Integrated Information Processing (IIP) Group
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ETH zürich

Image made with Midjourney

New Methods for Multi-Antenna Jammer Mitigation

Christoph Studer

Joint work with Gian Marti and Oscar Castañeda

Jammers threaten critical communication infrastructure

Russian Soldiers 'Shoot Down' Chinese-Origin Ukrainian UAV Using Anti-Drone 'Jammer' Gun – Watch

EUROPE By **Parth Satam** | November 24, 2022

November 25, 2022

By dpa

NATO Sends Jammers For Drone Defense To Ukraine

Satellite Imagery Exposes China's Space-Jammer Buildup

November 01, 2022

After watching Russia's and Ukraine's electronic warriors battle it out, the US military wants to 'dial up' up its own 'jamming power'

Michael Peck Oct 30, 2023, 11:23 PM GMT+1

Prelude:
The very basics of MIMO jammer mitigation

Introducing the main characters

Massive multi-user (MU) MIMO uplink:

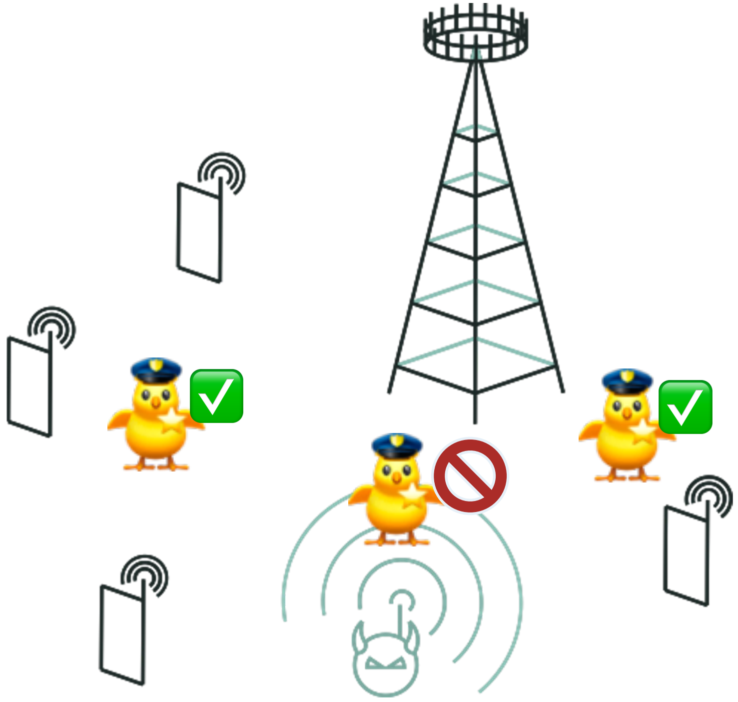
$$\mathbf{y} = \mathbf{Hs} + \mathbf{j}\mathrm{w} + \mathbf{n}$$

$\mathbf{y} \in \mathbb{C}^B$	BS receive signal
$\mathbf{H} \in \mathbb{C}^{B \times U}$	channel matrix; $B \gg U$
$\mathbf{s} \in \mathcal{S}^U$	UE transmit vector with variance E_s
$\mathbf{j} \in \mathbb{C}^B$	jammer channel
$\mathrm{w} \in \mathbb{C}$	jammer signal
$\mathbf{n} \in \mathbb{C}^B$	white Gaussian noise with variance N_0

Will later also consider multi-antenna jammers: $\mathbf{j} \to \mathbf{J} \in \mathbb{C}^{B \times I}$ and $\mathrm{w} \to \boldsymbol{w} \in \mathbb{C}^I$

Multi-antenna jammer mitigation

It’s not that difficult!



<u>Project onto orthogonal subspace (POS)</u>

$\mathbf{P} = \mathbf{I}_B - \mathbf{j}\mathbf{j}^\dagger$ is a projection onto $\text{span}(\mathbf{j})^\perp$

$$\mathbf{Py} = \mathbf{P}(\mathbf{Hs} + \mathbf{j}w + \mathbf{n}) = \mathbf{PHs} + \mathbf{Pn}$$

After nulling the jammer, detect transmitted data as follows:

$$\hat{\mathbf{s}} = \left((\mathbf{PH})^H\mathbf{PH} + (E_s/N_0)\mathbf{I}_U\right)^{-1}(\mathbf{PH})^H\mathbf{Py}$$

Q. Yan, H. Zeng, T. Jiang, M. Li, W. Lou, Y. T. Hou, “Jamming resilient communication using MIMO interference cancellation”, IEEE Trans. Inf. Forensics Security, 2016

T. T. Do, E. Björnsson, E. G. Larsson, S. M. Razavidazdeh, “Jamming-resistant receivers for the massive MIMO uplink”, IEEE Trans. Inf. Forensics Security, 2018

Multi-antenna jammer mitigation

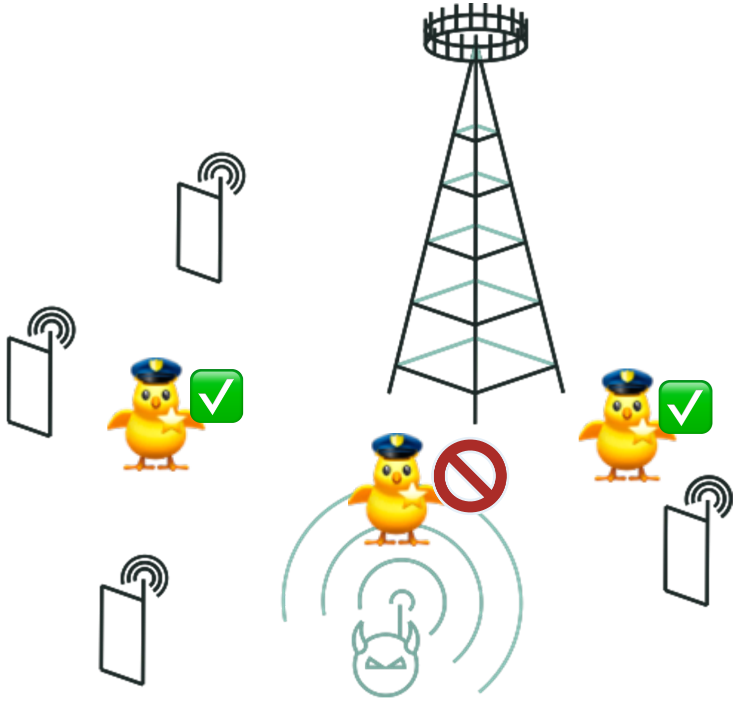
It's not that difficult!

Robust linear minimum mean square error (RLMMSE)

$$\hat{\mathbf{s}} = \mathbf{H}^H \left(\mathbf{H}\mathbf{H}^H + \frac{E_w}{E_s} \mathbf{j}\mathbf{j}^H + \frac{N_0}{E_s} \mathbf{I}_B \right)^{-1} \mathbf{y}$$

where E_w is the variance of the jammer signal w

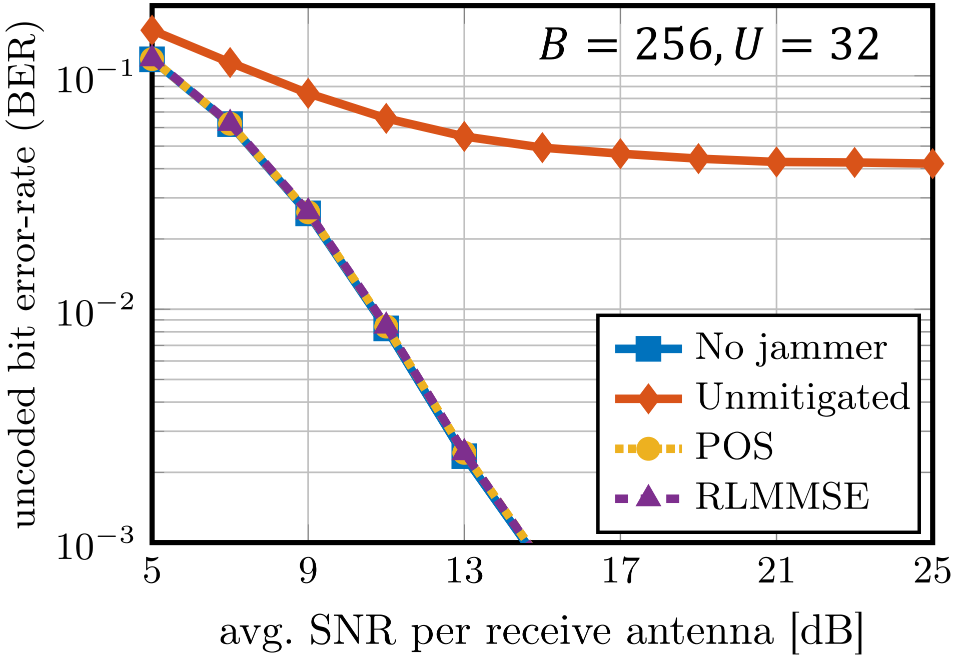
RLMMSE → POS as $E_w \to \infty$



T. T. Do, E. Björnsson, E. G. Larsson, S. M. Razavidazdeh, "Jamming-resistant receivers for the massive MIMO uplink", IEEE Trans. Inf. Forensics Security, 2018

Multi-antenna jammer mitigation

MIMO jammer mitigation is highly effective!



Strong jammer with $\rho = E_w/E_s = 30$ dB

but jammer mitigation with same performance as without jammer!

Why not stop here?

Things are never so simple…

- Medium access control under jamming?
- Synchronization under jamming?

} taken for granted in this talk 😇

- Hardware aspects of jamming?
- How do we learn $\mathbf{j}$?

$$\mathbf{P} = \mathbf{I}_B - \mathbf{j}\mathbf{j}^\dagger \qquad \hat{\mathbf{s}} = \mathbf{H}^H \left(\mathbf{H}\mathbf{H}^H + \frac{E_w}{E_s} \mathbf{j}\mathbf{j}^H + \frac{N_0}{E_s} \mathbf{I}_B \right)^{-1} \mathbf{y}$$

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- How do we learn **j** ? → **Part II: Joint mitigation and detection**

$$\mathbf{P} = \mathbf{I}_B - \mathbf{j}\mathbf{j}^\dagger \qquad \hat{\mathbf{s}} = \mathbf{H}^H \left(\mathbf{H}\mathbf{H}^H + \frac{E_w}{E_s}\mathbf{j}\mathbf{j}^H + \frac{N_0}{E_s}\mathbf{I}_B \right)^{-1} \mathbf{y}$$

Part I:
Jammer mitigation in low-resolution massive MIMO

Low-resolution basestations

- **All-digital** (= each antenna has its own ADCs/DACs) BSs have many **advantages**:
  - Maximum flexibility
  - Simplified synchronization, channel estimation, equalization, precoding, etc.
  - Less expensive testing and technology migration
- … but they also face **challenges**
  - Excessive interconnect, system costs, and power consumption
- **Low-resolution data converters** can be a remedy to these challenges
  - Lower power consumption
    exponential with number of bits
  - Lower hardware complexity
    RF circuitry just needs to operate above quantization noise floor

Pick your poison!

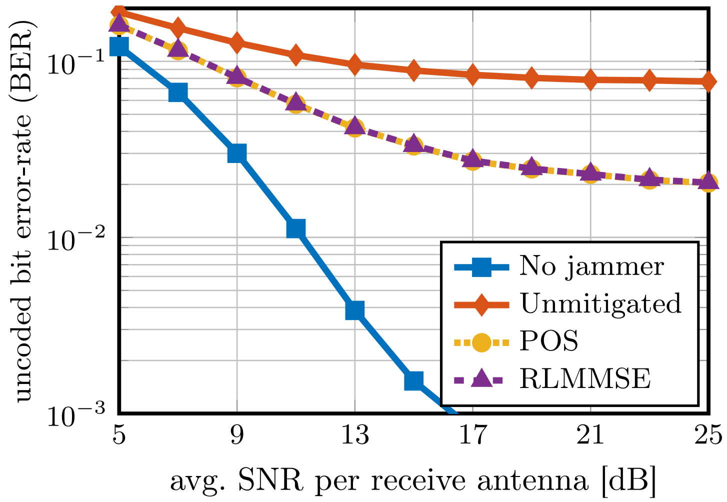
Keep the quantization range fixed…

… and let the jammer **saturate** the ADCs

Expand the quantization range…

… and drown the user signals in **quantization noise**

Either way, the linear I/O relation $\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{j}w + \mathbf{n}$ is not a good model anymore, and digital (post-ADC) jammer mitigation is not going to help much ☹



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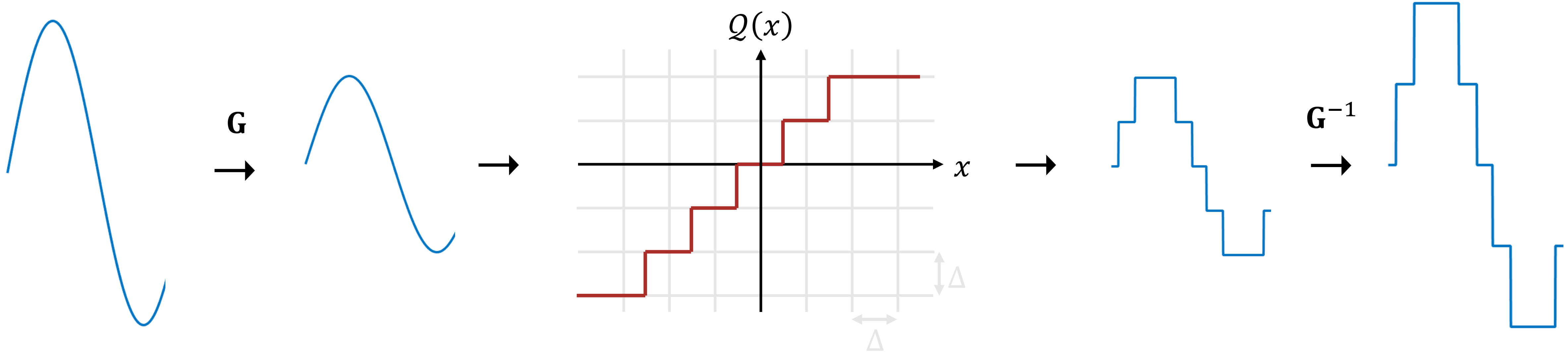
The math of quantization

Consider a q-bit quantizer with stepwidth Δ:



The BS quantizes $\mathbf{y}$ as follows:

$$\mathbf{r} = \mathcal{Q}(\mathbf{y}) = \mathbf{G}^{-1}\left(\mathcal{Q}(\Re\{\mathbf{Gy}\}) + i\mathcal{Q}(\Im\{\mathbf{Gy}\}) \right)$$

where $\mathbf{G} = \mathrm{diag}(g_1, \dots, g_B)$ is a gain control matrix

The math of quantization

Bussgang's Theorem (1952)

$Q(x)$ can be written as $Q(x) = \gamma x + d$

$\gamma = \mathbb{E}[xQ(x)]/\mathbb{E}[x^2]$ is the *Bussgang gain* (a constant)

The *distortion* d is a random variable **which is uncorrelated from** x,

and which has $\mathbb{E}[d^2] = \mathbb{E}[Q(x)^2] - \gamma^2\mathbb{E}[x^2]$

$\Longrightarrow$ We can write

$$\begin{aligned}\mathbf{r} &= Q(\mathbf{y}) \\ &= \mathbf{G}^{-1}(\,Q(\Re\{\mathbf{Gy}\}) + iQ(\Im\{\mathbf{Gy}\})\,) \\ &= \mathbf{G}^{-1}(\gamma\Re\{\mathbf{Gy}\} + \mathbf{d}_r + i(\gamma\Im\{\mathbf{Gy}\} + \mathbf{d}_i)) \\ &= \gamma\mathbf{y} + \mathbf{G}^{-1}(\mathbf{d}_r + i\mathbf{d}_i)\end{aligned}$$

J. J. Bussgang, "Crosscorrelation functions of amplitude-distorted Gaussian signals," MIT Technical Report, 1952

The math of quantization

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&= \gamma\mathbf{y} + \mathbf{G}^{-1}(\mathbf{d}_r + i\mathbf{d}_i)
\end{aligned}$$

The inverse gain matrix $\mathbf{G}^{-1}$ magnifies the quantization noise!

What to do about it?

We must do something before the signal is converted to digital!

What to do about it?

We must do something before the signal is converted to digital!

- Remove a large part of the jammer interference already in the analog domain
  HERMIT 🦀

- Concentrate the jammer interference to only a subset of ADCs, and detect the input data based on the jammer-free ADCs
  SNIPS ✂️

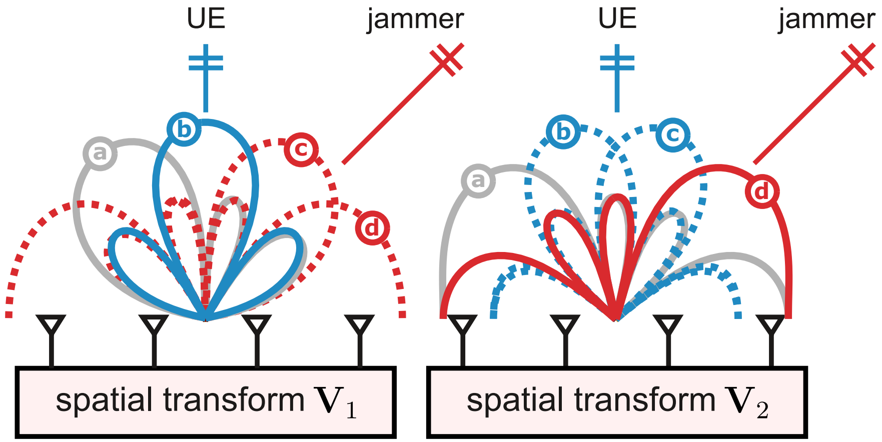
G. Marti*, O. Castañeda*, S. Jacobsson, G. Durisi, T. Goldstein, CS, " Hybrid Jammer Mitigation for All-Digital mmWave Massive MU-MIMO", Asilomar, 2021

G. Marti*, O. Castañeda*, CS, "Jammer Mitigation via Beam-Slicing for Low-Resolution mmWave Massive MU-MIMO", IEEE OJ-CAS, 2021

SNIPS ✂ – Beam-slicing

Key Idea: Use directivity of mmWave signals to focus jammer onto subset of ADCs

Leverage fact that the discrete Fourier transform (DFT) sparsifies mmWave receive signals



Cluster-wise analog transform with cluster size $S = B/C$: $\mathbf{y} = \begin{bmatrix} \mathbf{y}_1 \\ \vdots \\ \mathbf{y}_C \end{bmatrix}$

$$\hat{\mathbf{y}}_c = \mathbf{V}_c \mathbf{y}_c, \qquad c = 1, \dots, C$$

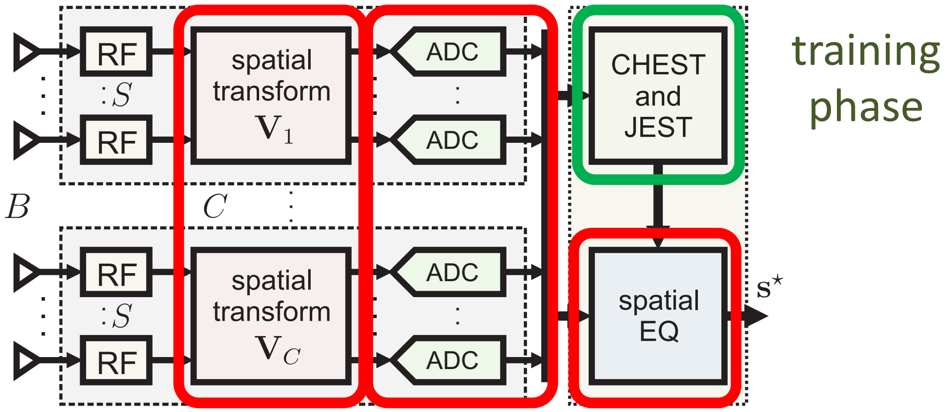
where the $\mathbf{V}_c$ are phase-rotated S-point DFT matrices

→ phase-rotations increase "angular diversity"

SNIPS ✂

Reconstruct UE signals using outputs of jammer-free ADCs

Take into account each ADC-output's fidelity by estimating amount of jammer interference at that ADC

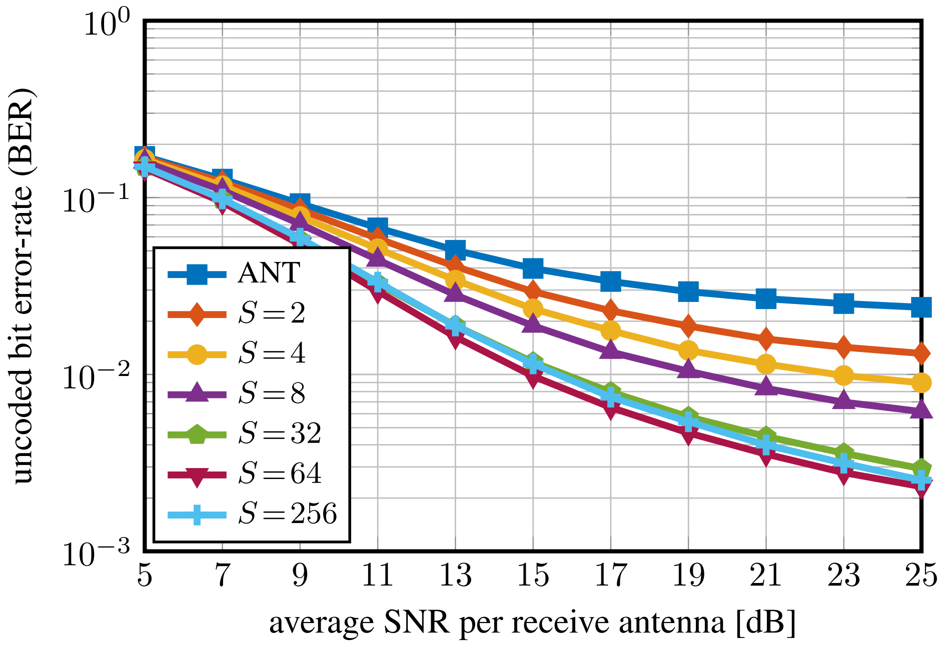


Beam-slicing: $\hat{\mathbf{y}} = \mathbf{V}\mathbf{y}$

A/D-conversion: $\hat{\mathbf{r}} = Q(\hat{\mathbf{y}})$

Digital equalization: $\mathbf{s}^\star = \frac{1}{\gamma}\widehat{\mathbf{H}}_{\text{est}}^H\left(\widehat{\mathbf{H}}_{\text{est}}\widehat{\mathbf{H}}_{\text{est}}^H + \frac{1}{E_s}([E_w\mathbf{j}\mathbf{j}^H]_{\text{est}} + N_0\mathbf{I} + 2\gamma^{-2}\mathbf{G}^{-2}\mathbf{I}\right)^{-1}\hat{\mathbf{r}}$

SNIPS ✂️ – Results



<u>Setup</u>

QuaDRiGA mmMAGIC line-of-sight, 256 BS-antennas, 32 UEs with $\pm$3dB power control, 16-QAM, 4-bit ADCs, single jammer with 25dB higher power than the average UE

SNIPS with different cluster sizes S vs. purely digital baseline (ANT)

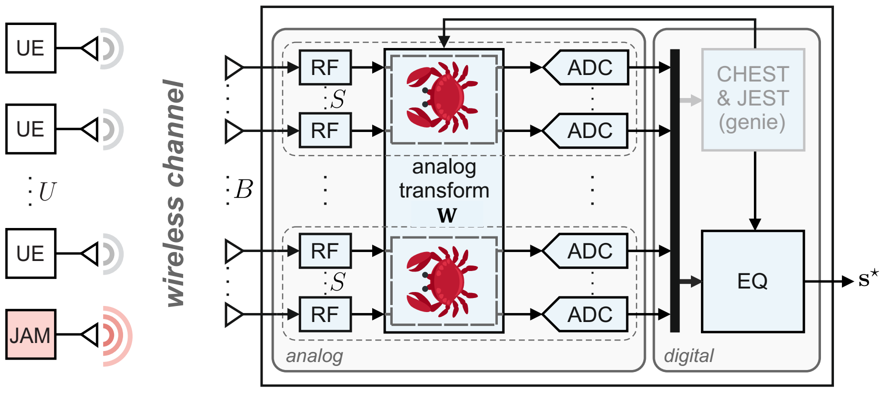
HERMIT

Key Idea: Remove as much jammer interference as possible in analog domain
Consider the constraints of analog circuit implementations

- $\mathbf{P}$ should minimize the MSE between $\mathbf{Wy}$ and $\mathbf{Hs}+\mathbf{n}$

$$\widehat{\mathbf{W}} = \mathrm{argmin}_{\mathbf{W}\in\mathcal{W}}\mathbb{E}\left[\|\mathbf{Wy} - (\mathbf{Hs}+\mathbf{n})\|^2\right]$$

  where $\mathcal{W}$ is the set of all matrices of the form
  $\mathbf{W} = \mathbf{I}_B - \beta\mathbf{b}\mathbf{a}^H$ with $\mathbf{b}\in\mathcal{B}^B, \mathbf{a}\in\mathcal{A}^B$



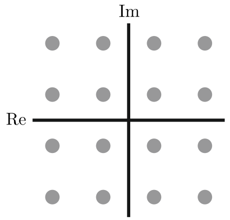
- Equivalent formulation: $\{\hat{\beta}, \hat{\mathbf{b}}, \hat{\mathbf{a}}\} = \mathrm{argmin}_{\beta\in\mathbb{C},\, \mathbf{b}\in\mathcal{B}^B,\, \mathbf{a}\in\mathcal{A}^B}\ \mathbb{E}\left[\|\beta\mathbf{b}\mathbf{a}^H\mathbf{y} - \mathbf{j}w\|^2\right]$

- **Proposition:** The optimiziation problem can be separated in $\mathbf{b}$ and $\mathbf{a}$, and the solutions are

$$\hat{\mathbf{b}} = \mathrm{argmax}_{\mathbf{b}\in\mathcal{B}^S}\frac{|\mathbf{j}^H\mathbf{b}|^2}{\|\mathbf{b}\|^2}, \qquad \hat{\mathbf{a}} = \mathrm{argmax}_{\mathbf{a}\in\mathcal{A}^S}\frac{|\mathbf{j}^H\mathbf{a}|^2}{\mathbf{a}^H\mathbf{C}_\mathbf{y}\mathbf{a}}, \qquad \hat{\beta} = \frac{E_w\mathbf{j}^H\hat{\mathbf{a}}\hat{\mathbf{b}}^H\mathbf{j}}{\|\hat{\mathbf{b}}\|^2\hat{\mathbf{a}}^H\mathbf{C}_\mathbf{y}\hat{\mathbf{a}}}$$

HERMIT 🦀 – Analog constraints

- Structure $\mathbf{W} = \mathbf{I}_B - \beta \mathbf{b}\mathbf{a}^H$ allows us to implement $\mathbf{W}\mathbf{y}$ as $\mathbf{W}\mathbf{y} = \mathbf{y} - \beta\langle \mathbf{y}, \mathbf{a} \rangle \mathbf{b}$
- The domains $\mathcal{A}, \mathcal{B}$ from which the vectors $\mathbf{a}, \mathbf{b}$ stem are discrete:
  Approximate algorithms are needed to compute $\hat{\mathbf{a}}$ and $\hat{\mathbf{b}}$



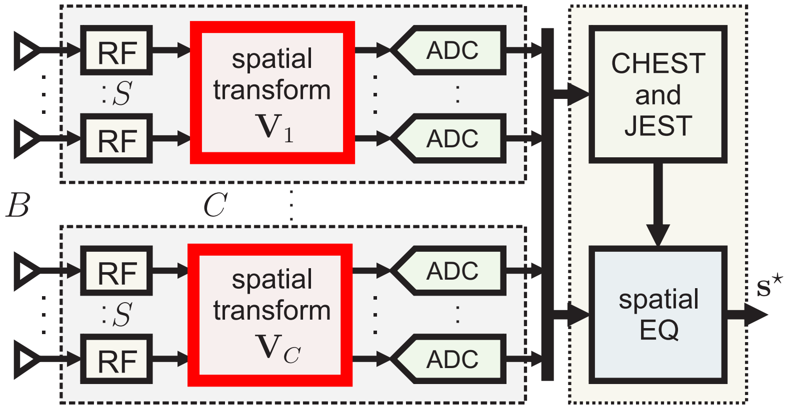
- We also decentralize the transform into clusters C clusters of size $S = B/C$

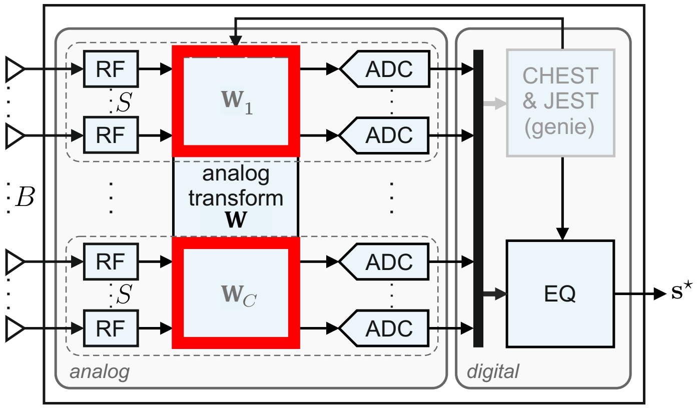
$$\mathbf{W} = \begin{bmatrix} \mathbf{W}_1 & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{W}_C \end{bmatrix}$$

where the blocks have structure $\mathbf{W}_c = \mathbf{I}_S - \beta_c \mathbf{b}_c \mathbf{a}_c^H$

HERMIT 🦀 or SNIPS ✂️ ?

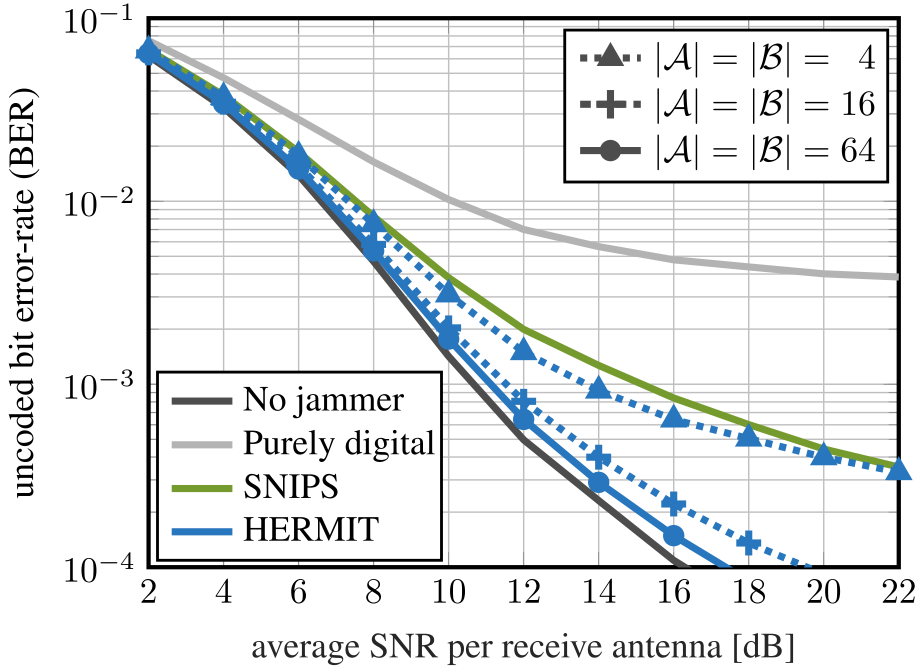
- Similar structure





- SNIPS has a **non-adaptive** analog transform ($\mathbf{V}$ does not depend on $\mathbf{H}$ and $\mathbf{j}$)
- HERMIT has an **adaptive** analog transform ($\mathbf{P}$ depends on $\mathbf{H}$ and $\mathbf{j}$)

HERMIT 🦀 or SNIPS ✂️ ? Results



Adaptive transform 🦀 has better performance than non-adaptive transform ✂️ – but at the prize of **higher** circuit **complexity** and more complicated control

<u>Setup</u>

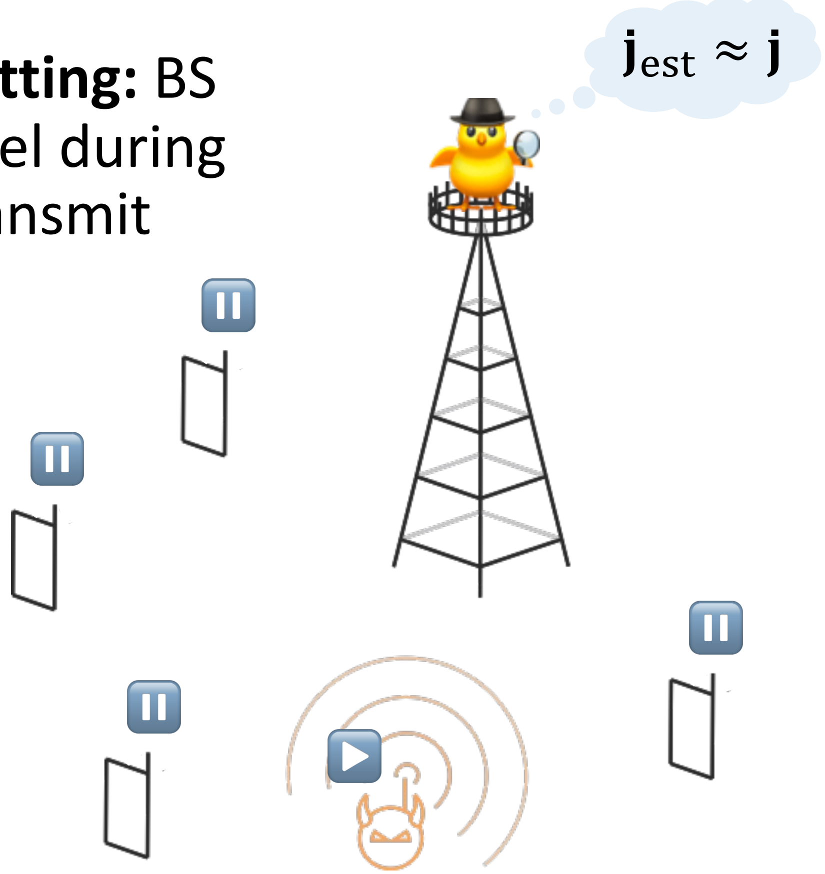
QuaDRiGA mmMAGIC line-of-sight, 256 BS-antennas, 32 UEs with $\pm$3dB power control, 16-QAM, 4-bit ADCs, single jammer with 25dB higher power than the average UE

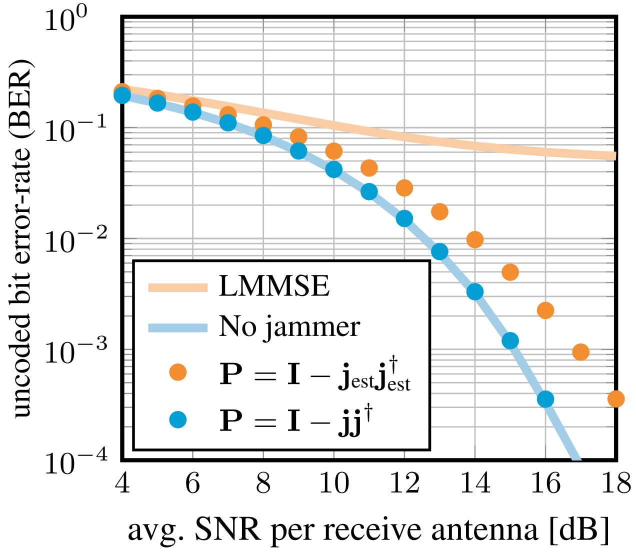
Cluster size is $S = 64$, both for HERMIT and for SNIPS

Part II:
Joint jammer mitigation and data detection

The perils of estimating $\mathbf{j}$

If jammer is constantly transmitting: BS can estimate the jammer channel during a period in which UEs do not transmit





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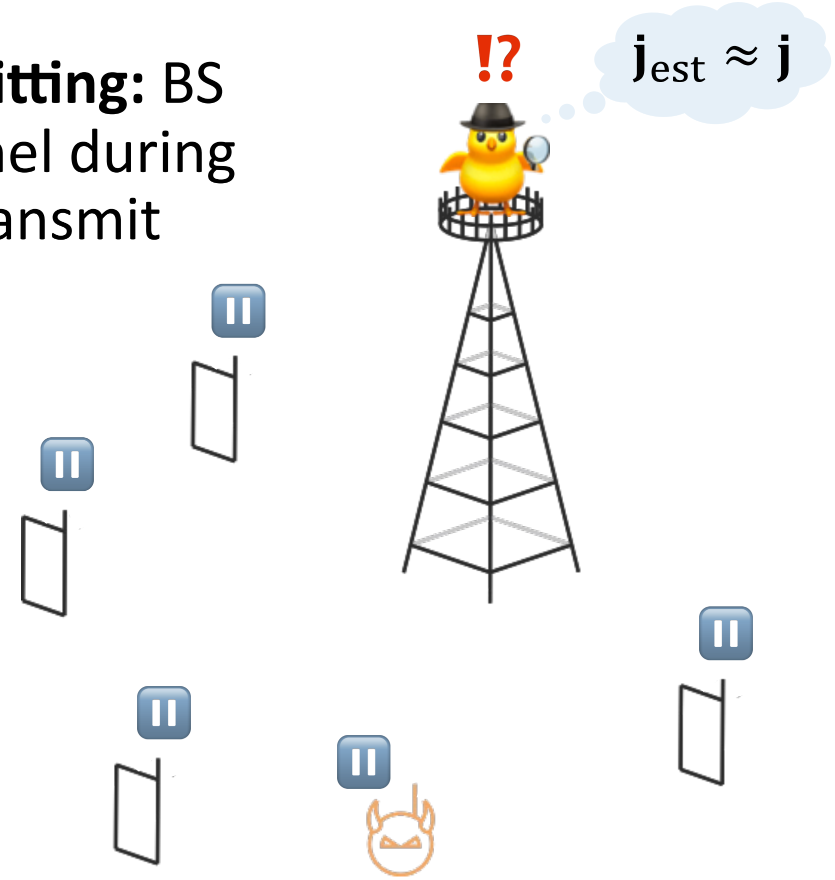
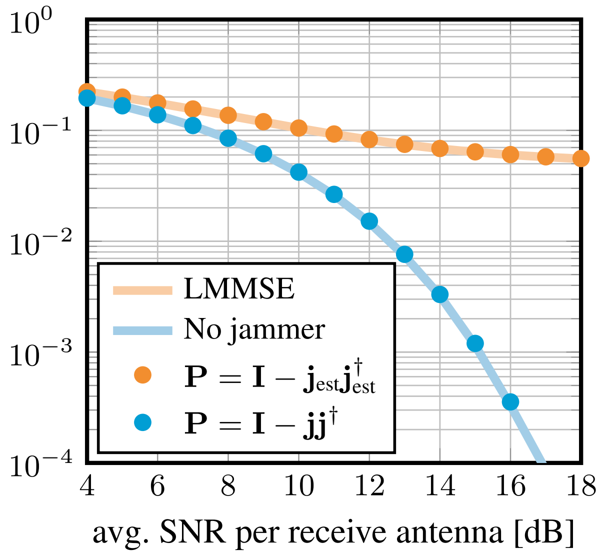
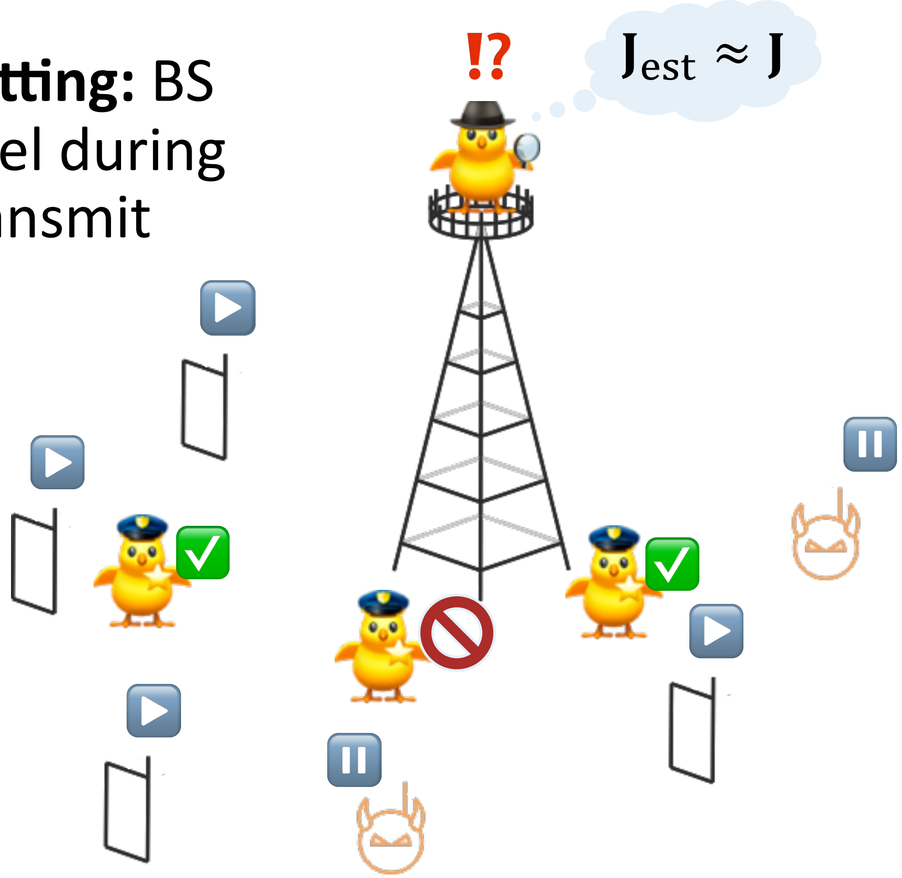




But what if the jammer is smart, and also stops transmitting during that period?

The perils of estimating $\mathbf{j}$ (or $\mathbf{J}$)

If jammer is constantly transmitting: BS can estimate the jammer channel during a period in which UEs do not transmit



Or what if the jammer has multiple antennas, and switches between them at times?

$\mathbf{J} \in \mathbb{C}^{B \times I}$ is now the jammer channel matrix with a total of I jammer antennas

New methods are needed to stop smart jammers

- Estimating the jammer once, and using that knowledge later for mitigation **will not work** against smart and dynamic jammers

- **Idea: Joint jammer mitigation and data detection (JMD):**
  The jammer cannot leave its subspace within a coherence interval
  Estimate and mitigate the jammer **jointly** with detecting the UE data over many timeslots
  The jammer subspace is identified with the subspace that is not explainable in terms of UE transmit signals, and removed with an orthogonal projection

- Mathematically, solve

$$\underset{\substack{\tilde{\mathbf{S}}_D \in \mathcal{S}^{U\times D} \\ \tilde{\mathbf{P}} \in \mathcal{G}_{B-I}(\mathbb{C}^B)}}{\text{minimize}} \left\| \tilde{\mathbf{P}}\left(\mathbf{Y}_D - \mathbf{H}\tilde{\mathbf{S}}_D\right)\right\|_F^2$$

$\mathbf{Y}_D \in \mathbb{C}^{B\times D}$ is the receive signal, $\tilde{\mathbf{S}}_D$ is the transmit data estimate, and $\tilde{\mathbf{P}}$ is an orthogonal projection onto a $(B-I)$-dimensional subspace ($\mathcal{G}_{B-I}(\mathbb{C}^B)$ is the Grassmannian manifold)

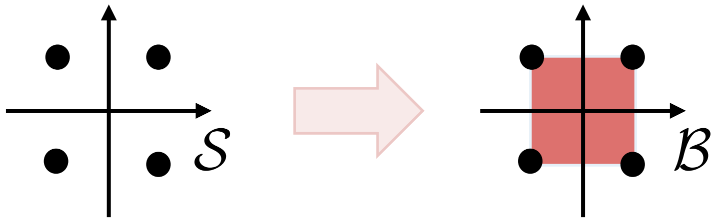
JMD: Joint jammer mitigation and data detection

$$\underset{\substack{\tilde{\mathbf{S}}_D \in \mathcal{S}^{U \times D} \\ \tilde{\mathbf{P}} \in \mathcal{G}_{B-I}(\mathbb{C}^B)}}{\text{minimize}} \left\| \tilde{\mathbf{P}}\left(\mathbf{Y}_D - \mathbf{H}\tilde{\mathbf{S}}_D\right) \right\|_F^2$$

- Like any problem worth solving, this problem is NP hard 😢

  → Luckily, approximate is good enough 🥲

- Relax domain of data symbol estimates $\tilde{\mathbf{S}}_D$ to convex hull:



- Solve with an alternating minimization strategy
  - Relaxed problem is convex in $\tilde{\mathbf{S}}_D$ (for fixed $\tilde{\mathbf{P}}$)
  - The $\tilde{\mathbf{P}}$ sub-problem has closed-form solution (for fixed $\tilde{\mathbf{S}}_D$): $\hat{\mathbf{P}} = \mathbf{I}_B - \mathbf{U}_I \mathbf{U}_I^H$ where are the dominant I left-singular vectors of $\mathbf{Y}_D - \mathbf{H}\tilde{\mathbf{S}}_D$

The problem of not knowing $\mathbf{H}$

$$\underset{\substack{\tilde{\mathbf{S}}_D \in \mathcal{S}^{U\times D} \\ \tilde{\mathbf{P}} \in \mathcal{G}_{B-I}(\mathbb{C}^B)}}{\text{minimize}} \left\| \tilde{\mathbf{P}}\left(\mathbf{Y}_D - \mathbf{H}\tilde{\mathbf{S}}_D\right) \right\|_F^2$$

The channel matrix $\mathbf{H}$ is not known a priori

Estimating $\mathbf{H}$ with pilots may lead to a jammer-contaminated estimate $\mathbf{H}_{\text{est}}$. What can we do?

1) Estimating $\mathbf{H}$ also jointly: $\underset{\substack{\tilde{\mathbf{S}}_D \in \mathcal{S}^{U\times D} \\ \tilde{\mathbf{P}} \in \mathcal{G}_{B-I}(\mathbb{C}^B) \\ \tilde{\mathbf{H}} \in \mathbb{C}^{B\times U}}}{\text{minimize}} \left\| \tilde{\mathbf{P}}\left([\mathbf{Y}_T, \mathbf{Y}_D] - \tilde{\mathbf{H}}[\mathbf{S}_T, \tilde{\mathbf{S}}_D]\right) \right\|_F^2$ → **MAED**

2) When using a linear channel estimator such as least squares (LS), then the jammer contamination of $\mathbf{H}_{\text{est}}$ is also restricted to the jammer subspace: $\mathbf{H}_{\text{est}} \approx \mathbf{H} + \mathbf{J}\mathbf{W}$
→ the optimal projector $\mathbf{P} = \mathbf{I}_B - \mathbf{J}\mathbf{J}^\dagger$ will also cancel the channel contamination in
$$\left\| \tilde{\mathbf{P}}\left(\mathbf{Y}_D - \mathbf{H}_{\text{est}}\tilde{\mathbf{S}}_D\right) \right\|_F^2$$
→ **SANDMAN**

G. Marti, T. Kölle, CS, “Mitigating Smart Jammers in Multi-User MIMO”, IEEE Trans. Sig. Proc., 2023

G. Marti, CS, “Joint Jammer Mitigation and Data Detection for Smart, Distributed, and Multi-Antenna Jammers”, IEEE Intl. Conf. Commun., 2023

Efficient approximate algorithms: SANDMAN

How to approximately solve $\underset{\substack{\tilde{\mathbf{S}}_D \in \mathcal{S}^{U\times D} \\ \widetilde{\mathbf{P}} \in \mathcal{G}_{B-I}(\mathbb{C}^B)}}{\text{minimize}} \left\| \widetilde{\mathbf{P}}\left(\mathbf{Y}_D - \mathbf{H}_{\text{est}}\tilde{\mathbf{S}}_D\right)\right\|_F^2$?

Alternate a forward-backward-splitting step in $\tilde{\mathbf{S}}_D$:

$$\tilde{\mathbf{S}}_D^{(t+1)} = \text{prox}_g\left(\tilde{\mathbf{S}}_D^{(t)} - \tau^{(t)}\nabla f\left(\tilde{\mathbf{S}}_D^{(t)}\right); \tau^{(t)}\right)$$

$$\nabla f\left(\tilde{\mathbf{S}}_D^{(t)}\right) = -2\mathbf{H}_{\text{est}}^H \widetilde{\mathbf{P}}^{(t)}\left(\mathbf{Y}_D - \mathbf{H}_{\text{est}}\tilde{\mathbf{S}}_D^{(t)}\right)$$

$$\text{prox}_g(\mathbf{Z}) = \text{clip}_{\sqrt{1/2}}(\Re(\mathbf{Z})) + i\ \text{clip}_{\sqrt{1/2}}(\Im(\mathbf{Z}))$$

with an approximate minimization in $\widetilde{\mathbf{P}}$:

$$[\mathbf{U}, \boldsymbol{\Sigma}, \mathbf{V}] = \text{ApproxSVD}\left(\mathbf{Y}_D - \mathbf{H}_{\text{est}}\tilde{\mathbf{S}}_D^{(t)}\right)$$

$$\mathbf{J}_{\text{est}} = \mathbf{U}[:, 1:\mathrm{I}]$$

$$\widetilde{\mathbf{P}}^{(t)} = \mathbf{I}_B - \mathbf{J}_{\text{est}}\mathbf{J}_{\text{est}}^{\dagger}$$

Algorithm 1 SANDMAN

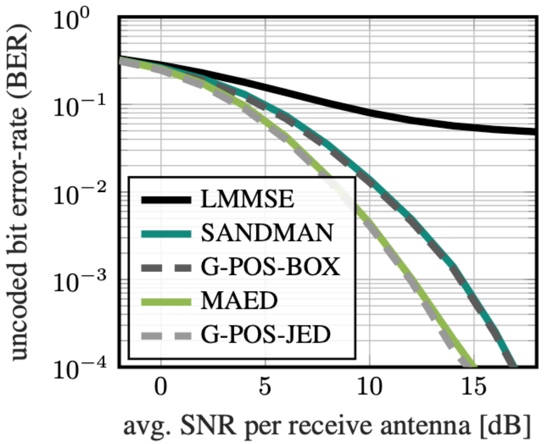
function SANDMAN($\mathbf{Y}_D, \mathbf{Y}_T, \mathbf{S}_T, I, t_{\max}$)
  $\hat{\mathbf{H}} = \mathbf{Y}_T\mathbf{S}_T^{\mathrm{H}}$
  $\tilde{\mathbf{S}}^{(0)} = \mathbf{0}_{U\times D}$
  for $t = 0$ **to** $t_{\max} - 1$ **do**
    $\tilde{\mathbf{E}}^{(t)} = [\mathbf{Y}_T, \mathbf{Y}_D] - \hat{\mathbf{H}}[\mathbf{S}_T, \tilde{\mathbf{S}}^{(t)}]$
    $\tilde{\mathbf{J}}^{(t)} = \text{APPROXSVD}(\tilde{\mathbf{E}}^{(t)}, I)$
    $\tilde{\mathbf{P}}^{(t)} = \mathbf{I}_B - \tilde{\mathbf{J}}^{(t)}(\tilde{\mathbf{J}}^{(t)})^{\dagger}$
    $\nabla f(\tilde{\mathbf{S}}^{(t)}) = -2\,\hat{\mathbf{H}}^{\mathrm{H}}\tilde{\mathbf{P}}^{(t)}(\mathbf{Y}_D - \hat{\mathbf{H}}\tilde{\mathbf{S}}^{(t)})$
    $\tilde{\mathbf{S}}^{(t+1)} = \text{prox}_g(\tilde{\mathbf{S}}^{(t)} - \tau^{(t)}\nabla f(\tilde{\mathbf{S}}^{(t)}); \tau^{(t)})$
  end for
  output: $\tilde{\mathbf{S}}^{(t_{\max})}$
end function

Results: Smart single-antenna jammers

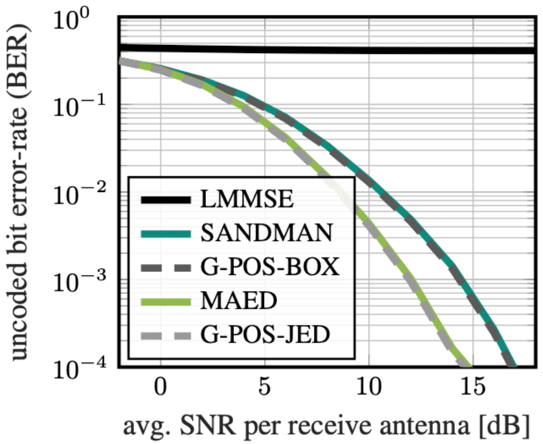
Setup

QuaDRiGA 3GPP 38.901 UMa channel model, 32 BS-antennas, 16 UEs, QPSK

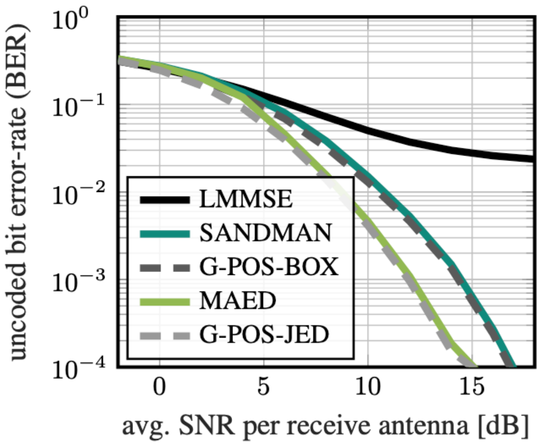
The jammers jam with 30dB more energy than the average UE



Jammer jams permanently (barrage)



Jammer only jams during the data phase

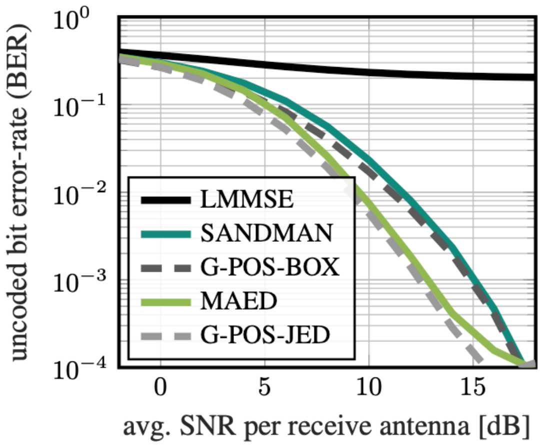


Jammer only jams during the pilot phase

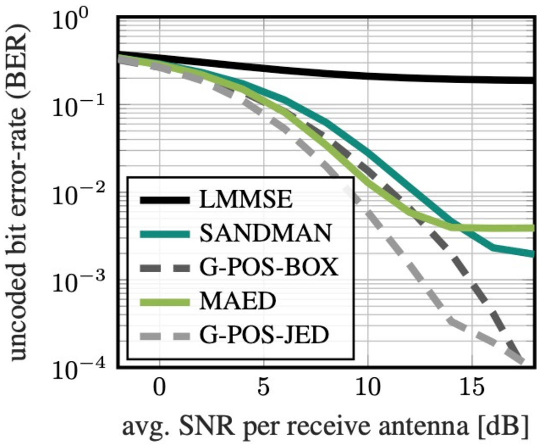
Results: Multi-antenna jammers

Setup

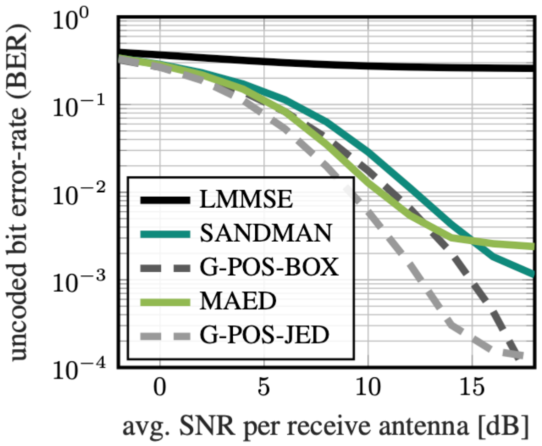
QuaDRiGA 3GPP 38.901 UMa channel model, 32 BS-antennas, 16 UEs, QPSK
The jammers jam with 30dB more energy than the average UE



4 distributed single-antenna barrage jammers



4-antenna jammer that dynamically turns antennas on and off



4-antenna jammer that dynamically modulates between different rank-1 subspaces

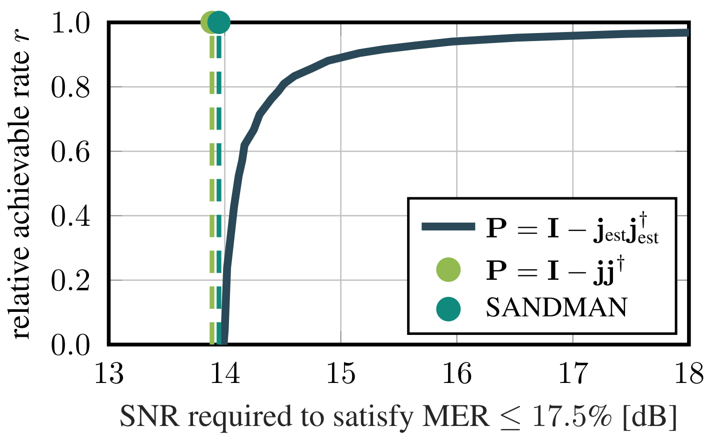
Results: Rate Savings

JMD also has the advantage that it removes the need for a jammer training-period, during which no data can be transmitted

This observation increases achievable rates

Setup
QuaDRiGA 3GPP 38.901 UMa channel, 32 BS-antennas, 16 UEs, QPSK, coherence time K=100
Single-antenna barrage jammer with 30 dB more power than the average UE

Consider smallest SNR at which $\mathrm{MER} = \frac{\mathbb{E}\left[\|\hat{\mathbf{S}}_D - \mathbf{S}_D\|_F\right]}{\mathbb{E}\left[\|\mathbf{S}_D\|_F\right]} \leq 17.5\%$



Summary, Conclusions, and Outlook

Summary and conclusions

Jammers threaten critical communication infrastructure and must be mitigated!

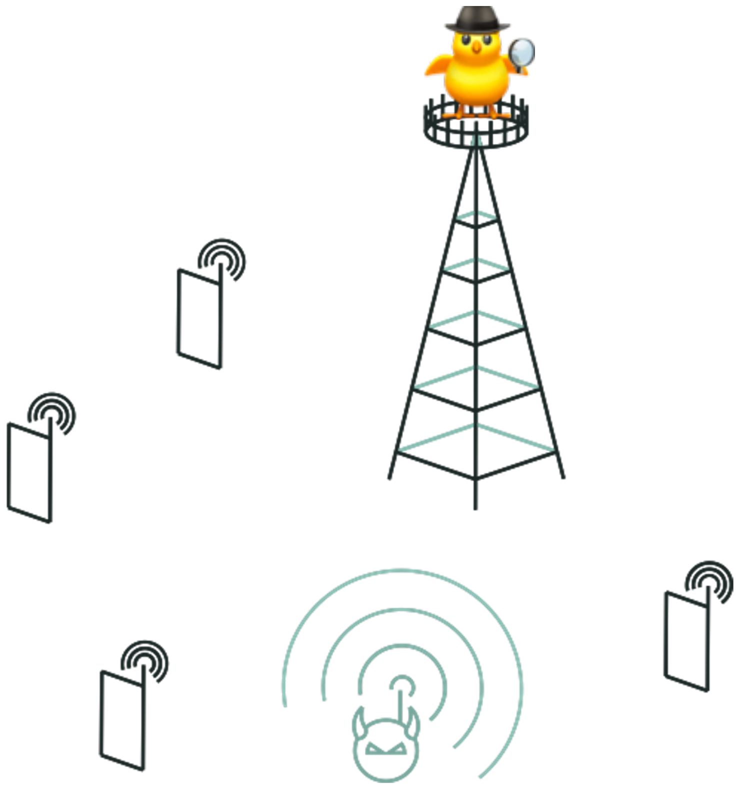
Jammers must be mitigated prior to data conversion:

- SNIPS ✂️ – nonadaptive analog transform prior to ADC
- HERMIT 🦀 – adaptive analog transform prior to ADC

Smart jammers may evade jammer channel estimation

Joint jammer estimation and data detection (JMD) to the rescue:

- SANDMAN and MAED can mitigate smart or reactive jammers



More results and future research

- SANDMAN is real!
- Universal jammer mitigation is possible with MASH [1]
- What happens to jammed MIMO-OFDM? [2]

- How to synchronize in presence of jamming?
- How to deal with jammers at UE side?

- **More information at iip.ethz.ch**

[1] G. Marti and CS, “Universal MIMO Jammer Mitigation via Secret Temporal Subspace Embeddings”, Asilomar, 2023

[2] G. Marti and CS, “Single-Antenna Jammers in MIMO-OFDM can Resemble Multi-Antenna Jammers”, IEEE Comm. Let., 2023

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