Interference Avoidance with Software Radios

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Overview

- (1-30) Motivation → The Anarchy of Unlicensed Spectrum
- (1-20) Signal Space Representations
- (1-20) Simple Interference Characterization & Mitigation (whitening)
- (1-15) Software radios → waveform agility → interference avoidance.
- (1-5) Future Directions and Extensions
- LUNCH!
**Interference Avoidance Takehome Messages**

- **General**
  - Signal space based: can be widely applied
- **Simple**
  - Put your signal where the interference is weakest
  - Might makes right (for the mighty)
  - We CAN all just get along if we’re equally strong

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**Where We Started: the U-NII**

The U-NII (Unlicensed National Information Infrastructure) bands are three bands of UNLICENSED spectrum in the 5GHz range designated for short-range high-speed wireless digital communications with:

- 10 to 30 times the bandwidth of any existing unlicensed band (900 MHz, 1.9 GHz and 2.4 GHz)
- NO imposed etiquette
- NO imposed channelization
- NO imposed spectrum efficiency
- Moderate power constraints (short range)
U-NII at a Glance

COMPARISON OF UNLICENSED BAND ALLOCATIONS

Kitchen Sink Band

Unlicensed PCS 1910-1930 MHz

Unlicensed PCS 2390-2400 MHz

U-NII 1

U-NII 2

U-NII 3

5150-5250 MHz

5250-5350 MHz

5725-5825 MHz

Some Technical Issues

- Peaceful Coexistence
  - Completely different systems in close opposition
  - Same technology but uncoordinated
  - Completely different technologies
    (AM/FM/TDM/FDM/CDM/FH/???)

- Network Architecture – Central Base, Peer Forwarding, Hierarchy?

**ROOT ISSUE:** Mutual interference
Research Approach for Unlicensed Systems

- Quantify interference
- Evasion and punishment games
- Simple system analysis

Back to Basics

A Simple Binary Detection Problem

\[ S(t) \xrightarrow{\times} b \xrightarrow{+} I(t) \xrightarrow{\text{Filter on } (0,T)} b \]
Karhunen-Loeve and Sufficient Statistics I

• Usual series representation

\[ I(t) \sim \lim_{N \to \infty} \sum_{i=1}^{N} a_i \Psi_i(t) \]  
(1)

The (non-unique) \( \{\Psi_i(t)\} \) define the space

• Want uncorrelated observations \( c_i \) (rails)

\[ I(t) \sim \lim_{N \to \infty} \sum_{i=1}^{N} c_i \Phi_i(t) \]  
(2)

The \( \{\Phi_i(t)\} \) are special

Karhunen-Loeve and Sufficient Statistics II

•

\[ E[c_i c_j] = E[\int_{0}^{T} \int_{0}^{T} \Phi_i(t) I(t) \Phi_j(\tau) I(\tau) dtd\tau] = \lambda_i \delta_{ij} \]  
(3)

• Integral Equation

\[ \lambda_i \Phi_i(t) = \int_{0}^{T} R(t, \tau) \Phi_i(\tau) d\tau \]  
(4)

• Eigenvalues \( \lambda_i \to \) interference energy on \( i^{th} \) "rail".
Discretization I

- I don’t like integral equations
- Assume space spanned by a finite sum of basis functions \( \{ \Psi_n(t) \} \) → finite set \( \{ \Phi_n(t) \} \). So:

\[
\phi_{in} = \int_0^T \Psi_n(t)\Phi_i(t)dt \tag{5}
\]

\[
\Phi_i(t) = \sum_{n=1}^N \Psi_n(t)\phi_{in} \tag{6}
\]

- Applies to a large number of scenarios

What Scenarios, You Ask?

- Classical Synchronous CDMA Interferers: \( \Psi_n(t) \) are the \( N \) non-overlapping single-chip waveforms.
- Time Limited to \([0, T] \), Almost Band Limited: \( 2WT \) Prolate spheroids
- Frequency Hopping, TDM, AM, FM whatever as long as a meaningful \( R(t, \tau) \) and an appropriate finite set of basis functions can be derived for the process.
- Antenna diversity (spatio-temporal basis set)
**Discretization II**

Integral equations $\to$ matrix equation

$$\lambda_i \phi_{ik} = \sum_{n=1}^{N} \phi_{in} r_{nk}$$  \hspace{1cm} (7)

where

$$r_{nk} = \int_{0}^{T} \int_{0}^{T} R_I(t, \tau) \Psi_k(t) \Psi_n(\tau) dt d\tau$$  \hspace{1cm} (8)

so

$$R \phi_i = \lambda_i \phi_i$$  \hspace{1cm} (9)

- Eigenvalues $\lambda_i \to i^{th}$ “rail” interference energies

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**Orthonormal Projection**

$I_j$ has variance $\lambda_j$
NOTE: Same as MMSE receiver, by the way

- **LRT**

\[
\sum_{n=1}^{N} \frac{s_n}{\sqrt{\lambda_n}} \frac{z_n}{\sqrt{\lambda_n}} \begin{cases} 
\text{say 1} & \text{if } \sum_{n=1}^{N} s_n^2 / \lambda_n > 0 \\
\text{say 0} & \text{otherwise}
\end{cases}
\]  

(10)

- **BER/SIR** depends on

\[
d^* = \sum_{n=1}^{N} \frac{s_n^2}{\lambda_n}
\]  

(11)

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SIR Maximization

Suppose we can choose \( \{ s_n \} \) to maximize \( d^* \):

- Make \( s_k \) a minimum eigenvalue eigenvector of \( R(k) \).
- Same as to placing all signal energy into the smallest eigenvalue eigenfunction of K-L expansion – where interference is weakest.

The K-L Interference Avoidance Algorithm

- Users are independent so correlation seen by user \( k \) is

\[
R(k) = \sum_{i=1, i \neq k}^{M} s_i s_i^T = SS^T - s_k s_k^T
\]

(12)

- Each user replaces \( s_k \) by \( \mathbf{x} \) where

\[
R(k)\mathbf{x} = (SS^T - s_k s_k^T)\mathbf{x} = \lambda^*(k)\mathbf{x}
\]

(13)

and \( \lambda^*(k) \) is a minimum eigenvalue of \( R(k) \).
K-L IA Distilled

- Start with user 1
- Find maximum SIR signal, $S_1^*(t)$
- Tell user 1 to replace $S_1(t)$ with $S_1^*(t)$
- Repeat for each user (in no particular order) until happy.
- This simple-minded algorithm converges!

Converges to What?

- The convergence set $\{s_k\}$ is a minimum sum square correlation signal set (meets Welch Bound) and also meets information theoretic maximum sum capacity bound (Rupf & Massey 1994). So the K-L Interference Avoidance Algorithm has a fixed point which is the “best” possible signal set.
  - Orthogonal channels when fewer users than basis waveforms
  - Egalitarian spreading if not
- minimum eigenvalue eigenvector = minimum sum of interference vector
  → Blind methods applicable
**K-L Fixed Point Properties**

- The optimal signal set of the K-L interference avoidance algorithm is essentially a “whitening” of the ensemble sum $\sum_{k=1}^{M} S_k(t)$ (equal variance, uncorrelated projections).

- Are there suboptimal fixed points? – yes mutually orthogonal groups of signals with different SIR’s.

- Starting with randomly chosen signatures $\{s_k\}$ seems to avoid suboptimal solutions.

- **Class warfare** also seems to work wonders! But details currently fuzzy.

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**Mixtures of Fixed and Agile Users**

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## Unequal Received Power

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Summary

- Software Radios $\rightarrow$ Waveform $A_g^{i \cdot i_{t_y}}$
- Waveform $A_g^{i \cdot i_{t_y}}$ $\rightarrow$ Interference Avoidance
- GENERAL
  - Signal space based: can be widely applied
- SIMPLE
  - Put your signal where the interference is weakest (or weaker)
  - Might makes right (for the mighty)
  - We CAN all just get along if we’re equally strong

Summary Cont’d

- Probably better for fixed wireless
- Good in licensed systems too
- Makes multiuser detection receiver simple $\rightarrow$ matched filters.
  More detailed info:
  - http://www.winlab.rutgers.edu/~ryates/papers/allerton98.ps
  - http://www.winlab.rutgers.edu/~crose/papers/mmt98.ps
Work To Be Done

- Convergence speed
- Stability
- Unequal performance requirements
- Multiple NON-co-located receivers
- Approximation with binary chips

Work To Be Done, cont’d

- Minimum power control – seems to make the multi-receiver system converge
- Antenna arrays
- Class warfare – the road to equality?
- Channel pre-emphasis
- Rapid channel estimation