Cognitive Radio: An Information Theoretic Perspective

Jovićić and Vishwanath, Trans. on IT

(Submitted 2006.. cited N times)

Reading Group Discussion

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Overview

Intro.

- Basic Idea: Allocated spectrum is underutilized ..in some cases it being as low as 5%..so use it either
  - Opportunistically or
  - Simultaneously $\rightarrow$ (overlay/underlay).
- In both cases the idea is to not decrease the performance/level of satisfaction of a primary user.
- What is this paper about : What does IT tell us about what enhancements in system utilization is possible
- Assumptions in the paper
  - Generate *NO* interference for primary user in vicinity.
  - No changes to the decoder for primary user - there could be multiple reasons for this.

(Note that in general interference does not have to be zero for the primary user .)

Transmission Model

Who knows what

- Secondary user knows primary user's message (..how is this relevant in practice)
- INR quantizes the interference caused the primary's base station by secondary.
- All noise + interference is iid (usually this will not be the case $\longrightarrow$ implications ??)

Main Result

- Precoding helps - how?? $\longrightarrow$ rest of the paper.
- Largest rate at which *reliable* transmission is possible.
- Closest to $\longrightarrow$ Interference Channel with degraded message sets.

The basics

Received Signal at each base station

- We get

$$\tilde{Y}_p = p\tilde{X}_p + f\tilde{X}_c + \tilde{Z}_p$$
$$\tilde{Y}_c = g\tilde{X}_p + c\tilde{X}_c + \tilde{Z}_s$$

- The above equations are *transformed* into standard form to have unity gains for the desired users. Resulting channel $\rightarrow (1, a, b, 1)$ channel

Achievable Rate R_p

- R_p is achievable if $\exists$ encoding map $E_p : \{1, 2, \cdots, 2^{nR_p}\} \mapsto \mathcal{X}_p^n$
- In contrast a *Cognitive* encoding code map is

$$E_c^n : \{1, 2, \ldots, 2^{nR_p}\} \times \{1, 2, \ldots, 2^{nR_p}\} \mapsto \mathcal{X}_c^n$$

Defn. 2.2 and 2.3 define achievability and capacity for the cognitive user (same as the conventional defns.)

Main Result : Mathematically

Capacity

- The capacity of the (1,a,b,1) cognitive radio channel is

$$R_c^* = \frac{1}{2}\log(1 + (1-\alpha^*)P_c)$$

  for $a \leq 1$ and α from Eqn.(17) in paper.
- Above holds for a *low interference gain* regime $\rightarrow \frac{f}{\sqrt{N_p}} \leq \frac{c}{\sqrt{N_s}}$

Other than the factor $(1-\alpha^*)$ everything is the same as the conventional cap. formula

A little digression: 2-user conventional GMAC

- If individual rates are R_1 and R_2 you get $R_1 + R_2 \leq 2C(P/\sigma_N^2)$ where $C(x)$ is Shannon Cap. and P is average power constraint.
- Achievable rate pair
  - Naive TDMA :$[R_1, R_2] = \{\alpha C(P/\sigma^2), (1-\alpha)C(P/\sigma^2)\}$
  - Smart TDMA :$[R_1, R_2] = \{\{\alpha C(P/\alpha\sigma^2), (1-\alpha)C(P/(1-\alpha)\sigma^2)$

Strategies for achieving capacity

Coding options

- Use Gaussian codebook for primary user according $\mathcal{N}(0, P_p)$.
- Use superposition coding (refer your notes on multiterminal source coding) with

$$X_c^n = \hat{X}_c^n + \sqrt{\frac{\alpha P_c}{P_p}} X_p^n$$

thereafter use DPC (writing on Dirty paper). This channel is considered similar to *Costa's Channel* (non-causal CSIT) .

Value of α

- P_e for primary user vanishes as $n \to \infty$ for

$$R_p < \frac{1}{2} \log \left(1 + \frac{(\sqrt{P_p} + a\sqrt{\alpha P_c})^2}{1 + a^2(1-\alpha)P_c} \right) \text{ Eqn(14) from paper}$$

- Now when you equate this with $C(P_p)$ you get α as the root of the resulting quadratic eqn.

Practical Implementations.. or are they ?

Issues

- Joint code design is advocated (Sect 4.2.5):
- For high interference gain $a \geq 1$
  - P knows m_c and C knows m_p ..everybody cancels out everything and the world is good..
  - PROBLEM: How do you propose to do this !!!
- This brings us to system level considerations.

Optimal Scheme

- Avoids Hidden Terminal problem or Why CR will never be truly opportunistic . . .
- Robust to noise statistics - I am not convinced (argument is vague).

What is *practical*

Obtaining Side - Information

- Estimates of p and f are required for implementing the scheme.
- Cognitive radio tuned to primary user's control channel and gets the feedback of p from it. (Highly improbable)
- It is assumed that the CR can decode m_p faster than P's base station due to physical proximity. (Again.. is this practical?)

All of Section 5 sounds like a fairy tale ... (although one can learn a lot from the excellent proofs in this paper.. I am still learning..)

Improvisation on an Interference Channel

- Causality has got a great role to play.
- Knowing all of m_p might be an over-idealization.
- Cooperation is key... However the assumption of non-causal information is ???

Where do we stand now?

Current focus - Finite State channels (and please correct me here if you know more)

- Number of papers where the cognitive transmitter is assumed to have non-causal information about the primary user
- Adv: Costa proved that if you non-causally know the state of the channel at transmitter, $C^{\text{CSIT}} = C^{\text{AWGN}}$
- Recent variation : Cognitive interference channel with finite state sequence S^n (*Verdu, ISIT08*)
- But rate region again obtained with S^n known non-causally.. relevant? why?

Open Issues

- We know that information needs to be shared -¿ Efficient ways? (Public/Private messages)
- Above is impossible where secondary keeps moving b/w multiple cells : Too much control information