A Brief History of Three Ideas in Signals: Estimation, Localization and Transmission

Arogyaswami Paulraj
Stanford University

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“Ten geographers who think the world is flat will tend to reinforce each other’s errors....Only a sailor can set them straight.” John Saul
Estimation of Signals in Noise
History, Prior to 1970

- Karl Gauss – Method of Least Squares
- Norbert Weiner – Covariance Model, Stationary Statistics
- Rudi Kalman – Dynamical (non-stationary) signal models (Gauss–Markov)
- Kolgomorov – Non-Gaussian models
Signal Extraction Problem

Signal corrupted by Additive White Gaussian Noise observed over the interval \([r,s]\) where

- \(s\) current time of observation
- \(r\) start time of observations
- \(t\) time for desired estimate of signal
1970 State of the Art

• Linear (Kalman Filtering KF) for Gauss-Markov signals. Propagates Cond. Mean and Covariance.

• Non-linear filtering for Non-Gaussian signal models. Propagate conditional pdfs of signal

• Limited formulations: $r$ is fixed, $t = s$, $t = s + u$, or $t = s - u$
  (u is a const.)
INS Betwa Fire Control System
Fire Control Problems

- r, s and t have more complex relationships
- Interrupted measurements
- Uncertain measurements
A solution where r, s and t could be related by a differential equation. In particular ‘r’ is also a variable. Also, Interrupted & Uncertain measurements
Applications

• Ito Calculus methods lost favor in Engg. but remain popular in financial modeling

• Flexible r, s and t useful in stock / derivative modeling
Localization – Directions of Arrivals (DOA) Problem
Directions-of-Arrival Estimation
Multiple Signals DOA

- Capons Method 1960s
- Burg’s Method – 1970s
- MUSIC (R Schmidt) – 1980s
- Not efficient (CR bound)
MUSIC Algorithm

• Array Manifold (AM) lies in $C^m$ and is induced by a planar wave front arriving at an M element antenna array

• $E_s$ is signal subspace induced by ‘d’ (< M) signals arriving at the array

• DOAs are intersections of $E_s$ and AM
Passive Sonar DOA

Beam Scanning vs Null Scanning
ESPRIT - 1985

\[ E_{xx} T = \phi E_{xy} T \]

\[ \phi \] Diag. Matrix = DOAs

\[ E_{xx} \] Signal Cov (m x m)

\[ E_{xy} \] Signal Cross (m x m)

\[ T \] d x d matrix
System Identification

- ESPRIT can also identify modes of linear system from its Impulse Response
ESPRIT Applications

- > 900 IEEE xplore papers, > 60 PhDs
- Radio DF
- Acoustic DF
- System ID
- MIMO Wireless Channel ID
- Spectrum Analysis

Curiosity – MARS Explorer
Transmission : MIMO Spatial Multiplexing
Signal Copy Problem

Blind Methods

- Bussgang Methods
- Finite Alphabet
- Constant Modulus
- MT-MORE

- Temporal side Information
- Spatial side information
DARPA Signal Copy Project

Co-channel Sources
SU Experiments 1992
Throughput \approx \log \det (I + \frac{\rho}{M} HH^*)

\approx \min (N_T, N_R)
• OFDMA was a good modulation scheme for MIMO
• But needed some “fixes” for improving signal and inference diversity
• Iospan -> Intel -> 4G
MIMO Today

- 14,000+ Pubs (Thompson)
- 12,000+ Patents (USPTO)
- 1000+ PhD Theses (ad hoc)

- WiFi 11n, 11ac
- 3GPP LTE
- WiMAX
- 3GPP HSPA+
Some Lessons & Observations
A Lesson

Disseminate/ Publish

- Reviews can refine or correct your ideas, recruit collaborators and find applications
- Do not wait for full solutions or complete results
- Great ideas are often simple or obvious (at least to you), but that should not deter publication
A Lesson

To bring an innovation or invention to practical use requires persistence in face of failures and sometimes blindness to criticism.
An Observation

Inspiration often come observing nature or from experiments

- The generalized estimation problem came from my curiosity about Navy fire control systems
- Localization formulation came from my sonar development experience
- MIMO spatial multiplexing came from Stanford signal copy experiments
An Observation

Good ideas can sometimes be rejected as totally ridiculous (but later miraculously become completely obvious)

- MIMO/SM
- Counter factual – ESPRIT
Breakthroughs often come from holding the problem in one’s mind for extended periods

- ESPRIT
- MIMO-OFDM
Thank you