Interference Avoidance with Software Radios

C. Rose & R. Yates
WINLAB
Dept of Electrical and Computer Engineering
Rutgers University

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Overview

- (L-30)Motivation → The Anarchy of Unlicensed Spectrum
- (L-25)Signal Space Representations
- (L-20)Simple Interference Characterization & Mitigation (whitening)
- (L-15)Software radios → waveform agility → interference avoidance.
- (L-5)Future Directions and Extensions
- **LUNCH!**

Interference Avoidance Takehome Messages

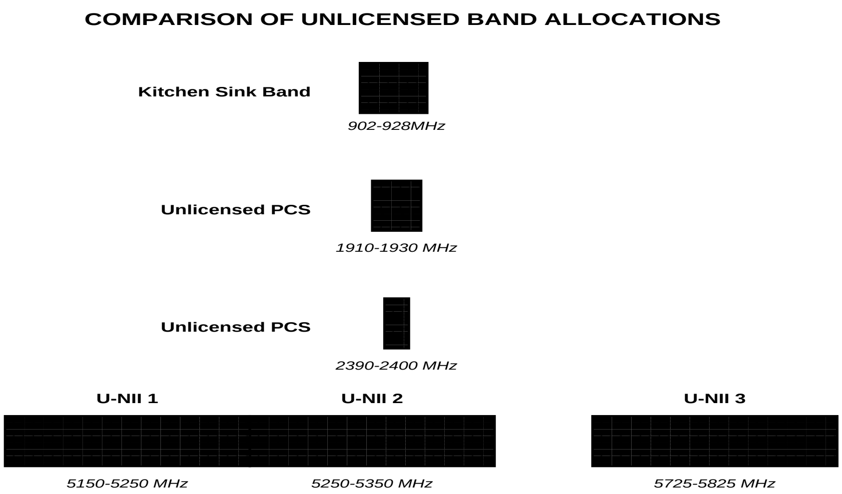
- General
  - Signal space based: can be widely applied
- Simple
  - Put your signal where the interference is weakest
  - Might makes right (for the mighty)
  - We CAN all just get along if we're equally strong

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



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?

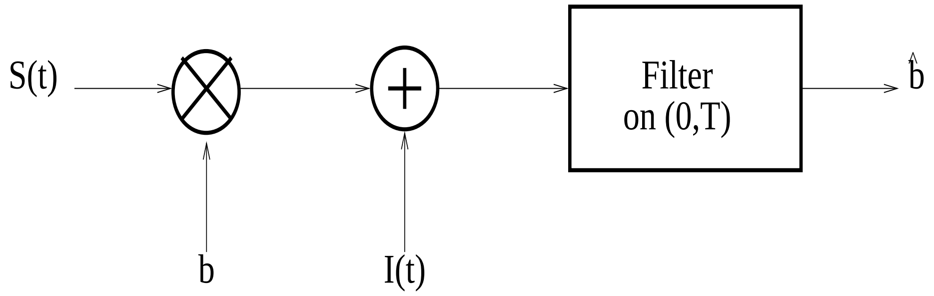
ROOT ISSUE: Mutual interference

Research Approach for Unlicensed Systems

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

Back to Basics

A Simple Binary Detection Problem



Karhunen-Loeve and Sufficient Statistics I

- Usual series representation

$$I(t) \stackrel{\sim}{=} \lim_{N\to\infty} \sum_{i=1}^{N} a_i \Psi_i(t) \tag{1}$$

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

- Want uncorrelated observations c_i (rails)

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

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

Karhunen-Loeve and Sufficient Statistics II

-

$$E[c_i c_j] = E[\int_0^T \int_0^T \Phi_i(t) I(t) \Phi_j(\tau) I(\tau) dt d\tau] = \lambda_i \delta_{ij} \tag{3}$$

- Integral Equation

$$\lambda_i \Phi_i(t) = \int_0^T R_I(t,\tau) \Phi_i(\tau) d\tau \tag{4}$$

- 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 $\{\Psi_n(t)\} \rightarrow$ 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 → matrix equation

$$\lambda_i \phi_{ik} = \sum_{n=1}^{N} \phi_{in} r_{nk} \tag{7}$$

where

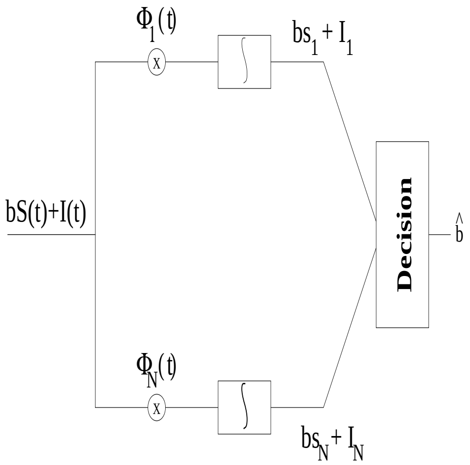
$$r_{nk} = \int_0^T \int_0^T R_I(t,\tau)\Psi_k(t)\Psi_n(\tau)dtd\tau \tag{8}$$

so

$$\mathbf{R}\boldsymbol{\phi}_i = \lambda_i \boldsymbol{\phi}_i \tag{9}$$

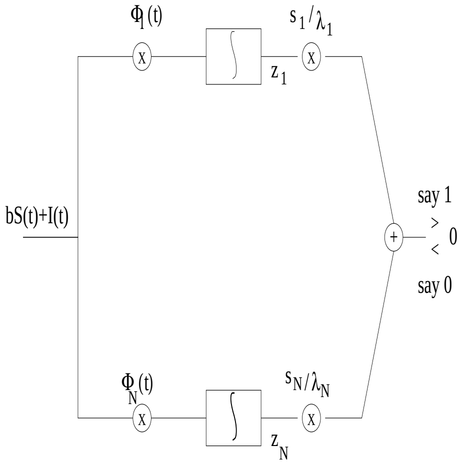
- Eigenvalues λ_i → i^{th} "rail" interference energies

Orthonormal Projection



I_j has variance λ_j

Whitening



NOTE: Same as MMSE receiver, by the way

BER/SIR Calculation

- LRT

$$\sum_{n=1}^{N} \frac{s_n}{\sqrt{\lambda_n}} \frac{z_n}{\sqrt{\lambda_n}} \underset{\text{say } 0}{\overset{\text{say } 1}{\gtrless}} 0 \tag{10}$$

- BER/SIR depends on

$$d^* = \sum_{n=1}^{N} \frac{s_n^2}{\lambda_n} \tag{11}$$

SIR Maximization

Suppose we can CHOOSE $\{s_n\}$ to maximize d^*

- Make $\mathbf{s}_k$ a minimum eigenvalue eigenvector of $\mathbf{R}(k)$.
- 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

$$\mathbf{R}(k) = \sum_{i=1, i\neq k}^{M} \mathbf{s}_i \mathbf{s}_i^T = \mathbf{S}\mathbf{S}^T - \mathbf{s}_k \mathbf{s}_k^T \tag{12}$$

- Each user replaces $\mathbf{s}_k$ by $\mathbf{x}$ where

$$\mathbf{R}(k)\mathbf{x} = (\mathbf{S}\mathbf{S}^T - \mathbf{s}_k \mathbf{s}_k^T)\mathbf{x} = \lambda^*(k)\mathbf{x} \tag{13}$$

and $\lambda^*(k)$ is a minimum eigenvalue of $\mathbf{R}(k)$.

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?

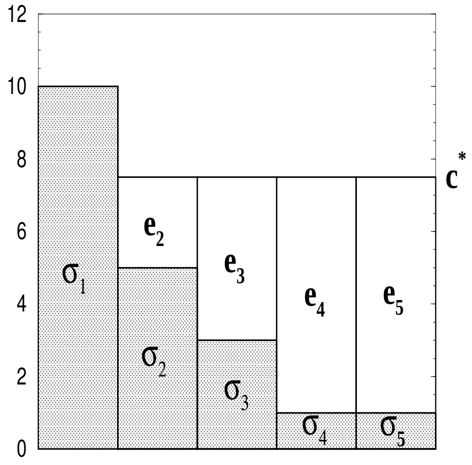
- The convergence set $\{\mathbf{s}_k\}$ is a minimum sum square correlation signal set (meets Welch Bound) and also meets information theoretic maximum sum capacity bound (Rupf & Massey 1994). So the K-L Interference Avoidance Algorithm has a fixed point which is the "best" possible signal set.
  -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

  $\rightarrow$Blind methods applicable

K-L Fixed Point Properties

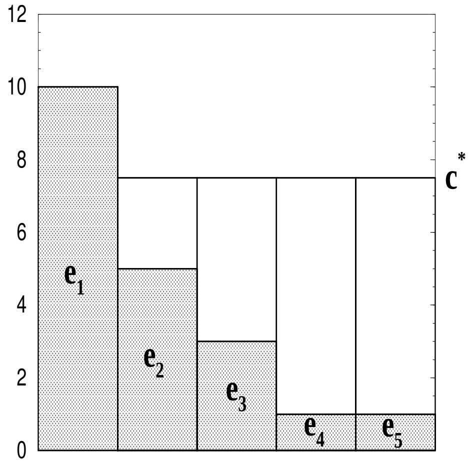
- The optimal signal set of the K-L interference avoidance algorithm is essentially a "whitening" of the ensemble sum $\sum_{k=1}^{M} S_k(t)$ (equal variance, uncorrelated projections).
- Are there suboptimal fixed points? – yes mutually orthogonal groups of signals with different SIR's.
- Starting with randomly chosen signatures $\{\mathbf{s}_k\}$ seems to avoid suboptimal solutions.
- Class warfare also seems to work wonders! But details currently fuzzy.

Mixtures of Fixed and Agile Users



Water filling on colored noise!

Unequal Received Power



Might makes right!

Relatively Simple Extensions

- Asynchronous Systems – we end up with $R(t-\tau)$ instead of $R(t,\tau)$ and might work through almost as before
- Non-coincident spaces – alternate water filling of identical adjacent overlapping space systems can be shown to settle down to social optimum. But no general proof yet.

  NOTE: *this is EXACTLY the smart base antenna with emitters at different positions – and therefore different subspaces – scenario*

Summary

- Software Radios → Waveform Agility
- Waveform Agility → 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 → 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