Communication, Sensing, and Resource Allocation

Research at Ohio State

Prof. Phil Schniter

(work performed with support from NSF, ONR, Motorola Labs, and Sandia Nat. Labs)

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Research Group

The work described here was conducted with my Ph.D. students

Mr. Rohit Aggarwal	2011	
Dr. Sun-Jung Hwang	2009	(Qualcomm Inc.)
Dr. Sibasish Das	2008	(Qualcomm Inc.)
Dr. Arun P. Kannu	2007	(IIT Madras)

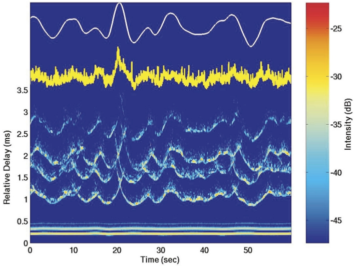
Equally interesting work was done with other Ph.D. students

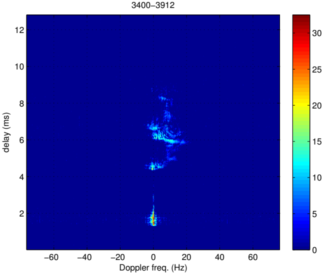
Mr. Sugumar Murugesan	2010	
Dr. Hong “Iris” Liu	2007	(Broadcom Inc.)
Dr. Kambiz Azarian	2006	(Qualcomm Inc.)
Dr. Adam Margetts	2005	(MIT Lincoln Labs)

and many M.S. students!

Applications

- RF communication at very high frequencies (e.g., 60GHz)
- RF communication in highly mobile environments
- underwater acoustic comms





Challenges

- Limited bandwidth
  - → want high spectral efficiency
- Additive noise
- Simultaneous fading in time and frequency domains
  - → noise overwhelms signal in fading locations
- Simultaneous dispersion in delay and Doppler domains
  - → induces self-interference
- Neither transmitter nor receiver know the channel state!

Capacity Analysis

- What is the maximum spectral efficiency (bits/sec/Hz) at which we can communicate with arbitrarily small probability of error?
- For a doubly selective channel characterized by Doppler and delay spreads B_{dop} and T_{dly} (where $B_{\text{dop}}T_{\text{dly}} < 1$), we have shown

  $$C \leq (1 - B_{\text{dop}}T_{\text{dly}})\log_2(1+\rho) \text{ as } \rho \to \infty$$

  for continuous inputs, with equality under a Gaussian codebook. *[Kannu/Schniter: TIT 10]*
- Recalling that $C = \log_2(1+\rho)$ for flat fading, we see that
  - time/freq channel uncertainty reduces spectral efficiency,
  - signal redundancy should be chosen in proportion to $B_{\text{dop}} \times T_{\text{dly}}$

Pilot Aided Transmission

- Pilots are often injected to help learn the channel. How well does this work relative to the optimal coding scheme?
- MSE-optimal pilot-aided transmission:
  - Choose pilot/data waveforms to minimize the MSE attained by pilot-based MMSE channel estimates. *[Kannu/Schniter: TSP 08]*
    - → multi-carrier modulation with blocks of pilot subcarriers
    - → single carrier modulation with blocks of pilot symbols
    - → chirp modulation with blocks of pilot chirp waveforms
- How good is the spectral efficiency (SE) of these PAT schemes?
  - Surprisingly, none of the MMSE-PAT yield maximal SE!
  - It is, however, possible to construct spectrally efficient PAT. (The trick is to allow joint channel-estimation / data-decoding.) *[Kannu/Schniter: ALL 06], [Das/Schniter: ALL 07]*

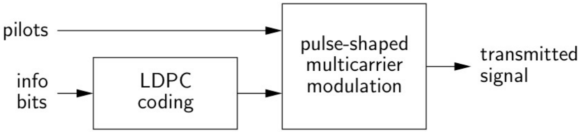
Optimized Multi-carrier Modulation

- Multi-carrier modulation is great for time-dispersive channels
  - Converts convolutive channel to parallel scalar channels.
  - Complexity is logarithmic (vs linear) in channel length, due to FFT.
- Problem: Standard OFDM is very sensitive to Doppler spreading
  - Doppler spoils null pattern of frequency-domain-sinc.
  - Slowly decaying sinc sidelobes $\Rightarrow$ wide-spread ICI!
- Solution: Optimize the multicarrier pulse-shape
  - Can't suppress *both* ISI & ICI (without lowering SE).
  - Thus...*allow* small ISI/ICI spread.
  - Better yet...*optimize* pulse-shape to maximize SINR for an allowed ISI/ICI span. (Optimize at Tx, Rx, or both.)
  - Usually sufficient to allow ICI from 1-2 neighboring subcarriers.
  - Permits the use of very sophisticated equalizers (e.g., Viterbi).
  - Permits complete elimination of time-domain guard interval!

[Schniter: TSP 04],[Hwang/Schniter: JASP 06],[Das/Schniter: TSP 07]

Turbo Equalization

Transmitter:



pilots

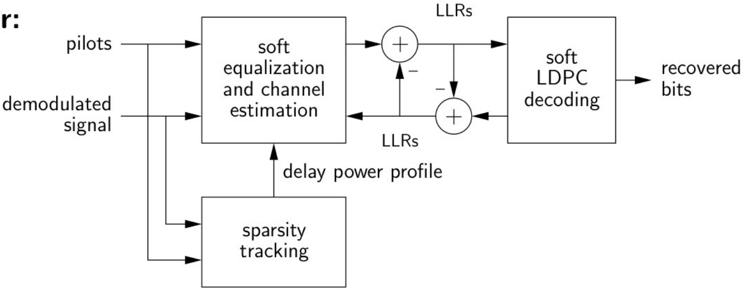
info bits

LDPC coding

pulse-shaped multicarrier modulation

transmitted signal

Receiver:



pilots

demodulated signal

soft equalization and channel estimation

LLRs

soft LDPC decoding

recovered bits

LLRs

delay power profile

sparsity tracking

Soft Noncoherent Equalization

- Goal: Given preliminary soft bit estimates produced by the decoder, improve those the soft bit estimates (subject to unknown channel state but known channel structure).
- Novel approaches:
  1. Efficient **tree search** using a noncoherent metric. *[Hwang/Schniter: JSAC 08]*
  2. **EM-based iteration** between soft channel estimation & soft coherent equalization. *[Hwang/Schniter: SPAWC 09]*
- Enablers:
  1. Basis-expansion channel models,
  2. Fast sequential-Bayesian updates,
  3. Sparsity in delay/Doppler domain (when applicable).
- BER Performance:

  Only 1–2 dB away from known-channel MAP equalizer!

Sparse Reconstruction

Estimate K-sparse $\boldsymbol{x}$ from an under-determined noisy linear mixture:

$$\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{w} \text{ for known } \boldsymbol{A} \in \mathbb{C}^{M \times N}, \text{ with } K < M \ll N$$

Many applications:

- sparse channel estimation
- image acquisition:
  - wavelet coefs of natural images are sparse
  - other images also have sparse representations:

    (e.g., MRI, radar, hyperspectral, etc.)
- change detection

...often referred to generically as "compressive sensing."

Sparse Reconstruction

Provably good performance!

- For “incoherent” $\boldsymbol{A}$, provably accurate reconstruction is possible using a number of techniques:
    - convex optimization
    - greedy search
    - iterative schemes
- When $M \gtrsim K \log(N/K)$, it’s easy to construct incoherent $\boldsymbol{A}$:
    - i.i.d (Gaussian, sub-Gaussian, ± 1) entries
    - random rows from a DFT matrix
- Bounds are sharp
    - a new “post-Nyquist” sampling theory.
    - without additional structure, impossible to do better!

Structured Sparsity

Practical signals often have structure *beyond simple sparsity*.

Examples:

- Persistence across scales

  With wavelet coefficients generated from natural scenes, each large child coefficient usually has a large parent coefficient.
- Clustered difference pixels

  Changes to a scene typically manifest as small *clusters* of perturbed pixels.
- Time-variant sparse processes

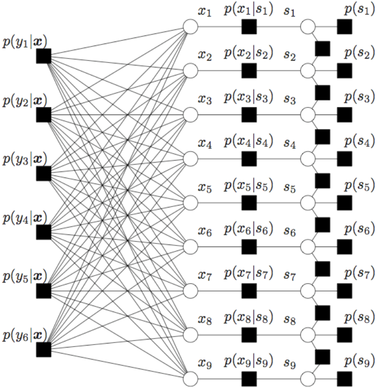
  The sparsity pattern at a given time is a small perturbation of the pattern at the preceding time.

Structured Sparsity

We use a probabilistic model for structured sparse coefficients x_n based on hidden binary indicators $s_n \in \{0, 1\}$:

$$\begin{aligned} p(x_n|s_n) &= s_n \mathcal{N}(x_n; 0, \sigma^2) + (1-s_n)\delta(x_n) \\ p(s_1, \dots, s_N) &\sim \text{Markov chain / tree / random field} \end{aligned}$$

- The overall structure can be understood from the factor graph:
- Inference can be performed using belief propagation.
- Close connections to noncoherent turbo equalization!
  - s_n is like a coded bit
  - $x_n = s_n h_n$ for unknown gain h_n



Belief Propagation

- Conventional wisdom:
  - BP provides exact inference for graphs without loops
    (e.g., forward-backward alg)
  - BP usually works well on graphs with a few loops
    (e.g., LDPC decoding, turbo decoding, inference on MRFs)
- Very recent results *[Donoho/Montanari: 2009, 2010]*:
  - For large dense graphs, very inexpensive forms of BP can yield asymptotically exact inference!
  - Example: Can estimate $\boldsymbol{x}$ from $\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{w}$ using only a few iterations of matrix-multiplication & nonlinear thresholding!

$$\begin{aligned} \hat{\boldsymbol{x}}^{i+1} &= \eta_i(\boldsymbol{A}^* \boldsymbol{z}^i + \hat{\boldsymbol{x}}^i) \\ \boldsymbol{z}^{i+1} &= \boldsymbol{y} - \boldsymbol{A}\hat{\boldsymbol{x}}^{i+1} + \tfrac{N}{M} \boldsymbol{z}^i \langle \eta_i'(\boldsymbol{A}^* \boldsymbol{z}^i + \hat{\boldsymbol{x}}^i) \rangle \end{aligned}$$

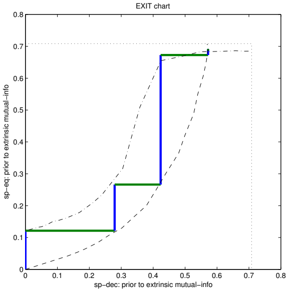
  - These ideas will revolutionize statistical signal processing!

Turbo Reconstruction of Structured-Sparse Signals

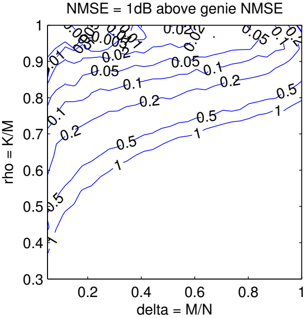
BP suggests to pass messages btwn two blocks *[Schniter CISS 2010]*:

1. Soft sparse reconstruction (implemented via iterative thresholding)
2. Soft pattern decoding (implemented via standard techniques)

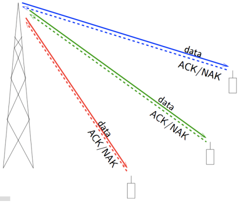
EXIT chart:



Phase transition curves:



The Resource Allocation Problem



- Consider an OFDMA downlink with
  - K users,
  - N subchannels,
  - L-length time-varying channels (one per user)
- At each time t, we would like to assign
  - the best users ("multiuser diversity") to...
  - their best subchannels ("frequency diversity") using...
  - optimal rates and powers.
- To do so, we need channel state information (CSI). How to get it?
  - Need dedicated low-latency feedback channels for each user?
  - Or are existing link-layer ACK/NAKs enough?

    $\leadsto$ "cross-layer resource allocation"

A Much Simpler Problem

- Consider: point-to-point communication with a single user,
  flat-fading Markov channel,
  ACK/NAK feedback.
- How should we choose the current transmission rate r_t?

  Goal: Maximize long-term goodput $G = \mathrm{E}\{\sum_{t=1}^{T}(1-\epsilon_t)r_t\}$

  $\epsilon_t \sim \exp(-\gamma_t/2^{r_t})$ is packet error rate,
  γ_t is SNR, which isn't perfectly known.
- Short-term thinking:

  Maximize instantaneous goodput $G_t = \mathrm{E}\{(1-\epsilon(\gamma_t, r_t))r_t\}$.
- Long-term thinking:
  - Balance between instantaneous goodput and learning γ_t.

    Perhaps sacrifice some packets as zero-rate “pilots”?
  - Classical tradeoff between exploitation and exploration.
  - Solved by a “partially observable Markov decision process.”

    Problem: POMDPs are intractable!

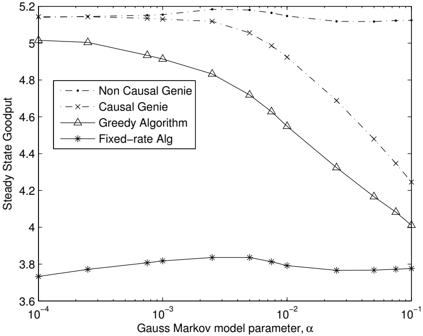
A Practical Approach to the Simpler Problem

In *[Aggarwal/Koksal/Schniter: TWC 09]* we designed a rate-adaptation algorithm that

1. tracks *distribution* of SNR γ_t using previously received ACK/NAKs.
2. assigns rates greedily (i.e., short term thinking).

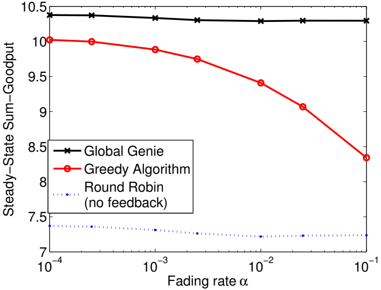
In addition, we derived an upper bound on POMDP performance.

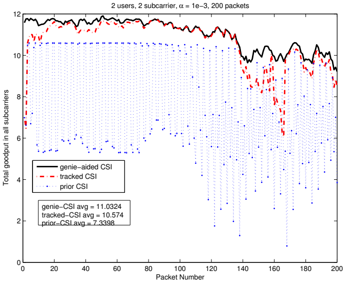
Numerical experiments show that greedy isn't far from the upper bound!



Back to the OFDMA Problem

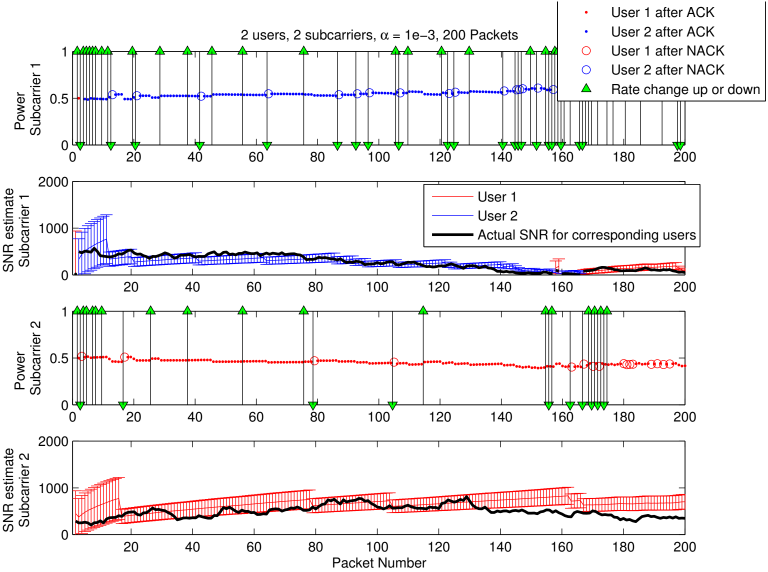
- In *[Aggaral/Assaad/Koksal/Schniter: Asil 09]*, we extended this approach to the K-user, N-subchannel, L-tap OFDMA resource allocation problem.
- This involved the design of a novel algorithm for joint optimization of user/rate/power on each subcarrier.





Performance is still quite good relative to the genie-aided POMDP bound.

Example OFDMA Adaptation Trajectories



Summary

This talk highlighted some recent and ongoing work on

1. communication over time- & frequency-selective channels,
2. soft and turbo sparse reconstruction, and
3. cross-layer resource allocation

in Prof. Schniter's group at Ohio State.

Thanks for listening!

(See `http://www.ece.osu.edu/~schniter/` for additional details.)