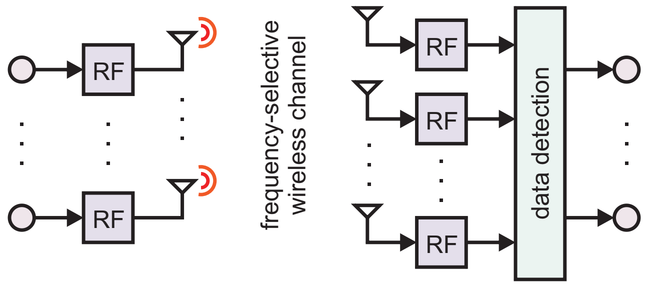
Optimal Data Detection in Large-MIMO Systems

Charles Jeon[1], Ramina Ghods[1], Arian Maleki[2], and Christoph Studer[1]
[1]Cornell University; [2]Columbia University

Large multiple-input multiple-output (MIMO)

Idea: Tens of users communicate with a base station having hundreds of antennas simultaneously and in the same frequency band



- Improves the spectral efficiency and reduces power consumption compared to conventional (small-scale) MIMO wireless systems
- Useful in practice for massive (or large-scale) multi-user MIMO
- Believed to be the key technology in 5G wireless systems

Data detection in large MIMO systems

- Goal: Recover M_T-dimensional vector $\mathbf{s}_0 \in \mathcal{O}^{M_\text{T}}$ with constellation $\mathcal{O}$ (e.g., QAM or PSK) from the following input-output relation:

$$\mathbf{y} = \mathbf{H}\mathbf{s}_0 + \mathbf{n},$$

where $\mathbf{H} \in \mathbb{C}^{M_\text{R}\times M_\text{T}}$ is the MIMO channel matrix ($\beta = M_\text{T}/M_\text{R}$) and $\mathbf{n}$ is i.i.d. additive white Gaussian noise with variance N_0

- Optimal data detection amounts to solving the following individually-optimal (IO) detection problem:

$$\text{(IO)} \quad s_\ell^{\text{IO}} = \underset{\tilde{s}_\ell \in \mathcal{O}}{\arg\max}\; p(\tilde{s}_\ell|\mathbf{y},\mathbf{H}),$$

- The (IO) problem is **combinatorial** and hence, its complexity scales exponentially in the number of transmit antennas M_T, i.e., $C \approx |\mathcal{O}|^{M_\text{T}}$.

With existing algorithms, optimal data detection is infeasible

State-of-the-art in large-MIMO data detection

- Existing detection methods for large-MIMO rely on approximations in order to attain low computational complexity
- Most prominent detection method is linear minimum mean-square error (MMSE) equalization followed by quantization:

$$\hat{\mathbf{s}}^{\text{MMSE}} = \mathcal{Q}_{\mathcal{O}}\big((\mathbf{H}^\text{H}\mathbf{H} + N_0/E_s\mathbf{I})^{-1}\mathbf{H}^\text{H}\mathbf{y}\big)$$

- Such linear detectors suffer from a **significant performance loss**

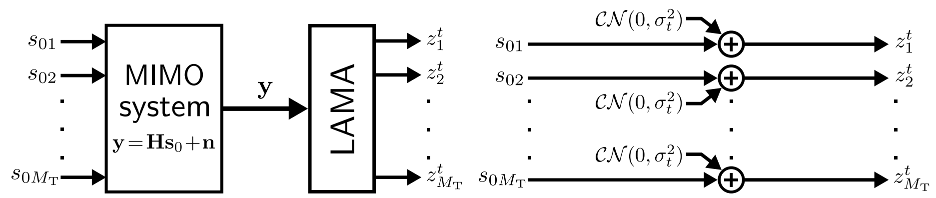
LAMA: Large-MIMO approximate message passing

We use recent methods from statistical physics and Bayesian inference in compressive sensing for large-MIMO data detection

- Asymptotic Gaussianity of our algorithm enables us to **predict the performance and complexity in the large-antenna limit**
- We can show analytically that if $\beta = M_\text{T}/M_\text{R} \leq \beta^*$ for some β^*, LAMA enables us to perform individually optimal data detection
- Performance and complexity prediction is accomplished via the state-evolution framework of a set of coupled fixed-point equations

LAMA decouples large MIMO systems

We can analytically show that LAMA decouples a massive MIMO system into parallel and independent AWGN channels



- This decoupling property enables us to deploy simple, stream-wise detection methods (e.g., required for soft-output computation)
- This decoupling property enables LAMA to naturally support soft-input soft-output MIMO detection to achieve near-capacity performance

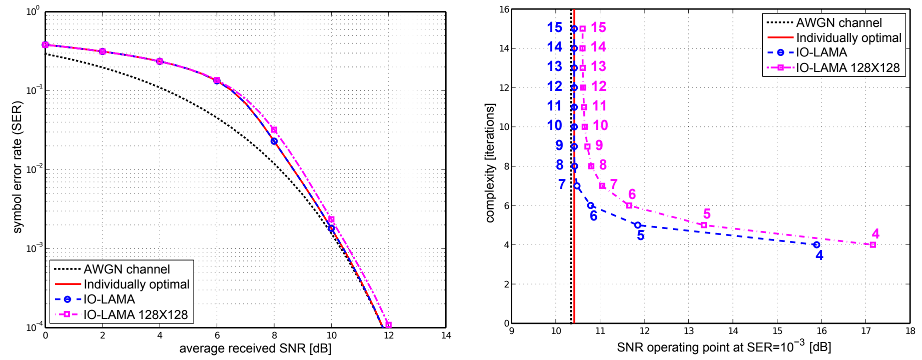
Optimality of LAMA can be studied theoretically

Theorem: The effective noise variance σ_{t+1}^2 can be computed by the recursion equation $\sigma_{t+1}^2 = N_0 + \beta\Psi(\sigma_t^2)$, where the MSE function is $\Psi(\sigma_t^2) = \mathbb{E}_{S,Z}\Big[\big|\mathsf{F}(S+\sigma_t Z, \sigma_t^2) - S\big|^2\Big]$ and $Z \sim \mathcal{CN}(0,1)$. Further, as $t \to \infty$, σ_t^2 converges to a fixed point of $\sigma^2 = N_0 + \beta\Psi(\sigma^2)$.

- If $\beta \leq \beta^* = \min_{\sigma^2>0}\left(\frac{\mathrm{d}\Psi(\sigma^2)}{\mathrm{d}\sigma^2}\right)^{-1}$, then LAMA converges to the **unique**, optimal fixed point and, consequently, solves the (IO) problem
- If $\beta > \beta^*$, then LAMA may converge to multiple fixed points and hence, convergence to (IO) is, in general, not guaranteed
- The use of LAMA in large MIMO is well justified as practical systems have $M_\text{R} \gg M_\text{T}$, i.e. $\beta = M_\text{T}/M_\text{R}$ is smaller than β^*

LAMA is able to perform optimal data detection in large MIMO

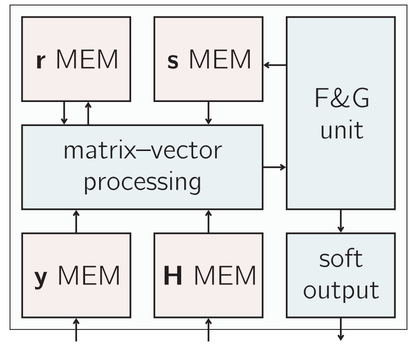
LAMA achieves near-optimal performance in practical systems

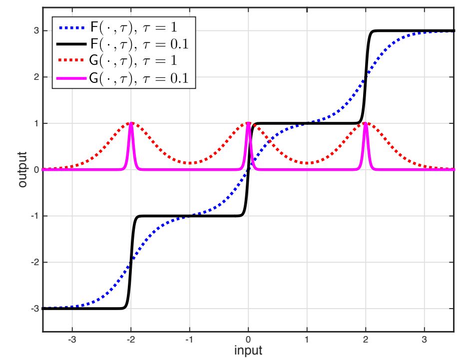


- LAMA also achieves **near-optimal data detection performance in finite dimensional systems** (e.g., in a 128×128 dimensional scenario)
- We can also **analytically predict the performance for a given complexity** (in terms of algorithm iterations) without simulations

LAMA can be implemented in VLSI at low complexity

LAMA mainly relies on very simple matrix–vector multiplications and hence, lends itself well for hardware implementations





- We are currently **developing a VLSI architecture** for high-throughput data detection in massive MIMO system using LAMA
- We are analyzing different approximations for $\mathsf{F}(\cdot,\cdot)$ and $\mathsf{G}(\cdot,\cdot)$ functions to even further reduce the implementation complexity
- Our planned ASIC design easily exceeds 1 Gbps throughput at low silicon area in a 65 nm CMOS process for a 128×8 system

Publications

- C. Jeon, R. Ghods, A. Maleki, C. Studer, "Optimality of Large MIMO Detection via Approximate Message Passing," submitted to the IEEE International Symposium on Information Theory, 2015
- C. Jeon, R. Ghods, A. Maleki, C. Studer, "Optimal Data Detection in Large-MIMO," in preparation for IEEE Transactions on Information Theory