A Message-Passing Receiver for BICM-OFDM over Unknown Time-Varying Channels

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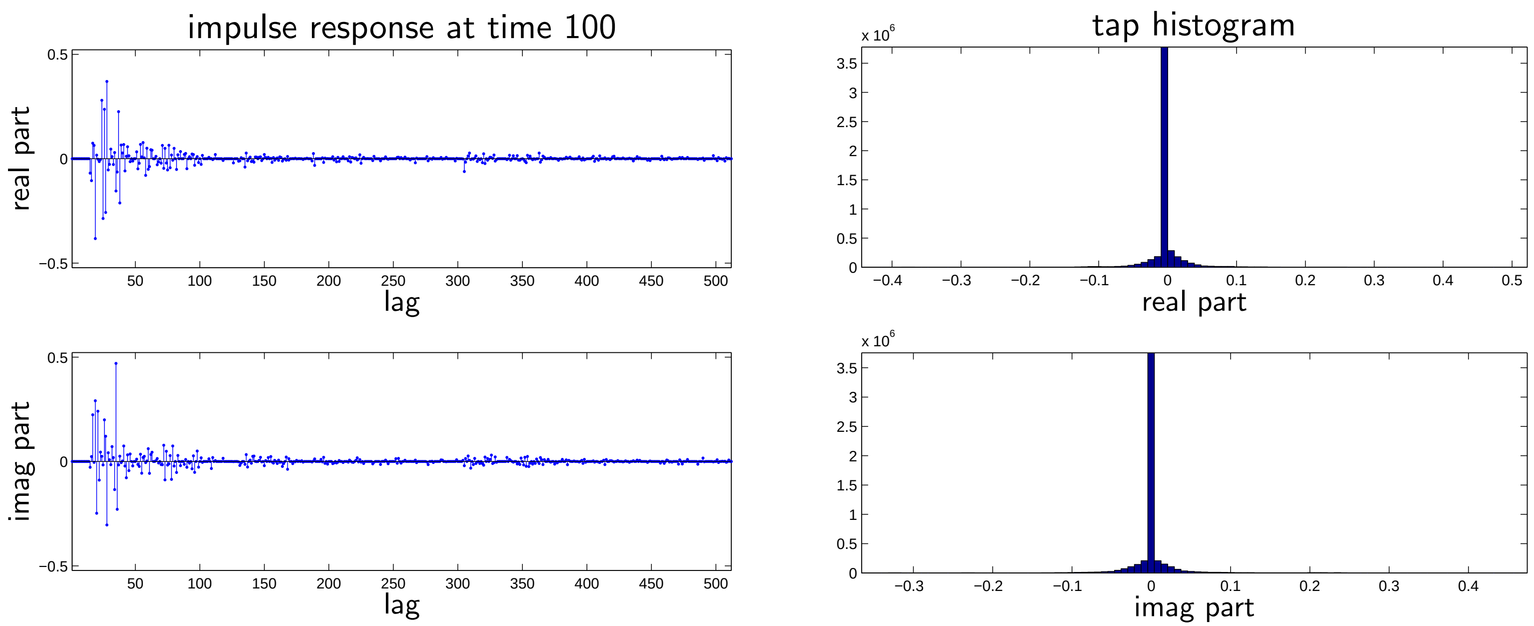
Sparsity and the underwater channel:

- Underwater channel impulse responses are often “sparse.”
- Statistically, their impulse response coefficients have heavy-tailed pdfs.



Extracted from SPACE-08 `2920156F038_C0_S6` (WHOI M-sequence)

Pilot-aided compressed channel sensing:

- Time-domain observation model:

$$\boldsymbol{y}_t = \boldsymbol{\Phi}_t \boldsymbol{h}_t + \boldsymbol{n}_t \qquad t: \text{ block index}$$

  where $\boldsymbol{n}_t$ is additive noise and

$$\begin{cases} \boldsymbol{h}_t \text{ channel impulse response} & \Rightarrow \boldsymbol{\Phi}_t \text{ is a pilot-symbol convolution mtx} \\ \boldsymbol{h}_t \text{ basis expansion coefs} & \Rightarrow \boldsymbol{\Phi}_t \text{ is more complicated.} \end{cases}$$

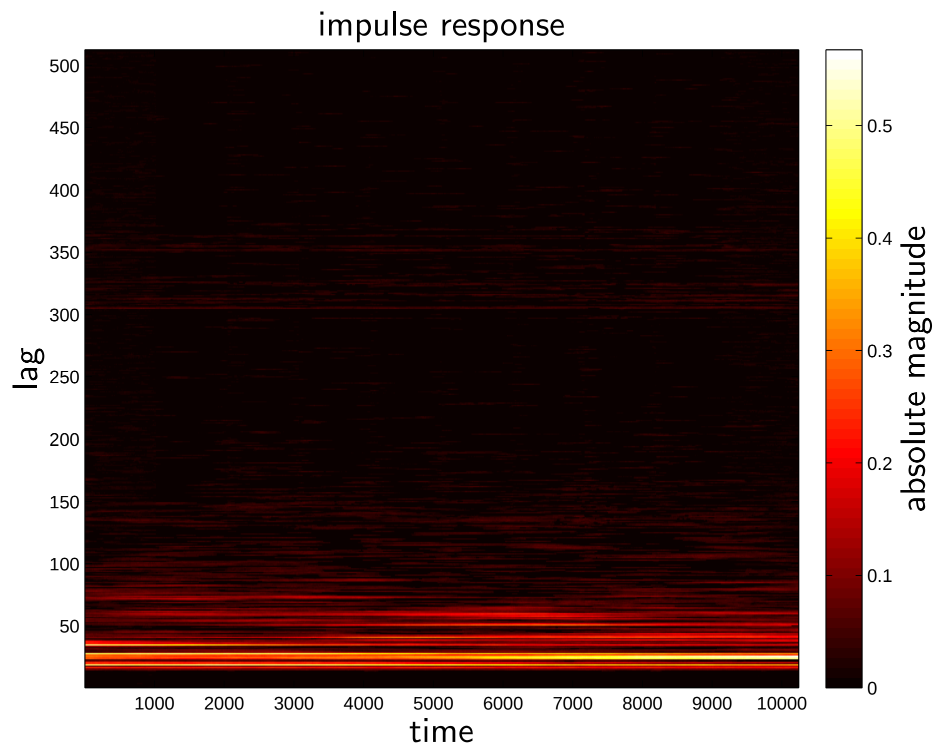
- Usually, $\boldsymbol{\Phi}_t$ is a **wide** matrix, so that some "sparse reconstruction" algorithm is required to estimate $\boldsymbol{h}_t$ given the nontrivial nullspace of $\boldsymbol{\Phi}_t$.

- Note: channel tap vector $\boldsymbol{h}_t$ can be quite long (e.g., > 1000), making estimation expensive. Some (but not all) sparse reconstruction algorithms can exploit FFT-based fast-convolution for complexity reduction.

Leveraging temporal channel structure:

- The classical compressed-channel-sensing method ignores the similarity of $\boldsymbol{h}_t$ *across* measurement blocks $t \in \{1, \ldots, T\}$.

$$\boldsymbol{y}_1 = \boldsymbol{\Phi}_1 \boldsymbol{h}_1 + \boldsymbol{n}_1$$
$$\boldsymbol{y}_2 = \boldsymbol{\Phi}_2 \boldsymbol{h}_2 + \boldsymbol{n}_2$$
$$\boldsymbol{y}_3 = \boldsymbol{\Phi}_3 \boldsymbol{h}_3 + \boldsymbol{n}_3$$
$$\vdots$$



- Note that we do not have the classical "multiple measurement vector" sparse recovery problem, since both the matrix $\boldsymbol{\Phi}_t$ and the support of $\boldsymbol{h}_t$ vary with t.

A simple Markov-based model:

- We propose to model channel sparsity using a Bernoulli-Gaussian model

$$h_l^{(t)} = a_l^{(t)} s_l^{(t)} \quad \text{with} \quad \begin{cases} a_l^{(t)} \in \mathbb{C} : \text{amplitude} \\ s_l^{(t)} \in \{0,1\} : \text{support indicator} \end{cases}$$

and temporal structure using

$$\{a_l^{(1)}, a_l^{(2)}, \ldots, a_l^{(T)}\} : \text{Gauss-Markov chain}$$

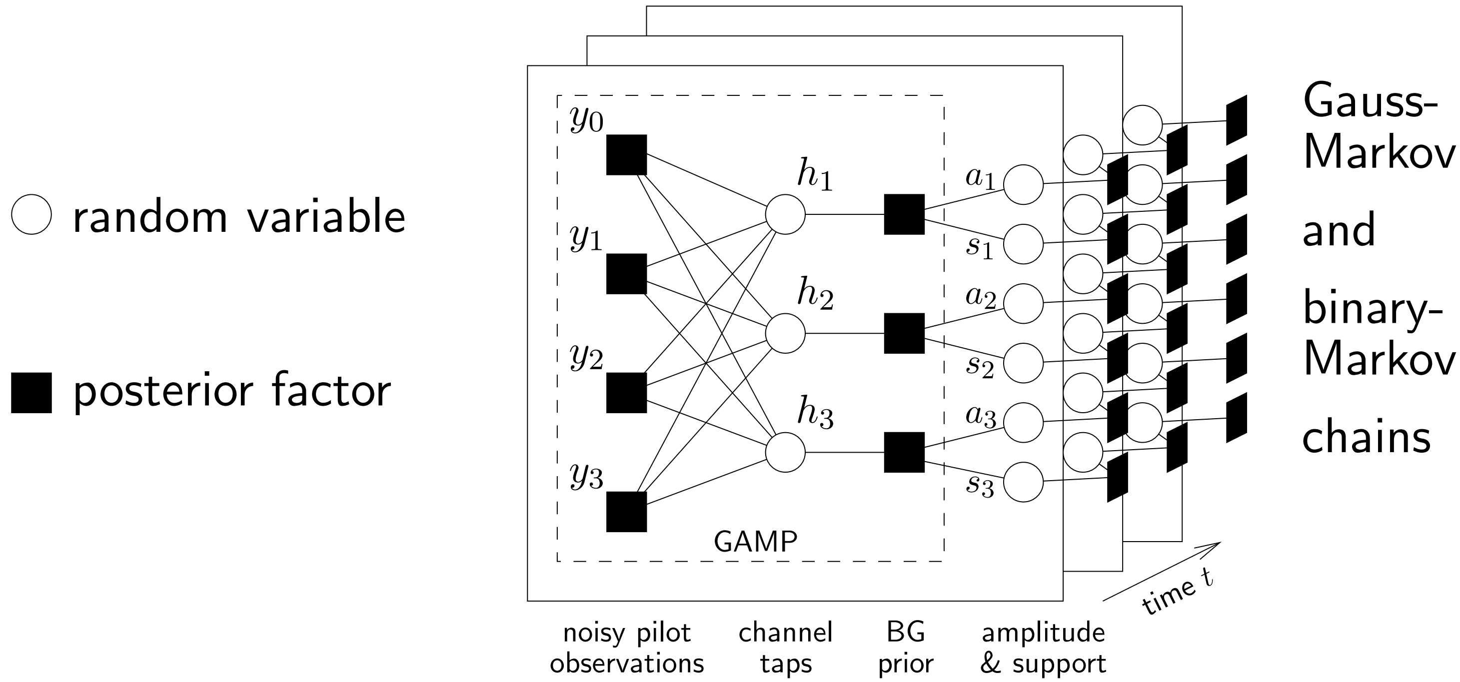
with mean m_l, variance v_l, correlation ρ_l.

$$\{s_l^{(1)}, s_l^{(2)}, \ldots, s_l^{(T)}\} : \text{binary Markov chain}$$

with transition probabilities p_l^{01}, p_l^{10}

- Note that the channel statistics are allowed to vary with the lag l.

The factor graph for pilot-aided channel estimation:



- We perform inference on this factor graph using **turbo-GAMP**:

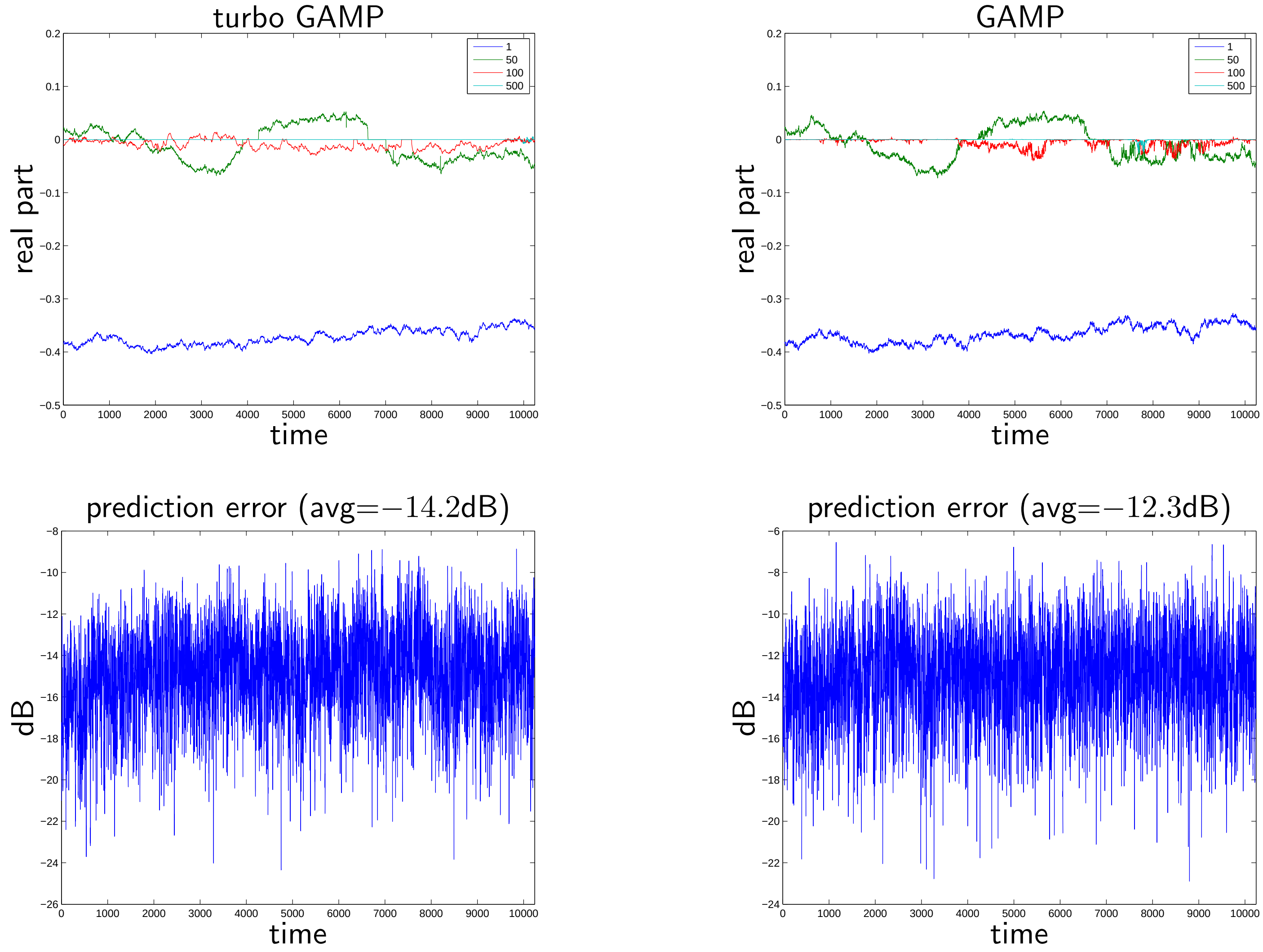
  [1] S. Rangan, "Generalized approximate message passing for estimation with random linear mixing," arXiv:1010.5141, Oct 2010.

  [2] J. Ziniel and P. Schniter, "Tracking and smoothing of time-varying sparse signals via approximate belief propagation," Asilomar 2010.

- We simultaneously learn channel/noise statistics via the EM algorithm.

Example of pilot-aided underwater channel recovery:

SPACE-08 2920156F038_C0_S6 (WHOI M-sequence)



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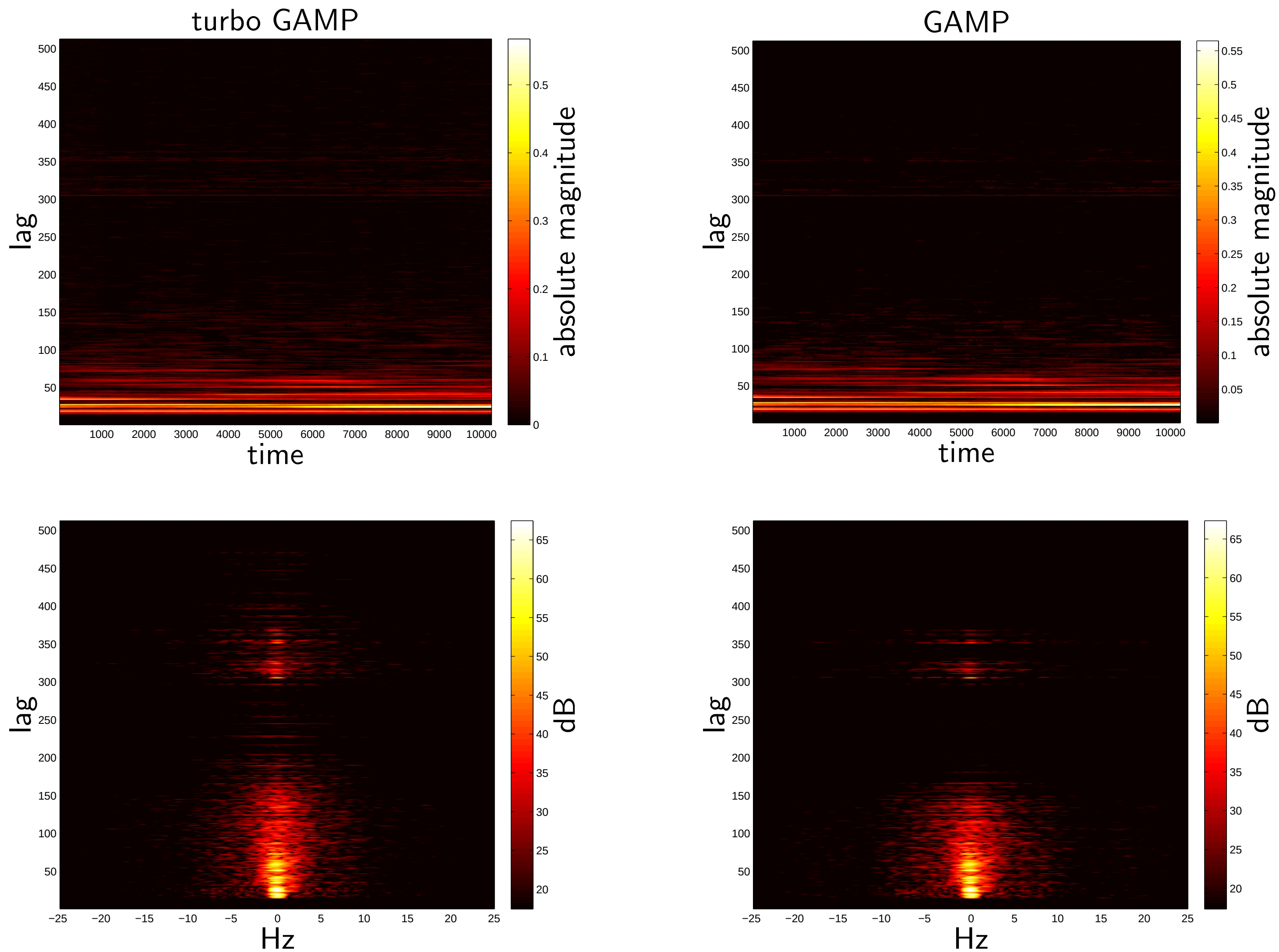


Communication over unknown sparse channels — Info Theory:

Consider a discrete-time channel that is

- *block-fading* with block size N,
- *frequency-selective* with L taps (where $L < N$),
- *sparse* with S non-zero complex-Gaussian taps (where $0 < S \leq L$),

with coefficients and support unknown at receiver. Then

1. In the high-SNR regime, the ergodic capacity obeys

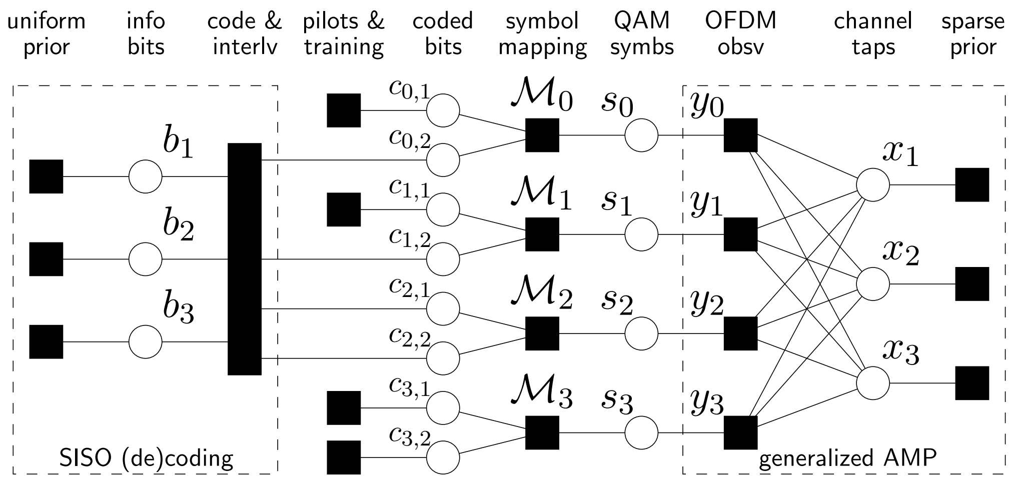
$$C_{\text{sparse}}(\text{SNR}) = \frac{N-S}{N}\log(\text{SNR}) + \mathcal{O}(1).$$

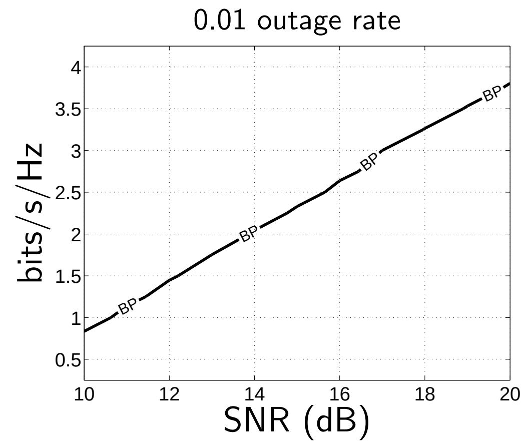
2. To achieve the prelog factor $R_{\text{sparse}} = \frac{N-S}{N}$, it suffices to use
   - pilot-aided OFDM (with N subcarriers, of which S are pilots)
   - with (necessarily) *joint* channel estimation and data decoding.

[3] A. Pachai-Kannu and P. Schniter, "On communication over unknown sparse frequency selective block-fading channels," *IEEE Trans. Info. Thy*, to appear.

Practical communication over unknown sparse channels:

- Transmission: pilot-aided BICM-OFDM transmission.
- Reception: joint estimation/equalization/decoding via turbo-GAMP.



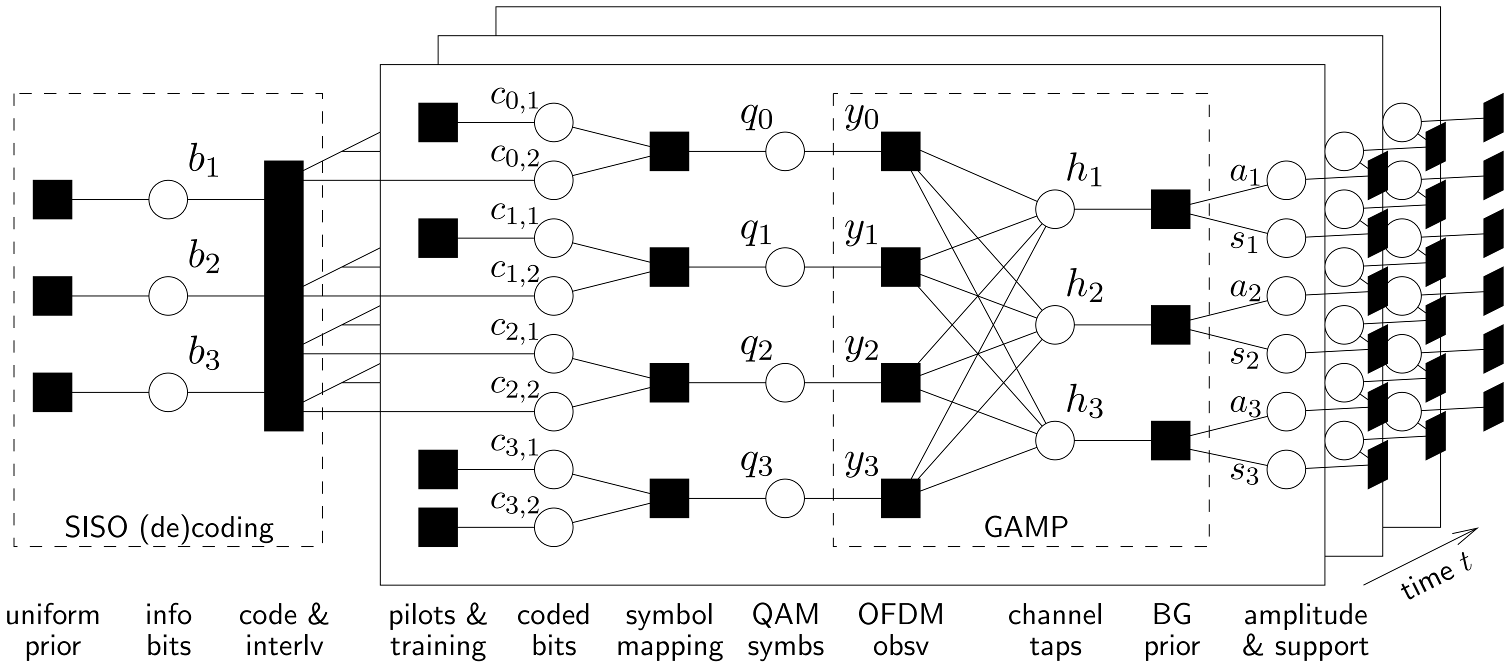


Empirically achieves the theoretical prelog factor!

[4] P. Schniter, "Belief-Propagation-Based Joint Channel Estimation and Decoding for Spectrally Efficient Communication over Unknown Sparse Channels," *Physical Communication (Elsevier): Special Issue on Compressive Sensing in Communications, 2011*.

[5] P. Schniter, "'A Message-Passing Receiver for BICM-OFDM over Unknown Clustered-Sparse Channels," *IEEE JSTSP, Special Issue on Soft Decoding*, to appear.

Extension that exploits temporal structure:



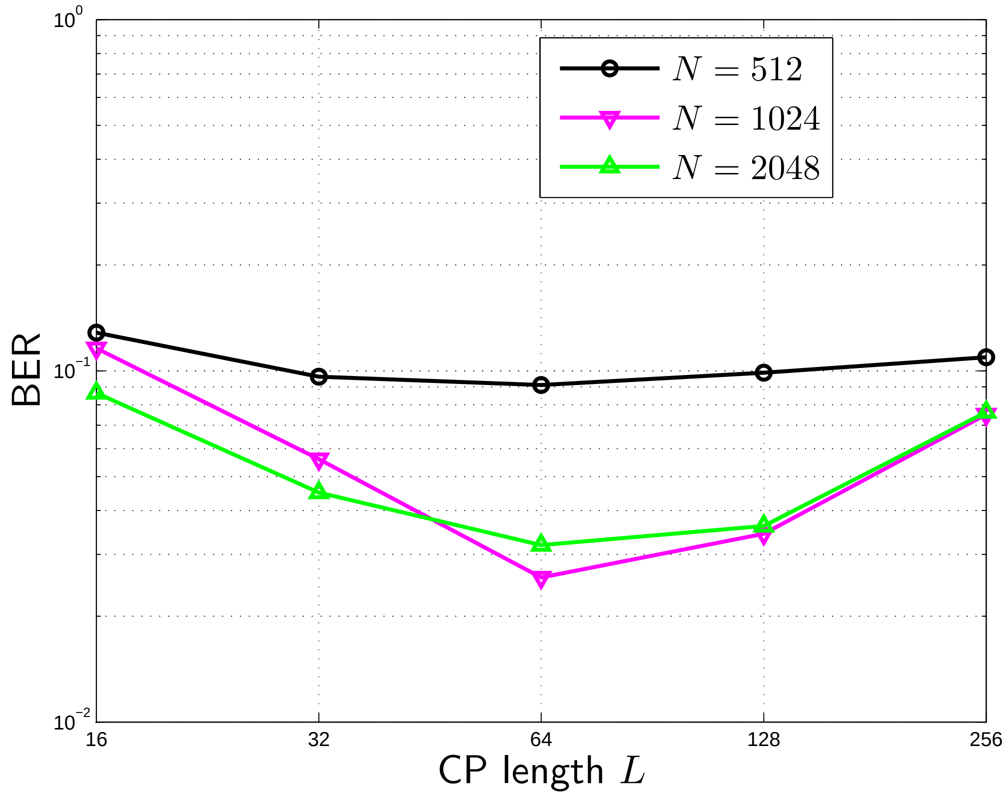
- Complexity is only $\mathcal{O}(\log_2 N + |\mathbb{S}|)$ per symbol!
- To reduce requirements on delay & memory...
  - Markov smoothing can be performed over shorter time-blocks.
  - Blocks can be overlapped to propagate beliefs forward in time.

Interesting system design questions:

For a **fixed** spectral efficiency (e.g., bits/s/Hz)...

- What is the optimal CP length?
  - too short and inter-symbol interference results,
  - too long and little redundancy is left for LDPC coding!
- What is the optimal number of training bits?
  - too few and channel estimation suffers,
  - too many and little redundancy is left for LDPC coding!
- Where should training bits be placed?
  - group bits together into pilot symbols?
  - if yes, place pilot-symbols randomly? on regular grid?
  - if no, place training bits randomly? at MSB locations?

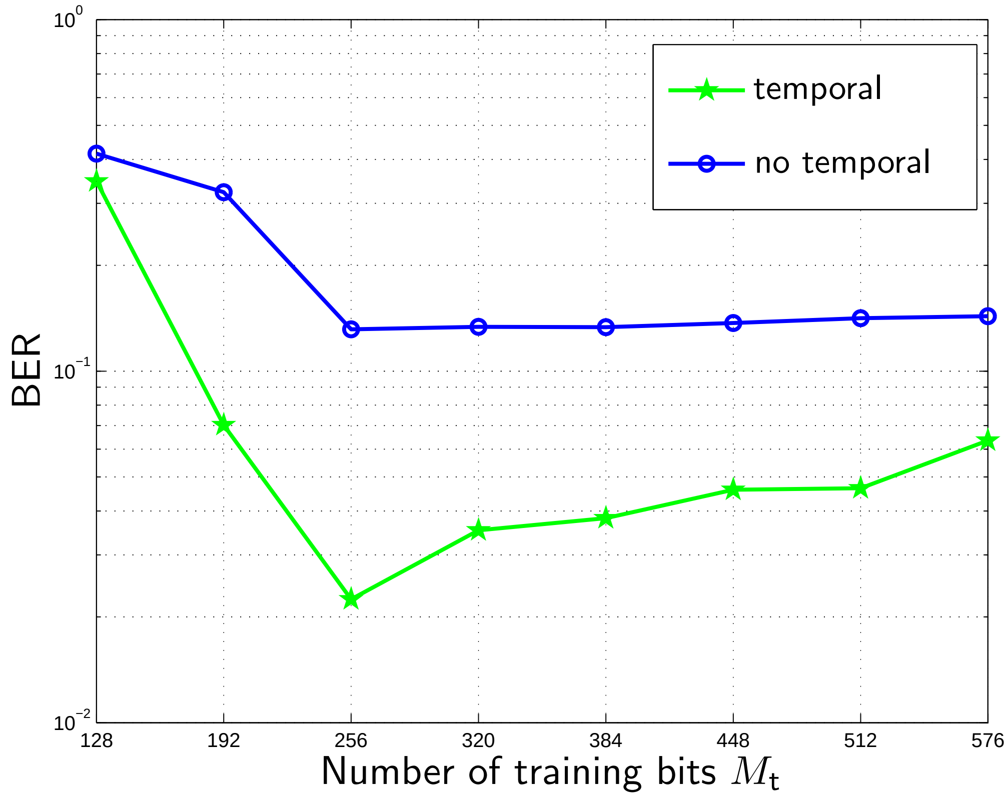
Performance versus CP length L:



Simulation params: SNR=14dB, 2 bits/s/Hz, 16-QAM, M_{t}=256, N_{p}=0.

Time-varying channel recovered from SPACE-08 2920156F038_C0_S6.

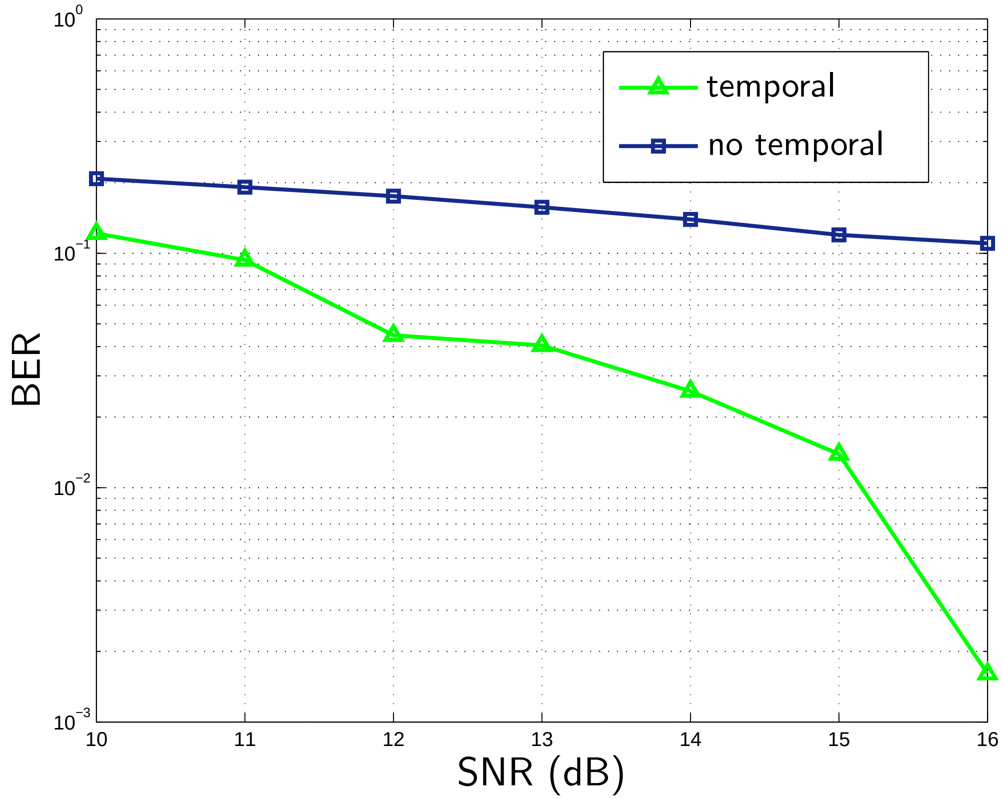
Performance versus number of training bits M_t:



Simulation params: N=1024, L=64, SNR=14dB, 2 bits/s/Hz, 16-QAM, N_p=0.

Time-varying channel recovered from SPACE-08 2920156F038_C0_S6.

Performance versus SNR:



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Conclusions:

- Wideband communication channels, such as the underwater channel, often have "sparse" impulse responses.
- Such channels also evolve smoothly with time.
- To exploit these two structures, we modeled the channel taps as Bernoulli-Gaussian, with a binary-Markov-chain for support evolution and a Gauss-Markov-chain for amplitude evolution.
- First, an approximate-message-passing scheme was proposed for pilot-aided channel estimation.
- Second, an approximate-message-passing scheme was proposed for joint channel-tracking / equalization / decoding of BICM-OFDM.
- In both cases, experiments using experimental underwater channel data suggest that the exploitation of temporal structure improves performance significantly.