EE360: Lecture 12 Outline
Underlay and Interweave CRs

- **Announcements**
  - HW 1 posted (typos corrected), due Feb. 24 at 5pm
  - Progress reports due Feb. 29 at midnight
- **Introduction to cognitive radios**
- **Underlay cognitive radios**
  - **Spread spectrum**
  - **MIMO**
- **Interweave cognitive radios**
  - **Basic premise**
  - **Spectrum sensing**

CR Motivation
Scarce Wireless Spectrum

and Expensive

Cognition Radio Introduction

- Cognitive radios can support new wireless users in existing crowded spectrum
  - Without degrading performance of existing users

- Utilize advanced communication and signal processing techniques
  - Coupled with novel spectrum allocation policies

- Technology could
  - Revolutionize the way spectrum is allocated worldwide
  - Provide sufficient bandwidth to support higher quality and higher data rate products and services

What is a Cognitive Radio?

Cognitive radios (CRs) intelligently exploit available side information about the

(a) Channel conditions
(b) Activity
(c) Codebooks
(d) Messages

of other nodes with which they share the spectrum

Cognitive Radio Paradigms

- **Underlay**
  - Cognitive radios constrained to cause minimal interference to noncognitive radios

- **Interweave**
  - Cognitive radios find and exploit spectral holes to avoid interfering with noncognitive radios

- **Overlay**
  - Cognitive radios overhear and enhance noncognitive radio transmissions

Knowledge and Complexity

Underlay Systems

- Cognitive radios determine the interference their transmission causes to noncognitive nodes
  - Transmit if interference below a given threshold
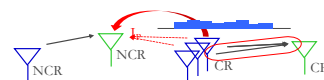
- The interference constraint may be met
  - Via wideband signalling to maintain interference below the noise floor (spread spectrum or UWB)
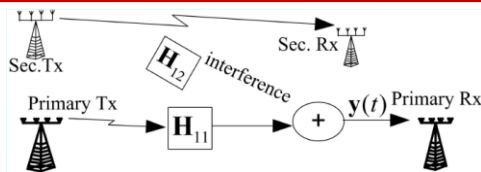 - Via multiple antennas and beamforming

Underlay Challenges

- **Measurement challenges**
  - **Measuring interference at primary receiver**
  - **Measuring direction of primary node for beamsteering**

- **Policy challenges**
  - **Underlays typically coexist with licensed users**
  - **Licensed users paid $$$ for their spectrum**
    - **Licensed users don't want underlays**
    - **Insist on very stringent interference constraints**
    - **Severely limits underlay capabilities and applications**

Ultrawideband Radio (UWB)

- **Uses 7.5 Ghz of "free spectrum" (underlay)**

- **UWB is an impulse radio: sends pulses of tens of picoseconds(10^{-12}) to nanoseconds (10^{-9})**
  - **Duty cycle of only a fraction of a percent**

- **A carrier is not necessarily needed**

- **Uses a lot of bandwidth (GHz)**

- **High data rates, up to 500 Mbps, very low power**

- **Multipath highly resolvable: good and bad**

- **Failed to achieve commercial success**

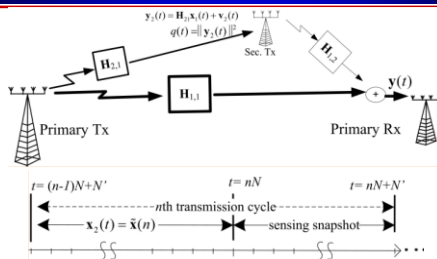## Null-Space Learning in MIMO CR Networks

- **Performance of CRs suffers from interference constraint**
- **In MIMO systems, secondary users can utilize the null space of the primary user's channel without interfering**
- **Challenge is for CR to learn and then transmit within the null space of the H_{12} matrix**
- **We develop blind null-space learning algorithms based on simple energy measurements with fast convergence**
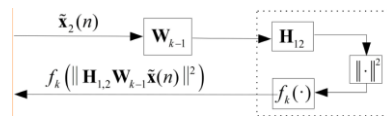
Problem Statement

- **Consider a single primary user, User 1**

- **Objective: Learn null space null(H_{1j}), j≠1 with minimal burden on the primary user**

- **Propose two schemes:**
  - **Passive primary user scheme: Primay user oblivious to secondary system**
  - **Active primary user scheme: Minimal cooperation (no handshake or synchronization). Faster learning time.**

System Setup

- **Note: $q(t)$ can be any monotonic function of $y_2(t)$**
- **Energy is easily measurable at secondary transmitter**

Learning Process

- **The SU's learns the null space of H_{12} by inserting a series of input symbols $\{W_{k-1}\tilde{x}_2(n)\}$ and measuring $q(n)=f_k(\cdot)$.**

- **The only information that can be extracted is whether $q(n)$ increases or decreases**

- **Is this sufficient to learn the null space of H_{12}?**

2

Yes!

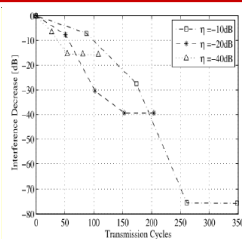**The problem is equivalent to a blind Jacobi EVD decomposition**

$$\mathbf{W}_k = \mathbf{W}_{k-1}\mathbf{R}_{l,m}(\hat{\theta}_k, \hat{\phi}_k),$$

$$\mathbf{R}_{l,m}(\theta, \phi) = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 \\ 0 & \cos(\theta) & 0 & e^{-i\phi}\sin(\theta) & \vdots \\ \vdots & 0 & 1 & 0 & \\ & -e^{i\phi}\sin(\theta) & 0 & \cos(\theta) & 0 \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix}$$

**Theorem** Let $S(\mathbf{x}) = \mathbf{x}^+\mathbf{H}_{12}^+\mathbf{H}_{12}\mathbf{x}$ and let $\mathbf{r}_{l,m}(\theta, \phi)$ be $\mathbf{R}_{l,m}(\theta, \phi)$'s l^{th} column. The optimal Jacobi parameters $\hat{\theta}$ can be obtained by two one-dimensional binary searches over $S(\mathbf{r}_{l,m}(\pi/3, \phi))$ and $S(\mathbf{r}_{l,m}(\hat{\theta}_k, \phi))$.

The theorem ensures that Jacobi can be carried out by a blind 2D optimization in which every local minimum is a global minimum.

Can Bound Search Accuracy

Theorem: Let T_k be the SU's pre-coding matrix. And let η be the accuracy of the binary search

$$\|\mathbf{H}_{12}\mathbf{T}_{k+m}\|^2 \leq O\left(\left(\frac{\|\mathbf{H}_{12}\mathbf{T}_k\|^2}{\delta^{3/2}}\right)^2\right) + O\left(\frac{\eta\|\mathbf{H}_{12}\mathbf{T}_k\|^3}{\delta^2}\right) + 2\left(2n_t n_r - n_r^2 - n_r\right)\eta^2\|G\|^2/\delta$$

- More relaxed constraints on PU interference leads to better performance of the secondary user
- This technique requires no cooperation with PU
- If PU transmits its interference plus noise power, can speed up convergence significantly
- The proposed learning technique also provides a novel spatial division multiple access mechanism

Performance

Simulation results of BNSL algorithm for different line search accuracies with two transmitting antenna at the SU transmitter
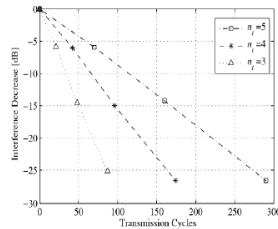
Simulation results of BNSL algorithm for non constant line search accuracy and different numbers of transmitting antenna at the SU transmitter

Summary of Underlay MIMO Systems

- **Null-space learning in MIMO systems can be exploited for cognitive radios**

- **Blind Jacobi techniques provide fast convergence with very limited information**

- **These ideas may also be applied to white space radios**

Interweave Systems:
Avoid interference

- **Measurements indicate that even crowded spectrum is not used across all time, space, and frequencies**
  - Original motivation for **"cognitive"** radios (Mitola'00)
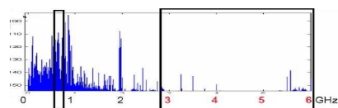
- **These holes can be used for communication**
  - Interweave CRs periodically monitor spectrum for holes
  - Hole location must be agreed upon between TX and RX
  - Hole is then used for opportunistic communication with minimal interference to noncognitive users

Interweave Challenges

- Spectral hole locations change dynamically
  - Need wideband agile receivers with fast sensing
    - Compresses sensing can play a role here
  - Spectrum must be sensed periodically
  - TX and RX must coordinate to find common holes
  - Hard to guarantee bandwidth
- Detecting and avoiding active users is challenging
  - Fading and shadowing cause false hole detection
  - Random interference can lead to false active user detection
- Policy challenges
  - Licensed users hate interweave even more than underlay
  - Interweave advocates must outmaneuver incumbents
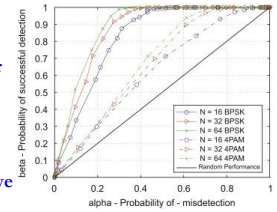
White Space Detection

Dedicated fusion center   Without a dedicated fusion center

○ Secondary user
● Fusion center
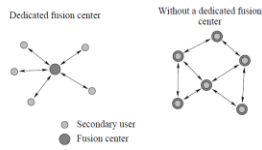
- **White space detection can be done by a single sensor or multiple sensors**
- **With multiple sensors, detection can be distributed or done by a central fusion center**
- **Known techniques for centralized or distributed detection can be applied**

Detection Errors

- **Missed detection of primary user activity causes interference to primary users.**
- **False detection of primary user activity (false alarm) misses spectrum opportunities**
- **There is typically a tradeoff between these two (conservative vs. aggressive)**

Summary

- **Wireless spectrum is scarce**
- **Interference constraints have hindered the performance of underlay systems**
  - **Exploiting the spatial dimension opens new opportunities**
- **Interweave CRs find and exploit free spectrum:**
  - **Primary users concerned about interference**
- **Much room for innovation**
- **Philosophical changes in system design and spectral allocation policy also required**

Presentation

- **"A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications"**
- **Authors: T, Yucek and H. Arslan**
- **Presented by Ceyhun Akcay**