Friedrich-Alexander-Universität
Erlangen-Nürnberg

Hybrid Precoding for Secure Transmission in Reflect-Array-Assisted Massive MIMO Systems

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Saba Asaad, Rafael F. Schaefer and H. Vincent Poor

Friedrich-Alexander Universität Erlangen-Nürnberg
Technische Universität Berlin
Princeton University

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Hybrid Architectures

- *Millimeter Wave Communications*
  - Key technology for next generation wireless networks
  - Support higher data rates by exploiting unused available spectrum
  - Packing a large number of antennas into small physical dimensions

Challenge in fully-digital architectures:

Separate RF chain for each antenna is impractical!

Solution:

Use hybrid analog-digital architectures assisted by reflect-arrays

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Reflect Arrays

RAs are passive meta-surfaces composed of a large set of reflecting units

- Example: Intelligent Reflecting Surfaces

Why RAs?

- Easily deployed in indoor spaces
- Capable of enhancing the signal quality
  - *Coverage*
  - *Energy-efficiency*
  - *Interference cancellation*
  - *Provide promising secrecy opportunity*

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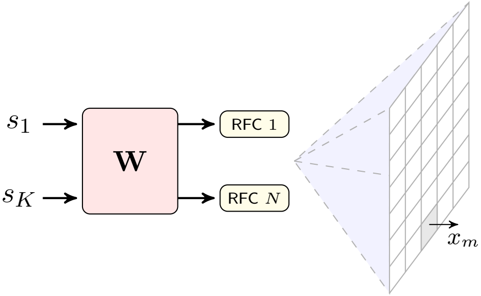
Hybrid Architecture via Reflect Arrays

Recently proposed RA-assisted hybrid analog-digital transmitter



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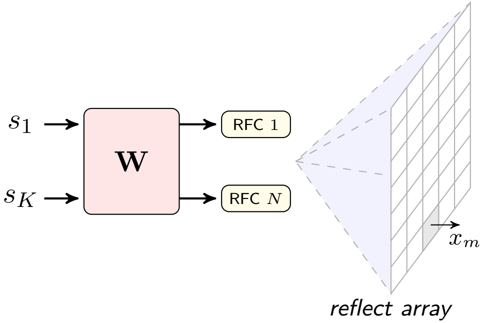

- *Linear digital precoding*

$$\boldsymbol{x}_{\mathrm{BB}} = \sum_{k=1}^{K} s_k \mathbf{w}_k$$

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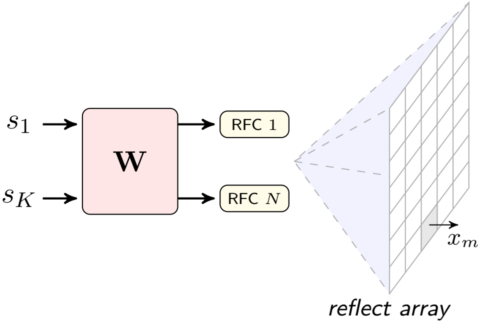

- $\boldsymbol{x}_{\mathrm{BB}}$ is radiated towards the RA

$$\mathbf{r} = \mathbf{T}\boldsymbol{x}_{\mathrm{BB}}$$

$\mathbf{T}$ has been determined explicitly

Hybrid Architecture via Reflect Arrays

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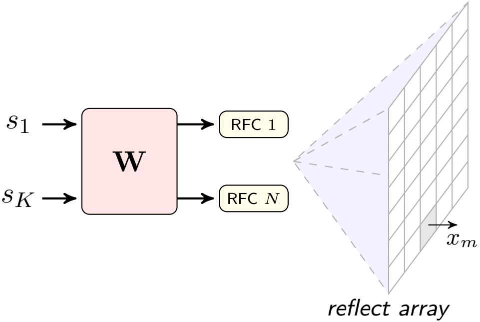
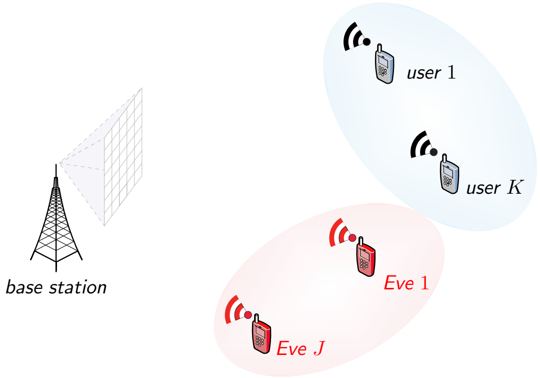


- $\mathbf{r}$ is phase-shifted and reflected

$$\boldsymbol{x} = \mathbf{D}\mathbf{r}$$

$$\mathbf{D} = \mathrm{diag}\left(\exp\left\{\mathrm{j}\phi_1\right\}, \ldots, \exp\left\{\mathrm{j}\phi_M\right\}\right)$$

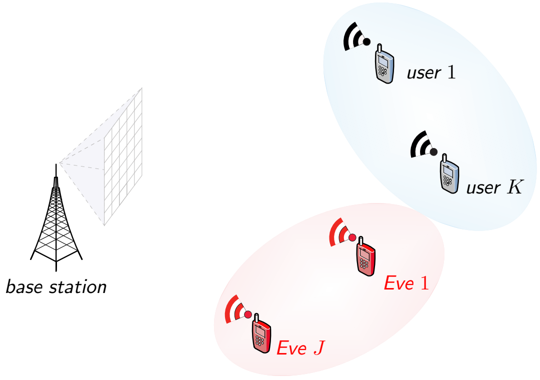
System Model



A MIMO wiretap setting is considered

- RA-assisted transmitter with N RFCs and M antennas
- K legitimate users and J eavesdroppers

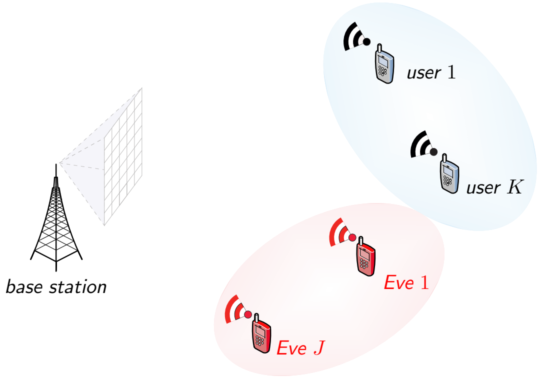
System Model



Signal received at the legitimate user k

$$y_k = \mathbf{h}_k^{\mathsf{T}} \boldsymbol{x} + v_k$$

System Model



Signal received by eavesdropper j

$$z_j = \mathbf{g}_j^{\mathsf{T}} \boldsymbol{x} + u_j$$

Main Objective

Remember that the transmit signal is of the form

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Downlink beamforming is performed by $\mathbf{W}$ *and* $\mathbf{D}$

Objective: *Design* $\mathbf{W}$ *and* $\mathbf{D}$ *to enhance secrecy performance*

Downlink Beamforming via Secure RZF

Alternative formulation for regularized zero forcing

- For fixed $\mathbf{D}$, let $\mathbf{H}_0 = [\mathbf{h}_1, \dots, \mathbf{h}_K]^\mathsf{T} \mathbf{D}\mathbf{T}$

$$\mathbf{W} = \mathbf{H}_0^\mathsf{H} \left(\mathbf{H}_0 \mathbf{H}_0^\mathsf{H} + \lambda \mathbf{I}_K \right)^{-1}$$

$$= \operatorname*{argmin}_{\mathbf{V} \in \mathbb{C}^{N \times K}} \| \mathbf{H}_0 \mathbf{V} - \mathbf{I}_K \|_F^2 + \lambda \| \mathbf{V} \|_F^2$$

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- We modify RZF by further constraining *information leakage*
  - Let $\mathbf{G}_0 = [\mathbf{g}_1, \dots, \mathbf{g}_J]^{\mathsf{T}} \mathbf{DT}$, we enforce $\mathbf{W}$ satisfy

$$\|\mathbf{G}_0 \mathbf{W}\|_F^2 \leq \epsilon$$

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Secure RZF finally reads

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$$= \left(\mathbf{H}_0^{\mathsf{H}}\mathbf{H}_0 + \tau\mathbf{G}_0^{\mathsf{H}}\mathbf{G}_0 + \lambda\mathbf{I}_N\right)^{-1}\mathbf{H}_0$$

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Remember that $\mathbf{W}$ is given for a fixed $\mathbf{D}$!

Tuning Phase-Shifts at RA

For fixed $\mathbf{W}$*, phase shifts can be effectively tuned as*

$$\mathbf{D} = \underset{\mathbf{D}}{\operatorname{argmin}} \| [\mathbf{h}_1, \ldots, \mathbf{h}_K]^\mathsf{T} \mathbf{DTW} - \mathbf{I}_K \|_F^2 + \tau \| [\mathbf{g}_1, \ldots, \mathbf{g}_J]^\mathsf{T} \mathbf{DTW} \|_F^2$$

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Our sub-optimal approach:

- Relax the constraint

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- Start with $\mathbf{D}_0$
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Numerical Results: *Setting*

- *RA-assisted hybrid transmitter with*
  - $N = 16$ RF-chains, RA of size $M = 64$ and $\lambda = 5$ mm
  - RF-chains are located on a ring of radius λ
  - Distance from RA to the ring is set to $4\lambda/\sqrt{\pi}$
- *Rayleigh fading channels with unit variance*
- *Digital precoder is scaled such that transmit power be P*
- *Noise variance at legitimate users and eavesdroppers is σ^2 and ρ^2*
- *Phase-shifts at the RA are quantized by 4 bits*

Numerical Result: *Performance Metrics*

- *Achievable secrecy sum-rate*

$$R_{\text{sum}}^{\text{sec}} = \sum_{k=1}^{K} \left[\log \left(\frac{1 + \text{SINR}_k}{1 + \text{ESNR}_k} \right) \right]^+$$

  - SINR_k is SINR at user k
  - ESNR_k is aggregated eavesdropper SNR when user k is overheard

Numerical Results

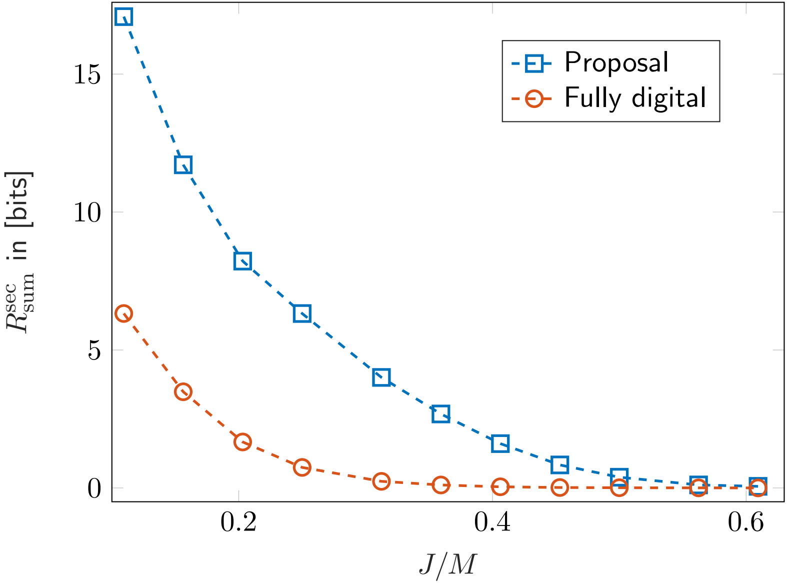
We consider two scenarios

- The RA-assisted hybrid architecture
- Fully digital transmitter with MRT beamforming

while setting

- $K = 8$ legitimate users
- $\log\left(P/\sigma^2\right) = \log\left(P/\rho^2\right) = 13$ dB

Further numerical results are given in the paper


15
10
5
0
0.2
0.4
0.6
$R_{\mathrm{sum}}^{\mathrm{sec}}$ in [bits]
J/M
Proposal
Fully digital

Final Remarks

- *Secure downlink beamforming via RA-assisted hybrid architectures*
  - Secure RZF digital precoder
  - Analog beamforming via convex optimization
  - Joint design via alternating optimization
  - Numerical results support efficiency of the design
- *Future work*
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