Al Oppenheim, DSPG MIT

General Research Interests and Style:

New algorithms for signal processing

Applications to speech, oceanography, video, communications, sensor networks, radar, sonar etc. etc.

• traditional

• speculative directions motivated by metaphors from physics and biology

• “Solutions in search of problems.”
Some Research Themes

• Sampling Theory and Signal Representations
• Signal Modelling
• Some “New” Mathematics For Signal Processing
• Biological Signal Processing
• Various applications
Multirate and Nonuniform Sampling

- Efficient reconstruction from nonuniform samples
- Data-dependent Sampling
- Sine wave sampling
- Efficient sample rate conversion
- The “missing pixel” problem
Compensation for Faulty D/A Converters

- Choose $c[n]$, such that $c[0] = -x[0]$
- Choose $c[n]$ to minimize reconstruction error
- Desire finite length solutions
Distributed Signal Processing

Processor Networks:
- Nodes sense, route, and process signals
- Cooperation between nodes accomplishes pre-defined signal processing task

Challenges for Efficient Algorithms:
- Inter-node communication more costly than local computation
- Nodes communicate asynchronously
Distributed Sensor Networks

- Sensors connected with wireless communications collaboratively detect, track, and classify targets in the environment.
- Communication cost can limit the network’s signal processing capability.
  - RF circuitry consumes valuable battery power.
  - Shared communication bandwidth limits data flow rates.
- In dense networks using thousands of simple nodes, position information may be unavailable to selection algorithms.
Hardware for Distributed Signal Processing

- Signal Source represents processors’ input data
- For LTI signal processing, local processors contain adders, multipliers, and memory
- Inter-processor communication over broadcast bus

Measure bus clock cycles per output sample to determine communication complexity of an algorithm
Example: Distributed Computation of a Discrete Fourier Transform

Communication Requirements:
- Direct Computation - N bus clock cycles
  - Communication structure is completely parallel
- FFT - approximately N/2 log N bus clock cycles
  - Each stage of butterfly computations requires N/2 bus cycles to exchange data between processors
- Communication parallelism of direct computation is well-matched to broadcast communication bus

Processor Load:
- Direct Computation - 1 multiply per bus cycle
- FFT - 1 multiply per N/2 bus cycles
- Lack of communication parallelism in FFT prevents efficient utilization of the processors
My Favorite Folk Theorems

• Anything’s optimum if you pick the criterion correctly

• Just because it’s optimum doesn’t mean it’s good
• speculative directions motivated by metaphors from physics and biology

• “Solutions in search of problems.”
Some Examples of Algorithms based on Nature as a Metaphor

- Cellular automata
- Simulated annealing
- Fractals for coding, modulation, and scene generation
- Chaotic dynamics
- Solitons
Chaotic Signals and Systems

- Nonlinear Dynamical Systems
  \[ x(t) = F[x(t), u(t), t] \]

Deterministic & SDIC ⇔ Chaotic Behavior

Lorenz System
- \[ x = \sigma(y - x) \]
- \[ y = rx - y - xz \]
- \[ z = xy - bz \]
Chaotic Communication Concepts

Chaotic Systems Provide:

- A Wide Variety of Broadband Waveforms
- A Class of Self-Synchronizing Receivers

Kevin Cuomo, Alan Oppenheim, Steve Strogatz
Generalized FM

- Carrier waves are generated by dynamical systems that have:
  1. A periodic, almost periodic, or chaotic attractor,
  2. A known exponentially convergent observer.
- FM is a special case.
**Generalized Frequency Modulation**  
*(Torres, Oppenheim and Rosales)*

The Lorenz System  
*(Chaotic)*

- Gradient Vector

Circuit Implementation

**Dynamical System Equations:**

**Without Modulation**

\[
\begin{align*}
\dot{x}_1 &= \sigma(x_2 - x_1) \\
\dot{x}_2 &= rx_1 - x_1x_3 - x_2 \\
\dot{x}_3 &= x_1x_2 - bx_3
\end{align*}
\]

**With Modulation**

\[
\begin{align*}
\dot{x}_1 &= (\omega_c + \beta m(t))\sigma(x_2 - x_1) \\
\dot{x}_2 &= (\omega_c + \beta m(t))(rx_1 - x_1x_3 - x_2) \\
\dot{x}_3 &= (\omega_c + \beta m(t))(x_1x_2 - bx_3)
\end{align*}
\]
Soliton Multiplexing

- Modulate time-separated solitons with OOK, PAM or PPM

Multiplex individual solitons together using Toda lattice
Low-Energy Signaling

Signal Energy Minimized by Multiplexing
Quantum Signal Processing

Quantum Physics

QSP

Signal Processing

Quantum Computing

Algorithms
Quantum Signal Processing

Quantize: 1. To subdivide into small but measurable increments
2. To calculate or express in terms of quantum mechanics


- QSP borrows from the principles of quantum mechanics and some of its interesting axioms and constraints
- QSP is not constrained by physics
Quantum Mechanics

• Measurement of the system: probabilistic outcome $M(x)$ with probabilities dependent on the state $x$

• Consistency of the measurement: repeated measurements on a system yield the same outcomes $M(M(x))=cM(x)$

• Determinate states: states for which $M(x)$ is determinate i.e. not probabilistic

• Various other constraints imposed by the physics

  $\Rightarrow$ Measurement “collapses” the system into a determinate state
The QSP framework has led to interesting new results in:

- Quantum detection
- Matched filter banks
- Multiuser detection
- Sampling theory
- Frames

Y.C. Eldar and A.V. Oppenheim “Quantum Signal Processing ”
*IEEE Signal Processing Magazine*, November 2002
Biological Signal Processing

Signal Transduction

Signal Processing

Signal Transduction Modeling

Biological Signal Processing
Objectives

- Formulate underlying principles governing biological signal transduction pathways using signal processing theory.
- Develop signal processing algorithms inspired from signal transduction pathways.
- Exploit biological hardware to perform signal processing.

How are stream processing and signal processing related?
How are stream processing and signal processing related?

Yesterday I thought I had a guess
How are stream processing and signal processing related?

Yesterday I thought I had a guess

Today I’m confused about the definition
How are stream processing and signal processing related?

Yesterday I thought I had a guess

Today I’m confused about the definition

The day after tomorrow I’m looking forward to understanding it better