A Transmit Beamforming Technique for MIMO Cognitive Radios

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Outline

Motivations

- Growing success of wireless communications systems + conventional approach to spectrum management ⇒ **lack of available spectrum**
- Many studies have pointed out:
  - relatively low utilization of the licensed spectrum
  - new solution to exploit underutilized bands:

⇓

Cognitive Radio for **Opportunistic Spectrum Sharing**

- CR allows a dynamic and effective management of the spectrum ⇒ many **new** issues
  - primary users have to be protected from detrimental interference
  - acceptable Quality-of-Service (QoS) to the secondary systems
  - effective coexistence

Cognitive Radios with multiple antennas

- Most of prior researches focus on
  - detection of primary users' activity in frequency or time domain (i.e., **Spectrum Sensing**)
  - single antenna at both primary and secondary transceivers
- Introduction of multiple antennas at transceivers can lead to many benefits
  - capacity enhancement, effective co-channel interference reduction, spatial division multiple access, etc.

$$\Downarrow$$

Cognitive Radios with multiple antennas

- Multi–antenna CRs have gained attention
  - theoretical and practical benefits
  - a few researches have been carried out and some open issues persist

Research goal

- Research goal: Evaluate the benefits due to the introduction of multiple antennas in CR networks
- A Cognitive Radio equipped with two antenna is developed
  - to completely avoid interference from secondary transmitter toward primary receiver
  - to maximize the sum-rate throughput
- For practical reasons
  - no modifications are required to the primary terminals
  - no prior knowledge of primary message, signal or transmission standard

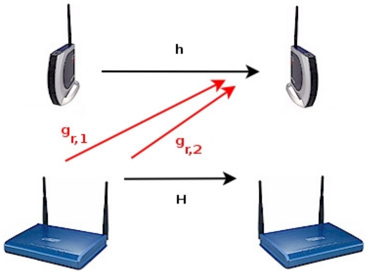
A technique similar to Zero–Forcing beamforming is proposed to **avoid interference** among primary and secondary systems while **maximizing** the achievable **rates**

Reference scenario

- A simple coexistence opportunistic scenario is considered
  - a couple of primary terminals and a couple of cognitive radios communicate sharing the same resource
- the channel of interest (i.e., MIMO Z channel) is described by the equations

$$y_p = \mathbf{g}_r^T \mathbf{x}_c + h x_p + n_p \tag{1}$$

$$\mathbf{y}_c = H \mathbf{x}_c + \mathbf{n}_c \tag{2}$$



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  - $y_p \in \mathbb{C}$ and $x_p \in \mathbb{C}$ are the received and transmitted complex baseband signals of the primary terminals
  - $\mathbf{y}_c \in \mathbb{C}^2$ and $\mathbf{x}_c \in \mathbb{C}^2$ are the received and transmitted complex baseband signal vectors of the cognitive terminals
  - $H \in \mathbb{C}^{2\times 2}$ is the complex channel matrix between the cognitive terminals, $h \in \mathbb{C}$ is the complex channel coefficient between the primary terminals
  - $\mathbf{g}_r \in \mathbb{C}^2$ is the complex channel vector between the cognitive transmitter and the primary receiver
  - $n_p \in \mathbb{C}$ and $\mathbf{n}_c \in \mathbb{C}^2$ are the zero-mean complex Gaussian noise quantities for the primary and the cognitive receivers.

Proposed algorithm for interference free communications

- **Transmit beamforming** can be used by a CR system to steer the power towards secondary receivers while nulling the interference to primary receivers
  - It allows to avoid the interference caused to primary users while maximizing the SINR for the cognitive users.
- A transmit precoding matrix $A \in \mathbb{C}^{2\times 2}$ such that $\mathbf{x}_c = A\mathbf{x}_a$ is introduced
- The considered channel expressed by (1) and (2) becomes

$$y_p = \mathbf{g}_r^T \mathbf{x}_c + hx_p + n_p = \mathbf{g}_r^T A\mathbf{x}_a + hx_p + n_p \quad (3)$$

$$\mathbf{y}_c = HA\mathbf{x}_a + \mathbf{n}_c. \quad (4)$$

- To guarantee that the cognitive transmitter does not cause interference to the primary receiver $\mathbf{g}_r^T A = 0$ has to be enforced

Proposed algorithm for interference free communications

- Finally the considered channel is expressed by

$$y_p = h x_p + n_p \tag{5}$$

$$\mathbf{y}_c = \widetilde{H}\mathbf{x}_a + \mathbf{n}_c \tag{6}$$

in which $\widetilde{H} = HA$.

- Such a process allows an **effective decoupling** of the scalar AWGN channel of the primary users (5) from that one of the cognitive users (6).

Goal

Explicitly find the optimal matrix A such that $\mathbf{g}_r^T A = 0$ holds and the sum-rate throughput is maximized

$\Rightarrow$ the achievable rates of the considered channel has to be evaluated

Achievable rates in the considered scenario

- The 2×2 channel expressed by (6) can be exploited through the singular value decomposition (SVD).
- By assuming $\widetilde{H} = U \Sigma V^\dagger$, with Σ diagonal matrix and U and V unitary matrices, and by introducing $\mathbf{x} = V^\dagger \mathbf{x}_a$ and $\mathbf{y} = U^\dagger \mathbf{y}_c$ from (6)

$$\mathbf{y} = U^\dagger \mathbf{y}_c = U^\dagger \widetilde{H} V \mathbf{x} + U^\dagger \mathbf{n}_c = \Sigma \mathbf{x} + U^\dagger \mathbf{n}_c \quad (7)$$

- Equation (7) represents two parallel Gaussian channels

$$\mathbf{y} = \mathbf{z} + \mathbf{n} \quad (8)$$

with input $\mathbf{z} = \Sigma \mathbf{x}$ and complex Gaussian noise $\mathbf{n} = U^\dagger \mathbf{n}_c$.

- It is possible to show that the DOFs of the considered MIMO Z channel is 2 and the number of DOFs of the primary link is 1

Achievable rates in the considered scenario

- Then the number of DOFs available for the cognitive link is 1 $\Rightarrow \Sigma$ will have at most one not trivial diagonal entry ε.
- Therefore, no signal power is received on the last component of **y** and the achievable rates of the channel have to be evaluated by taking into account only the non trivial component of **x**, accordingly.
- Hence, the channel of interest represented by (8) can be rewritten as a scalar equation

$$y = z + n \tag{9}$$

- The achievable rates of the MIMO cognitive link with the proposed linear processing scheme and $\varepsilon \neq 0$ can be expressed by

$$C = E_{H,\mathbf{g}_r}\left[\frac{1}{2}\log\left(1 + \frac{\varepsilon^2 P}{\eta_c^2}\right)\right] \tag{10}$$

where P is the transmitted power

Achievable rates in the considered scenario

- In order to complete the analysis, an explicit expression for C has to be found.
- The expression for matrix A (and consequently ε) which guarantees the maximum achievable rate has to be computed.
- By assuming that $g_{r,i} \neq 0$, $(i = 1, 2)$ and by enforcing $\mathbf{g}_r^T A = 0$

$$A = \begin{bmatrix} a_{11} & \frac{-a_{22} g_{r,2}}{g_{r,1}} \\ \frac{-a_{11} g_{r,1}}{g_{r,2}} & a_{22} \end{bmatrix}. \tag{11}$$

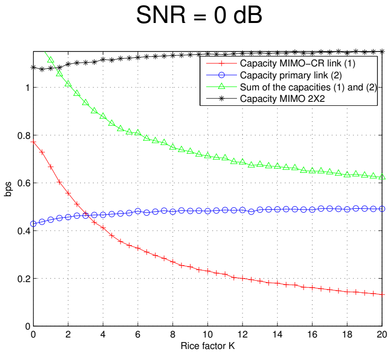
- Hence, the (possibly) non-trivial singular value of $\widetilde{H} = HA$ (i.e., ε) depends only on the components of A
- By substituting ε in (10), an explicit expression for the achievable rates is obtained

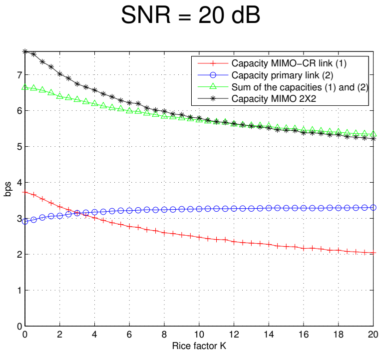
Simulations in different multipath channel

Parameters used for simulations

- varying the multipath conditions $\rightarrow$ MIMO Rice channels with different values of the Ricean factor K.
- SNR $\in \{0, \ldots, 20\}$ dB both at the cognitive and at the primary receiver.
- Comparison of the capacity of different systems
  - SISO channel (i.e., primary link)
  - MIMO 2×2 channel (i.e., secondary link in the case of absence of primary users)
  - MIMO Cognitive Radio 2×2 channel (i.e., secondary link in the case of presence of primary users)
  - Sum-rate throughput of the considered system (i.e., SISO channel + MIMO Cognitive Radio 2×2 channel)

Sum-rate throughput for the considered MIMO Cognitive Radio





- Proposed pre-processing scheme allows to obtain satisfying sum-rate throughput in low SNR environment
  - interference is avoided while the secondary system rate is maximized
- The performances increase as the SNR increases

Conclusions and future works

- A linear transmit pre-coding similar to a ZF-beamforming technique is developed for a two antenna CR system to
  - **completely avoid interference** from secondary transmitter toward primary receiver
  - **maximize the throughput** at the secondary system
- The effectiveness of the proposed processing scheme has been shown
  - satisfactory performance even in low SNR environment
  - low computational complexity
- Future developments
  - more practical scenarios (i.e., MIMO Interference Channel) $\Rightarrow$ please refer to the Journal paper "Cognitive Radios with Multiple Antennas Exploiting Spatial Opportunities", IEEE Trans. on Sig. Proc., Aug. 2010, Vol. 58, no. 8, pp. 4453–4459
  - Effective strategies for CSI estimation

Improvements needed but **promising preliminary results**