users are assumed to perform 16-HQAM which provides different levels of error protection for HP and LP bits in the transmitted stream.



$$d_{1,i} = \sqrt{\frac{\alpha^2 P_i(h,\hat{g})}{2(\alpha+1)^2+2}}$$

$$d_{2,i} = \sqrt{\frac{P_i(h,\hat{g})}{2(\alpha+1)^2+2}}$$

Figure: Signal constellation diagram of Gray coded 16-HQAM

- $2d_{1,i}$: minimum distance between each quadrant,
  $2d_{2,i}$: minimum distance between the signal constellation points within each quadrant under the sensing decision $\hat{\mathcal{H}}_i$ for $i \in \{0, 1\}$.
- Let us define the ratio $\alpha = d_{1,i}/d_{2,i}$. By changing the value of α, we can control the protection level for HP and LP bits.

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Bit Error Rate Analysis

- The most significant bit, b_1, does not change, and only the second bit b_2 changes in the form of $0 - 0 - 1 - 1$. Hence, BER of HP bits for a given fading coefficient h and $\hat{g}$ can be expressed as

$$P_{\text{HP}}(\mathbf{P}, h, \hat{g}) = \frac{1}{2} \sum_{j=0}^{1} \sum_{i=0}^{1} \sum_{l=0}^{1} \Pr\{\mathcal{H}_j, \hat{\mathcal{H}}_i\} Q\left(\sqrt{\frac{c_l P_i(h, \hat{g})|h|^2}{\sigma_j^2}}\right)$$

where $\mathbf{P} = [P_0(h, \hat{g}), P_1(h, \hat{g})]$, $c_1 = \frac{(\alpha+2)^2}{(\alpha+1)^2+1}$ and $c_2 = \frac{\alpha^2}{(\alpha+1)^2+1}$, $Q(x)$ is the Gaussian Q-function. Above,

$$\sigma_j^2 = \begin{cases} \sigma_n^2, & j = 0 \\ \sigma_n^2 + \sigma_\omega^2, & j = 1 \end{cases}.$$

Bit Error Rate Analysis

- Similarly, BER of LP bits can be calculated by considering the change of quadrature bits. The third bit, b_3, changes according to the pattern $0-1-1-0$ while b_4 does not change. As a result, BER expression is given by

$$P_{\mathrm{LP}}(\mathbf{P}, h, \hat{g}) = \frac{1}{2} \sum_{j=0}^{1} \sum_{i=0}^{1} \Pr\{\mathcal{H}_j, \hat{\mathcal{H}}_i\}$$

$$\left\{ 2Q\left(\sqrt{\frac{\beta_0 P_i(h,\hat{g})|h|^2}{\sigma_j^2}}\right) + Q\left(\sqrt{\frac{\beta_1 P_i(h,\hat{g})|h|^2}{\sigma_j^2}}\right) - Q\left(\sqrt{\frac{\beta_2 P_i(h,\hat{g})|h|^2}{\sigma_j^2}}\right) \right\}$$

where $\beta_0 = \frac{1}{(\alpha+1)^2+1} \quad \beta_1 = \frac{(2\alpha+1)^2}{(\alpha+1)^2+1} \quad \beta_2 = \frac{(2\alpha+3)^2}{(\alpha+1)^2+1}$.

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Peak Transmit and Average Interference Power Constraints

- The optimal choice of the power levels that minimize the sum of bit error rates of HP and LP bits under peak power and average interference constraints can be determined by solving

$$\min_{P_0(h,\hat{g}),P_1(h,\hat{g})} \mathbb{E}\{\lambda P_{\text{HP}}(\mathbf{P},h,\hat{g}) + (1-\lambda)P_{\text{LP}}^{u}(\mathbf{P},h,\hat{g})\}$$

$$\text{subject to } \; P_0(h,\hat{g}) \leq P_{\rm pk}, \; P_1(h,\hat{g}) \leq P_{\rm pk}$$

$$\mathbb{E}\{[(1-P_{\rm d})\,P_0(h,\hat{g}) + P_{\rm d}\,P_1(h,\hat{g})]\,|g|^2\} \leq Q_{\text{avg}}$$

- $P_{\rm pk}$ denotes the peak transmit power limit of the secondary transmitter due to hardware/battery constraints and Q_{avg} represents average interference power limit at the primary receiver.

Peak Transmit and Average Interference Power Constraints

Theorem

The optimal power control policy that minimizes the BER upper bound under peak transmit and average interference power constraints is obtained as

$$P_{opt}^{(0)}(h,\hat{g}) = \min(P_0^*(h,\hat{g}), P_{\mathrm{pk}}),$$
$$P_{opt}^{(1)}(h,\hat{g}) = \min(P_1^*(h,\hat{g}), P_{\mathrm{pk}})$$

where $P_0^*(h,\hat{g})$ *and* $P_1^*(h,\hat{g})$ *are solutions to the following equations, respectively:*

$$\sum_{j,l=0}^{1} \frac{P(\mathcal{H}_j,\hat{\mathcal{H}}_0)}{4\sqrt{2\pi}} \left\{ \lambda \frac{\mathrm{e}^{\frac{-c_l P_0(h,\hat{g})|h|^2}{2\sigma_j^2}}}{\sqrt{\frac{P_0(h,\hat{g})\sigma_j^2}{c_l|h|^2}}} + (1-\lambda)\rho_l \frac{\mathrm{e}^{\frac{-\beta_l P_0(h,\hat{g})|h|^2}{2\sigma_j^2}}}{\sqrt{\frac{P_0(h,\hat{g})\sigma_j^2}{\beta_l|h|^2}}} \right\} - \mu_1(1-P_{\mathrm{d}})(|\hat{g}|^2+\sigma_e^2) = 0,$$

$$\sum_{j,l=0}^{1} \frac{P(\mathcal{H}_j,\hat{\mathcal{H}}_1)}{4\sqrt{2\pi}} \left\{ \lambda \frac{\mathrm{e}^{\frac{-c_l P_1(h,\hat{g})|h|^2}{2\sigma_j^2}}}{\sqrt{\frac{P_1(h,\hat{g})\sigma_j^2}{c_l|h|^2}}} + (1-\lambda)\rho_l \frac{\mathrm{e}^{\frac{-\beta_l P_1(h,\hat{g})|h|^2}{2\sigma_j^2}}}{\sqrt{\frac{P_1(h,\hat{g})\sigma_j^2}{\beta_l|h|^2}}} \right\} - \mu_1 P_{\mathrm{d}}(|\hat{g}|^2+\sigma_e^2) = 0,$$

where $\rho_1 = 2$, $\rho_2 = 1$.

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Average Transmit and Average Interference Power Constraints

- In this case, secondary transmission is subject to average transmit and average interference power constraints. Hence, the optimal power control problem is expressed as

$$\min_{P_0(h,\hat{g}),P_1(h,\hat{g})} \mathbb{E}\{\lambda P_{\text{HP}}(\mathbf{P},h,\hat{g}) + (1-\lambda)P^{u}_{\text{LP}}(\mathbf{P},h,\hat{g})\}$$
$$\text{subject to } \mathbb{E}\{P(\hat{\mathcal{H}}_0)\,P_0(h,\hat{g}) + P(\hat{\mathcal{H}}_1)P_1(h,\hat{g})\} \leq P_{\text{avg}}$$
$$\mathbb{E}\{[(1-P_{\mathrm{d}})\,P_0(h,\hat{g})+P_{\mathrm{d}}\,P_1(h,\hat{g})]\,(|\hat{g}|^2+\sigma_e^2)\} \leq Q_{\text{avg}}$$

where P_{avg} denotes the average transmit power limit at the secondary transmitter.

Average Transmit and Average Interference Power Constraints

Theorem

The optimal power control scheme subject to average transmit and average interference power constraints is given by

$$P_{opt}^{(0)}(h,\hat{g}) = P_0^*(h,\hat{g}),\ \ P_{opt}^{(1)}(h,\hat{g}) = P_1^*(h,\hat{g})$$

where $P_0^*(h,\hat{g})$ *and* $P_1^*(h,\hat{g})$ *are solutions to the following equations, respectively:*

$$\sum_{j,l=0}^{1}\frac{P(\mathcal{H}_j,\hat{\mathcal{H}}_0)}{4\sqrt{2\pi}}\left\{\lambda\frac{\mathrm{e}^{\frac{-c_l P_0^*(h,\hat{g})|h|^2}{2\sigma_j^2}}}{\sqrt{\frac{P_0^*(h,\hat{g})\sigma_j^2}{c_l|h|^2}}}+(1-\lambda)\rho_l\frac{\mathrm{e}^{\frac{-\beta_l P_0^*(h,\hat{g})|h|^2}{2\sigma_j^2}}}{\sqrt{\frac{P_0^*(h,\hat{g})\sigma_j^2}{\beta_l|h|^2}}}\right\}=\mu_1(1-P_{\mathrm{d}})(|\hat{g}|^2+\sigma_e^2)+\mu_2 P(\hat{\mathcal{H}}_0),$$

$$\sum_{j,l=0}^{1}\frac{P(\mathcal{H}_j,\hat{\mathcal{H}}_1)}{4\sqrt{2\pi}}\left\{\lambda\frac{\mathrm{e}^{\frac{-c_l P_1^*(h,\hat{g})|h|^2}{2\sigma_j^2}}}{\sqrt{\frac{P_1^*(h,\hat{g})\sigma_j^2}{c_l|h|^2}}}+(1-\lambda)\rho_l\frac{\mathrm{e}^{\frac{-\beta_l P_1^*(h,\hat{g})|h|^2}{2\sigma_j^2}}}{\sqrt{\frac{P_1^*(h,\hat{g})\sigma_j^2}{\beta_l|h|^2}}}\right\}=\mu_1 P_{\mathrm{d}}(|\hat{g}|^2+\sigma_e^2)+\mu_2 P(\hat{\mathcal{H}}_1),$$

where μ_1 *and* μ_2 *are the Lagrange multipliers associated with the average transmit power and average interference power constraints, respectively.*

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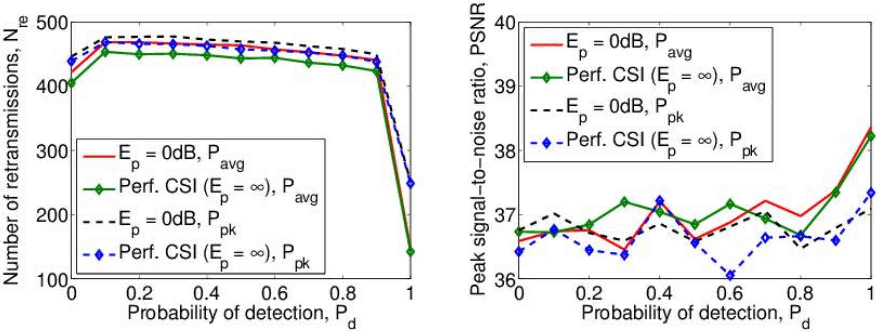
Simulation Setting

- In the case of image transmission, test image is chosen as gray scale "Boat.bmp" image with size 512× 512 pixels.
- It is assumed that $\sigma_{n_e}^2$ and σ_n^2 are both set to 0.01, $\sigma_\omega^2 = 0.5$.
- $\Pr\{\mathcal{H}_1\} = 0.4$ and $\Pr\{\mathcal{H}_0\} = 0.6$.
- Fading powers $|h|^2$and $|g|^2$ are exponentially distributed with unit mean.
- Modulation parameter α is set to 1.
- Retransmission is requested if received power is smaller than a certain threshold denoted by $Thr = 1.8$.
- $P_{\text{pk}} = P_{\text{avg}} = 10$ dB, and $Q_{\text{avg}} = 4$ dB.

Simulation Results



(a) (b)

Figure: (a) Number of retransmissions, N_{re} vs. P_{d}; (b) Peak signal-to-noise ratio, PSNR vs. P_{d} while $P_{\mathrm{f}} = 0.1$

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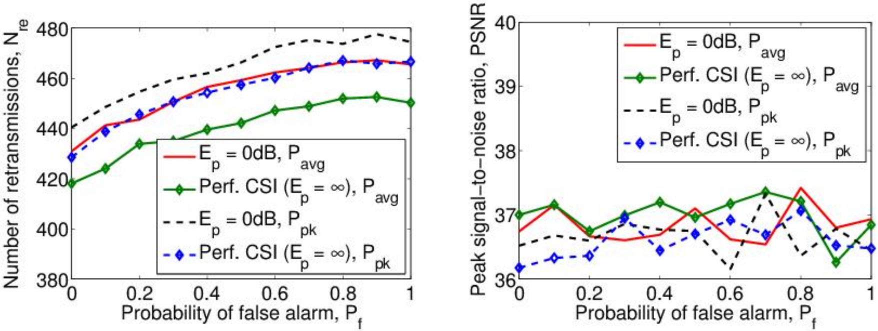

(a) (b)

Figure: (a) Number of retransmissions, N_{re} vs. P_f; (b) Peak signal-to-noise ratio, PSNR vs. P_f while $P_\mathrm{d} = 0.9$

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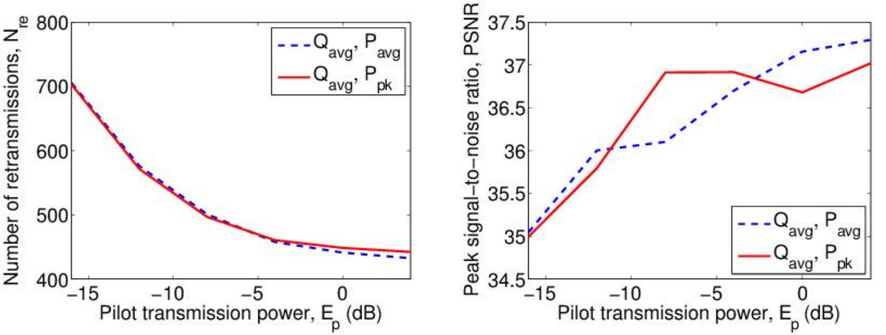

(a) (b)

Figure: (a) Number of retransmissions, N_{re} vs. E_p; (b) Peak signal-to-noise ratio, PSNR vs. E_p while $P_{\mathrm{d}} = 0.9$ and $P_{\mathrm{f}} = 0.1$

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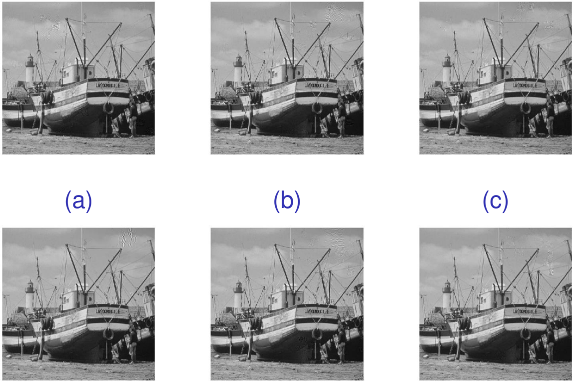

(a) (b) (c)

(d) (e) (f)

Figure: (a) $E_p = -16$ dB, PSNR $= 35.07$ and $N_{re} = 705$; (b) $E_p = -12$ dB, PSNR $= 35.99$ and $N_{re} = 576$; (c) $E_p = -8$ dB, PSNR $= 36.12$ and $N_{re} = 500$; (d) $E_p = -4$ dB, PSNR $= 36.70$ and $N_{re} = 458$; (e) $E_p = 0$ dB, PSNR $= 37.14$ and $N_{re} = 441$; (f) $E_p = 4$ dB, PSNR $= 37.29$ and $N_{re} = 433$ while $P_\mathrm{d} = 0.9$ and $P_\mathrm{f} = 0.1$

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- We have studied the performance of image transmissions with hierarchical QAM in cognitive radio systems in the presence of imperfect sensing results, interference link estimation and constraints on both the transmit and interference power levels.

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- We have determined BER expressions for the HP and LP bits in Rayleigh fading under channel and sensing uncertainty.

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- We have determined BER expressions for the HP and LP bits in Rayleigh fading under channel and sensing uncertainty.
- We have shown that received data quality is robust to imperfect channel sensing results if there is no upper bound on the number of retransmissions. The number of retransmissions increases with decreasing P_{d} or increasing P_{f}, resulting in larger delays and energy consumption.

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- We have observed that improved sensing performance leads to better quality at reception. In addition, simulation results demonstrate that HQAM performs better than conventional QAM in terms of average PSNR.

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- We have observed that improved sensing performance leads to better quality at reception. In addition, simulation results demonstrate that HQAM performs better than conventional QAM in terms of average PSNR.
- Higher quality of the estimate of the interference link due to higher pilot transmission power level leads to less number of retransmissions and higher quality of the received image.