MIMO physical layer security using multiple Reconfigurable Intelligent Surfaces

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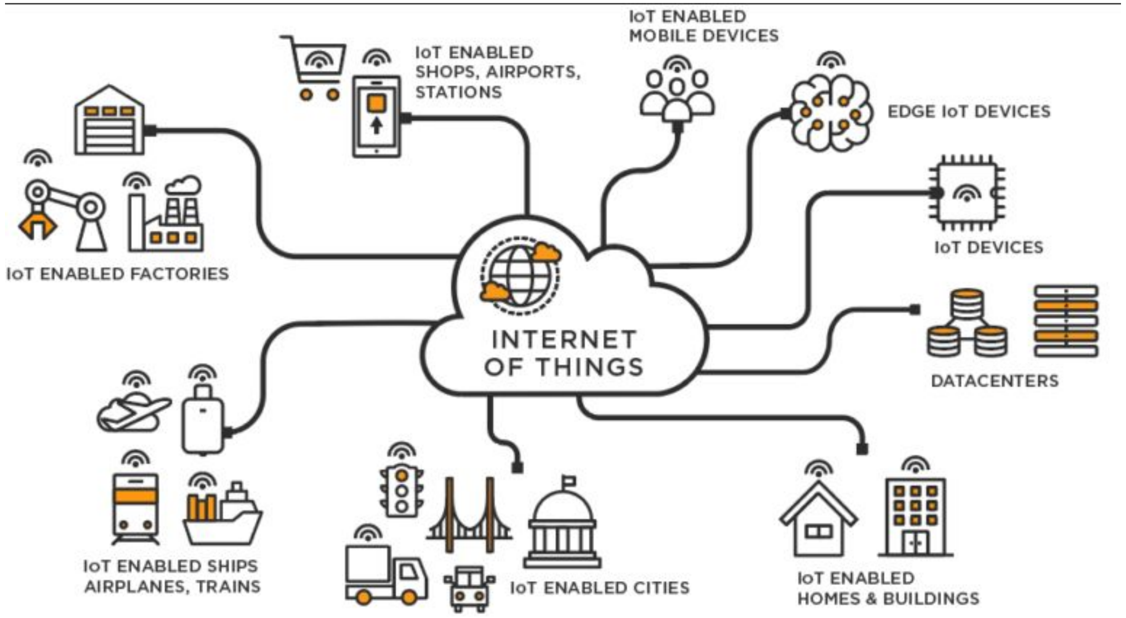
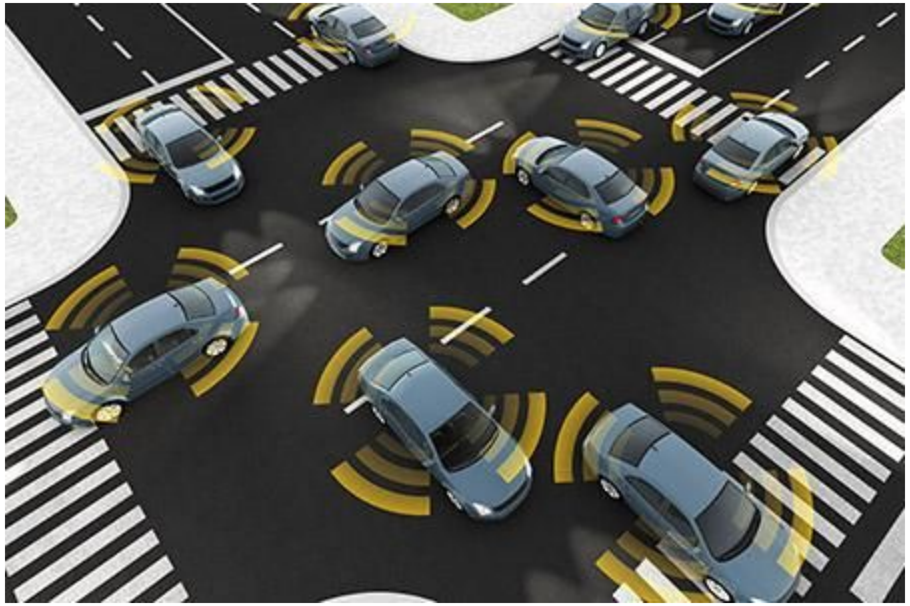
MANTA
Mobile Adaptive and Pervasive Network Communications

UNIVERSITÀ DI TRENTO

Background and motivation



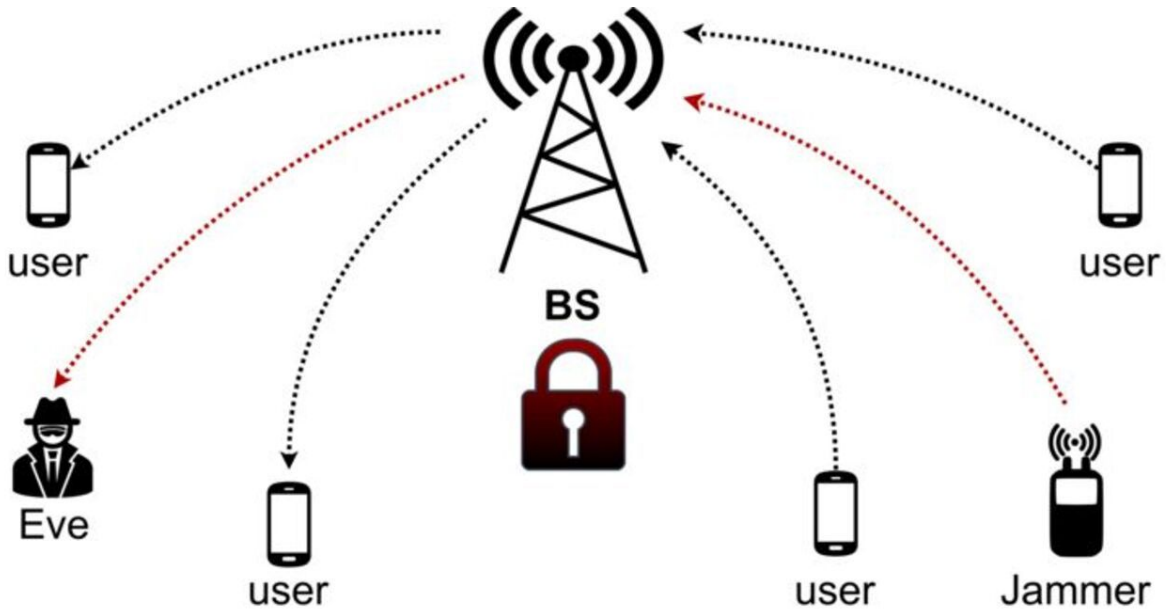
https://businesstech.bus.umich.edu/uncategorized/tech-101-internet-of-things/



https://www.itf-oecd.org/co-operative-mobility-systems-automated-driving-roundtable

- Our lives depend more and more on various devices
- They need to communicate fast, reliably and securely with each other
- These requirements cannot be mutually exclusive anymore

Physical Layer Security

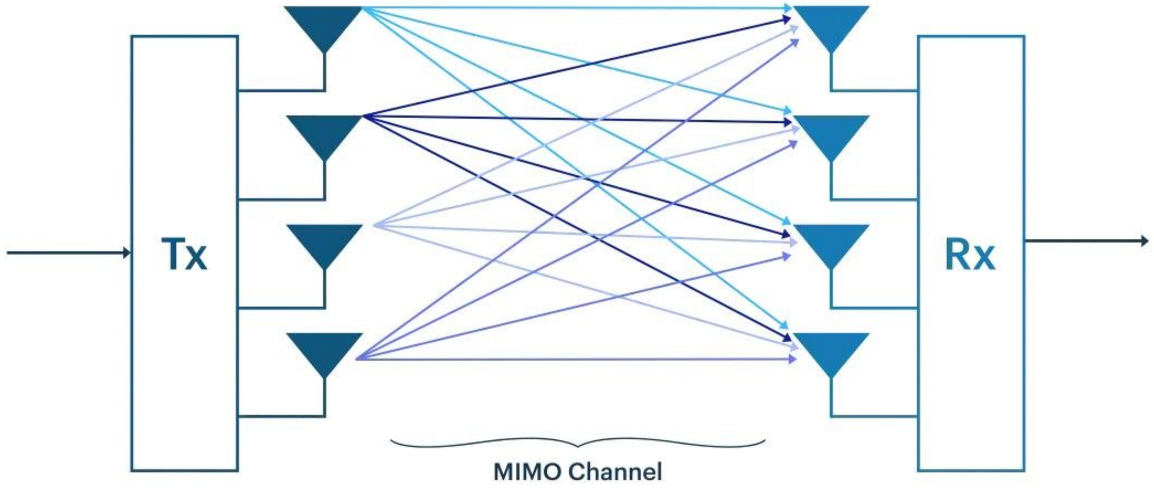


https://liu.se/en/research/physical-layer-security-in-massive-mimo

https://quantumai.google/discover/whatisqc

- With our lives depending more and more on technology, we need to be protected from malicious actors that may hear or disrupt our communications
- Quantum computing could break encryption
- We need new, low latency security schemes

Multiple Input Multiple Output (MIMO)



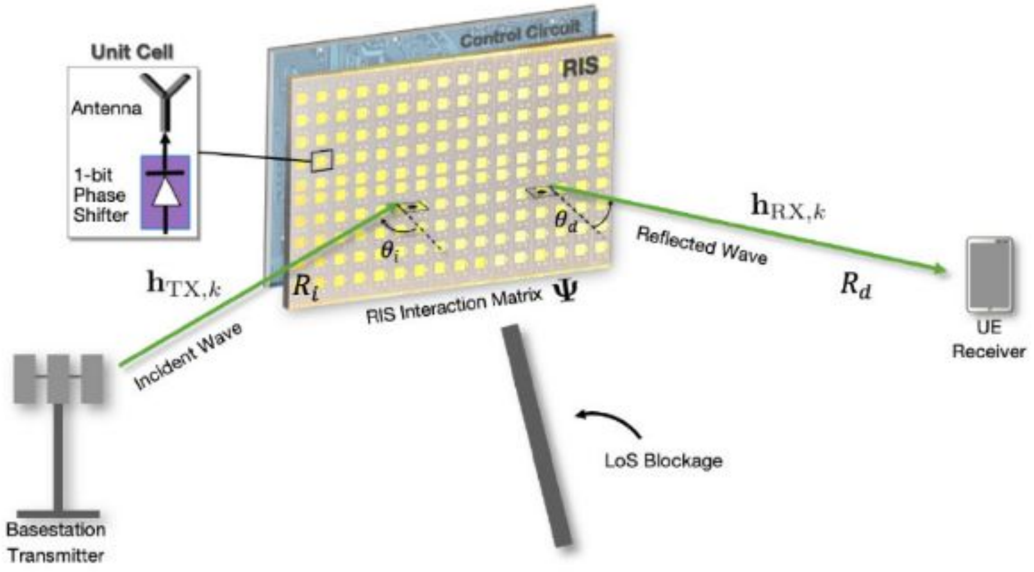
https://www.linkedin.com/pulse/enhancing-wireless-communication-mimo-technology-cavliwireless-wzooe/

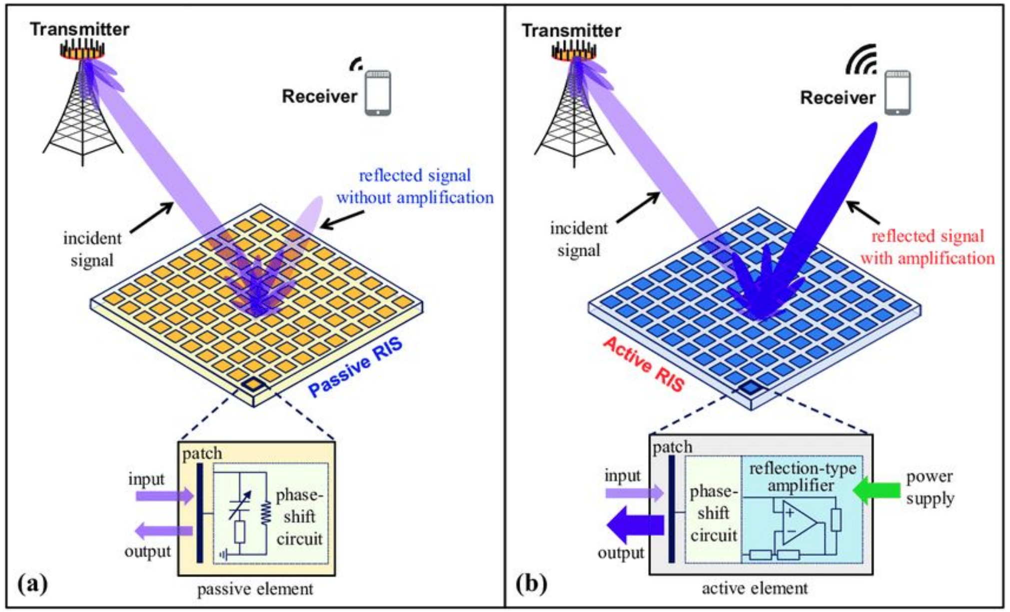
$$\boldsymbol{B} = \begin{bmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1K} \\ \beta_{21} & \beta_{22} & \cdots & \beta_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{K1} & \beta_{K2} & \cdots & \beta_{KK} \end{bmatrix} \in \mathbb{C}^{K \times K}$$

$$y = \boldsymbol{B}x = \begin{bmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1K} \\ \beta_{21} & \beta_{22} & \cdots & \beta_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{K1} & \beta_{K2} & \cdots & \beta_{KK} \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \\ \vdots \\ \xi_K \end{bmatrix} = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_K \end{bmatrix} \in \mathbb{C}^K$$

- We can use multiple antennas to communicate
- The signals from each transmitter antenna to each receiver antenna form a matrix of complex numbers, the *channel gain matrix*
- The received total signal at the receiver is the transmitter signal multiplied by the transmitted signal

Reconfigurable Intelligent Surfaces (RISs)



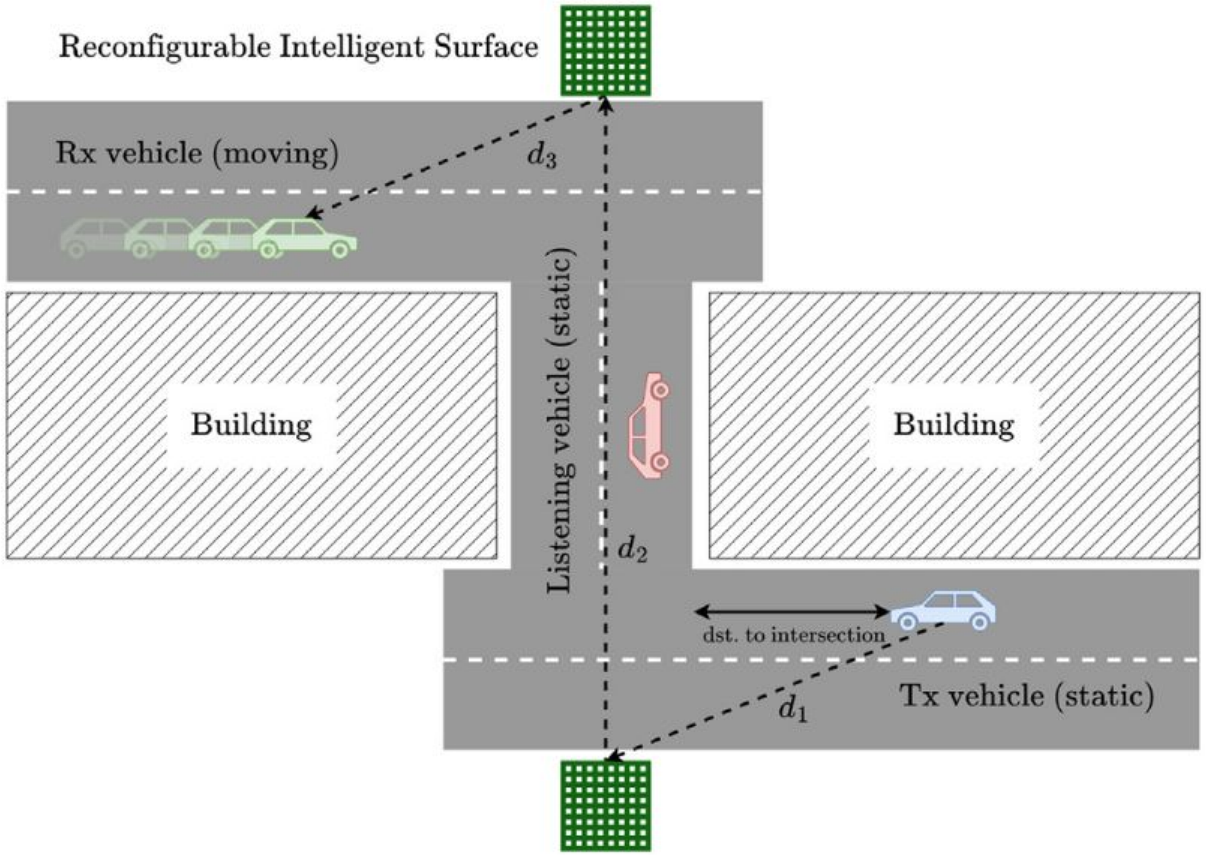


https://www.researchgate.net/figure/Comparison-between-the-existing-passive-RIS-a-and-the-proposed-active-RIS-b_fig1_350484632

- RISs are a promising technology that can help us expand the signal reach
- We can modulate the reflection to better suit our needs
- They can be either passive or active

G. C. Trichopoulos *et al*., "Design and Evaluation of Reconfigurable Intelligent Surfaces in Real-World Environment,"

Using RISs for physical layer security



(b) Z-intersection scenario

- Our objective is to find a way to hide our signal in NLoS scenarios, using the same RISs we use for actors to communicate
- This is crucial in crossroads used by cooperative autonomous vehicles

Michele Segata, Paolo Casari, Marios Lestas, Alexandros Papadopoulos, Dimitrios Tyrovolas, Taqwa Saeed, George Karagiannidis, Christos Liaskos, CoopeRIS: A framework for the simulation of reconfigurable intelligent surfaces in cooperative driving environments,

Space Shift Keying (SSK) Modulation

$\mathbf{b} = [b_1 \quad b_2]$	symbol	antenna index j	$\mathbf{x} = [x_1 \quad \cdots \quad x_4]^T$
$[0 \quad 0]$	0	1	$[1 \quad 0 \quad 0 \quad 0]^T$
$[0 \quad 1]$	1	2	$[0 \quad 1 \quad 0 \quad 0]^T$
$[1 \quad 0]$	2	3	$[0 \quad 0 \quad 1 \quad 0]^T$
$[1 \quad 1]$	3	4	$[0 \quad 0 \quad 0 \quad 1]^T$

$$j = \arg\max_j \; p_y(y|x_j, \boldsymbol{B}) = \arg\min_j \; ||y - b_j||^2$$

$$y = \boldsymbol{B}x = \begin{bmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1K} \\ \beta_{21} & \beta_{22} & \cdots & \beta_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{K1} & \beta_{K2} & \cdots & \beta_{KK} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} \beta_{11} \\ \beta_{12} \\ \vdots \\ \beta_{1K} \end{bmatrix}$$

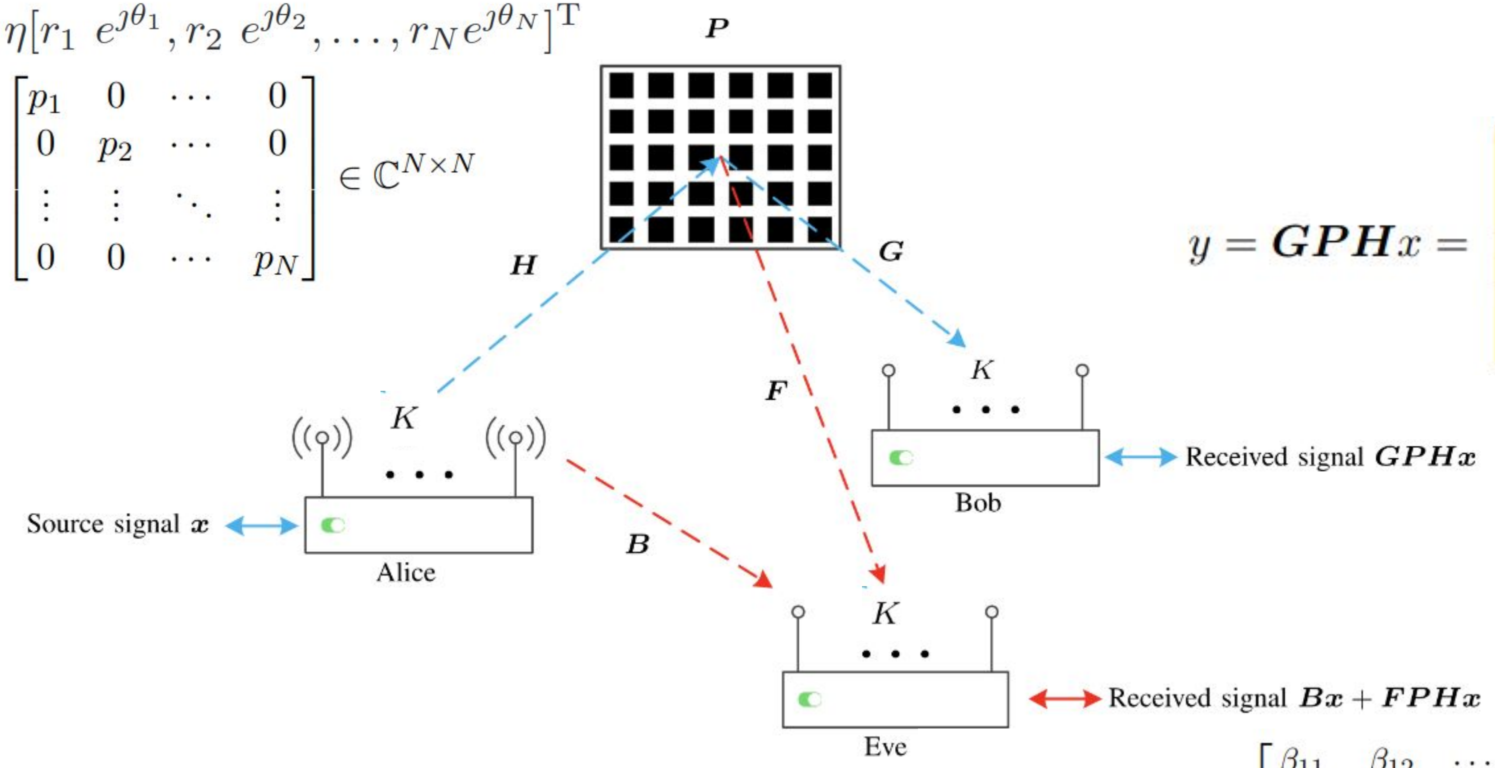
- Communicate using the antenna index
- Resistant to noise and signal variations
- More complex schemes exist to use multiple antennas at the same time

J. Jeganathan, A. Ghrayeb, L. Szczecinski and A. Ceron,
"Space shift keying modulation for MIMO channels,"

Reference scenario

$$\boldsymbol{p} = \eta[r_1\ e^{\jmath\theta_1}, r_2\ e^{\jmath\theta_2}, \ldots, r_N e^{\jmath\theta_N}]^{\mathrm{T}}$$

$$\boldsymbol{P} = \begin{bmatrix} p_1 & 0 & \cdots & 0 \\ 0 & p_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & p_N \end{bmatrix} \in \mathbb{C}^{N\times N}$$



$$j = \arg\max_j\ y_j$$

$$y = \boldsymbol{GPH}x = \begin{bmatrix} \alpha_{11} & 0 & \cdots & 0 \\ 0 & \alpha_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \alpha_{KK} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} \alpha_{11} \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

$$y = \boldsymbol{B}x + \boldsymbol{FPH}x = \begin{bmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1K} \\ \beta_{21} & \beta_{22} & \cdots & \beta_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{K1} & \beta_{K2} & \cdots & \beta_{KK} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} + \begin{bmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1K} \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{K1} & \gamma_{K2} & \cdots & \gamma_{KK} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_K \end{bmatrix}$$

J. Luo, F. Wang, S. Wang, H. Wang and D. Wang,
"Reconfigurable Intelligent Surface: Reflection Design Against Passive Eavesdropping,"

RIS parametrization

https://ieeexplore.ieee.org/document/9328149

$$||\boldsymbol{GPH} - [\boldsymbol{GPH}]_{diag}||^2 = 0$$

$$\boldsymbol{W} = \sum_{i,k=1,i\neq k}^{K} (g_k \odot h_i^T)^H (g_k \odot h_i^T)$$

$$\boldsymbol{W} p = 0$$

$$\boldsymbol{W} = \boldsymbol{R\Sigma V}^H$$

$$N(\boldsymbol{W}^H) = [r_{N-K(K-1)}, \cdots, r_N] = \boldsymbol{U}$$

$$p = \frac{\eta \boldsymbol{U} q}{\max(|\boldsymbol{U} q|)}$$

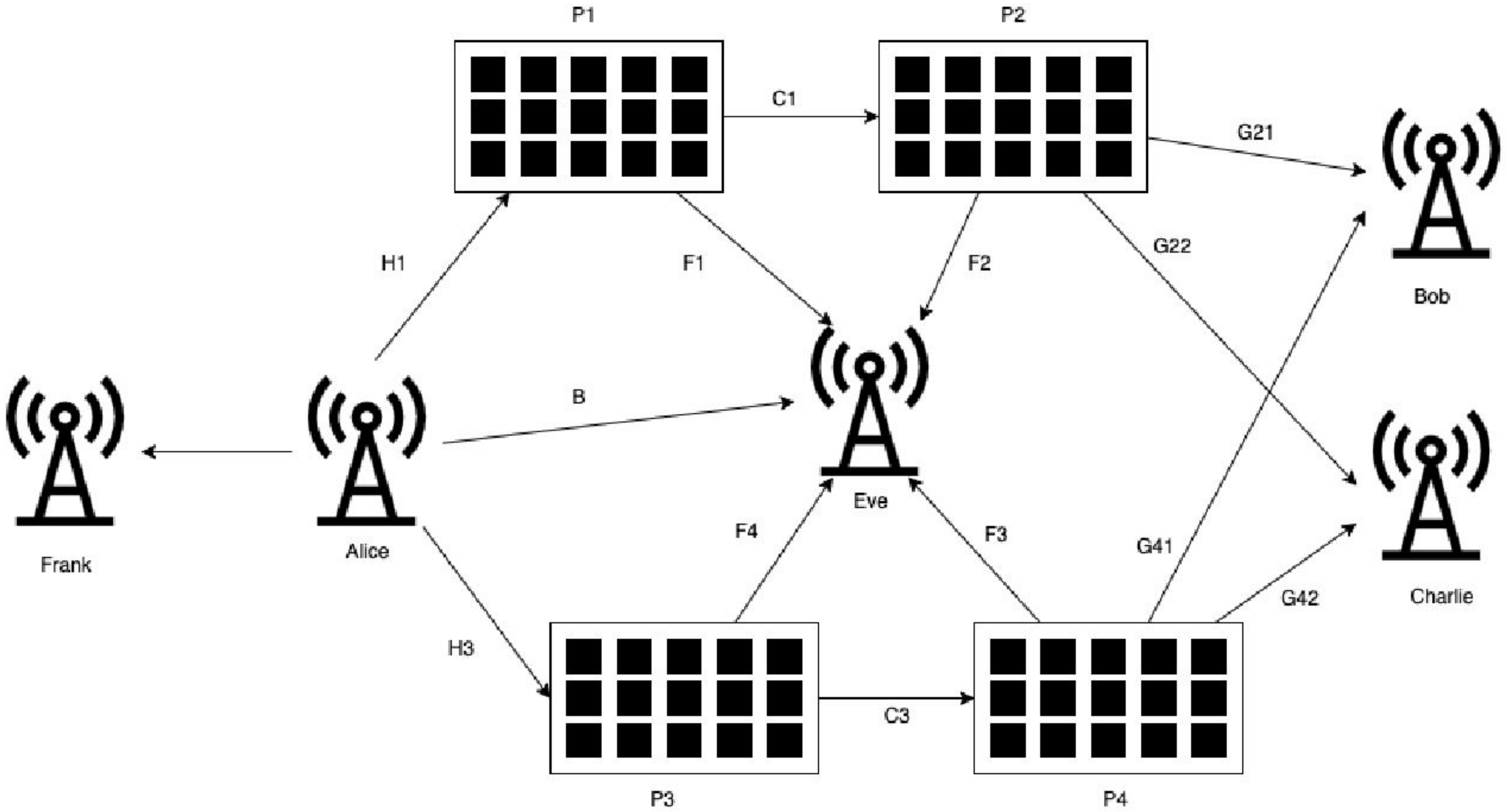
- The idea is finding a RIS vector to satisfy our condition
- By analyzing the null space of ***W***, we have a family of solutions in the last N-K(K-1) columns of ***R***
- We can multiply this matrix ***U*** by a random complex vector *q* to get the RIS configuration
- We are now able to communicate between two stationary antennas

J. Luo, F. Wang, S. Wang, H. Wang and D. Wang,
"Reconfigurable Intelligent Surface: Reflection Design Against Passive Eavesdropping,"

Contribution

- Can we send the message to multiple receivers at the same time?
- Can we concatenate multiple RIS together (in series)?
- Can we send the message through multiple paths (in parallel)?
- What are the performance of all these cases?
- Is our framework valid for realistic communications?

Multi-user and multi-RIS scenario



Multi-user and multi-RIS scenario

$$\forall j \in \{1,2,\ldots,J\} \rightarrow ||\boldsymbol{G}_j\boldsymbol{P}\boldsymbol{H} - [\boldsymbol{G}_j\boldsymbol{P}\boldsymbol{H}]_{diag}||^2 = 0$$

$$\forall j \in \{1,2,\ldots,J\} \rightarrow \boldsymbol{W}_j = \sum_{i,k=1,i\neq k}^{K} (g_{j_{k,:}} \odot h_i^T)^H (g_{j_{k,:}} \odot h_i^T)$$

$$\forall j \in \{1,2,\ldots,J\} \rightarrow \boldsymbol{W}_j p = 0$$

$$\begin{bmatrix} \boldsymbol{W}_1 \\ \boldsymbol{W}_2 \\ \ldots \\ \boldsymbol{W}_J \end{bmatrix} p = 0$$

$$\begin{bmatrix} \boldsymbol{W}_1 \\ \boldsymbol{W}_2 \\ \ldots \\ \boldsymbol{W}_J \end{bmatrix} = \boldsymbol{W} \in \mathbb{C}^{JNxN}, \boldsymbol{W} = \boldsymbol{R\Sigma V}^H$$

- By having the condition of using multiple receivers, our matrix ***W*** is not square
- We cannot use ***R*** to find the null space of dimension N anymore
- We can however use the last N-K(K-1) rows of ***V^H***

$$N(\boldsymbol{W}) = \begin{bmatrix} v_{N-K(K-1)}^H \\ \cdots \\ v_N^H \end{bmatrix}^H = \boldsymbol{U}$$

$$p = \frac{\eta \boldsymbol{U} q}{\max(|\boldsymbol{U} q|)}$$

Multi-user and multi-RIS scenario

- *RIS in parallel*

$$\sum_{m=1}^{M} \boldsymbol{G}_j \boldsymbol{P}_m \boldsymbol{H}_m x = (\sum_{m=1}^{M} \boldsymbol{G}_j \boldsymbol{P}_m \boldsymbol{H}_m) x$$

- For RISs in parallel, the sum of multiple diagonal matrices is still a diagonal matrix

- *RIS in series*

$$||\boldsymbol{G}\boldsymbol{P}_1\boldsymbol{C}_1 ... \boldsymbol{P}_M\boldsymbol{H} - [\boldsymbol{G}\boldsymbol{P}_1\boldsymbol{C}_1 ... \boldsymbol{P}_M\boldsymbol{H}]_{diag}||^2 = 0$$

$$\forall m \in [1, M-1] : p_m[i] = \eta r_i e^{j\theta_i}$$

$$\boldsymbol{G}' = \boldsymbol{G}\boldsymbol{P}_1\boldsymbol{C}_1 ... \boldsymbol{P}_{M-1}\boldsymbol{C}_{M-1} \in \mathbb{C}^{K \times N}$$

$$||\boldsymbol{G}'\boldsymbol{P}_M\boldsymbol{H} - [\boldsymbol{G}'\boldsymbol{P}_M\boldsymbol{H}]_{diag}||^2 = 0$$

- For RISs in series, we can setup the first (or last) M-1 RISs randomly, and setup only the last one
- Complex configuration can also be set up

Performance evaluation

- We first make simulations correlating the Bit Error Rate (BER) to the Signal to Noise Ratio (SNR)
- The BER indicates the percentage of wrong bits in a message
- The SNR indicates how strong the noise is in relation to the correct signal
- We will show that for higher SNR, the receiver reception gets clearer, while the eavesdropper error rate remains constant due to the RIS noise

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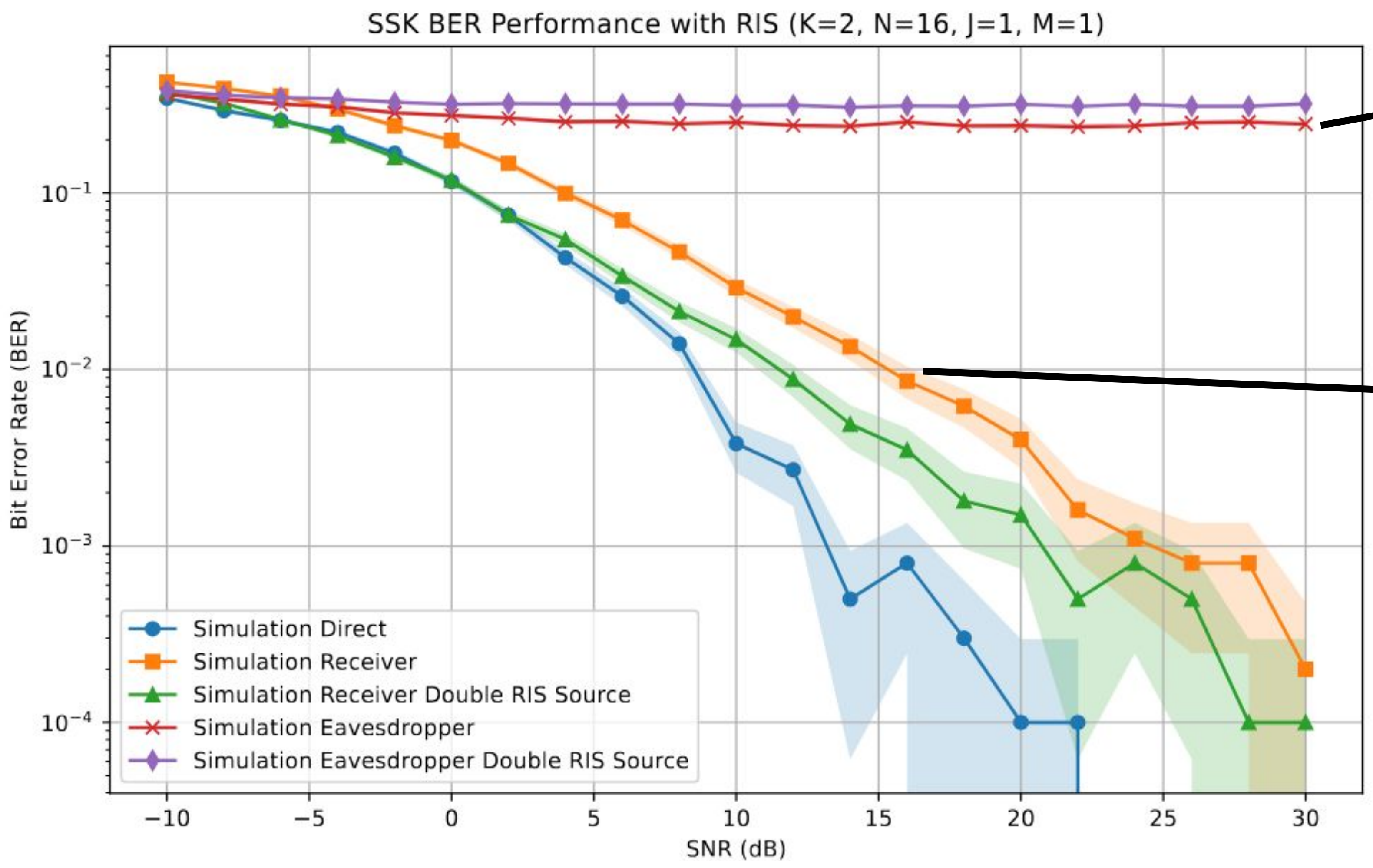
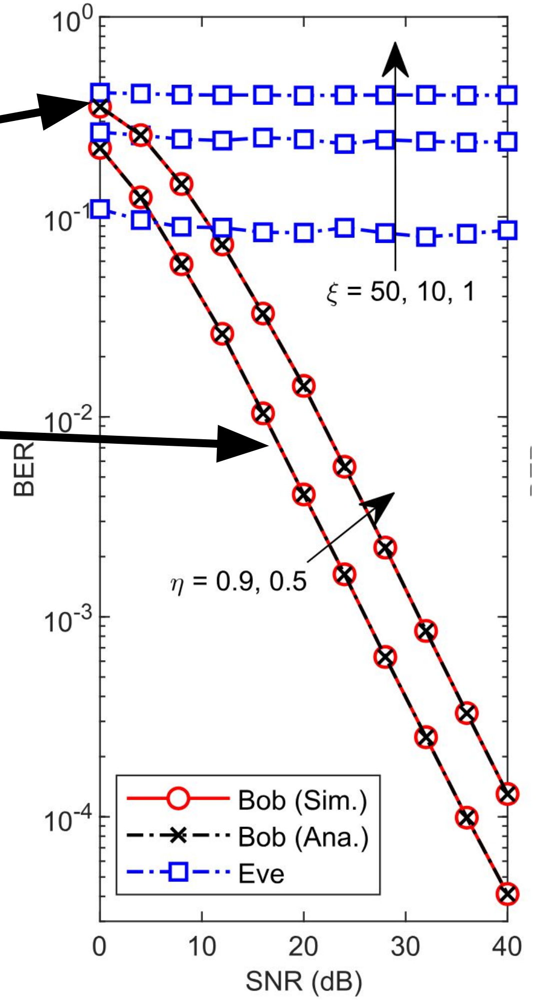
- We will then realistically model the channel gains and the path loss considering the distance between two points
- We will create an heatmap showing for each point the received BER
- We will discuss how the type of the RIS influence the signal received by an eavesdropper

Bit Error Rate (BER) simulations



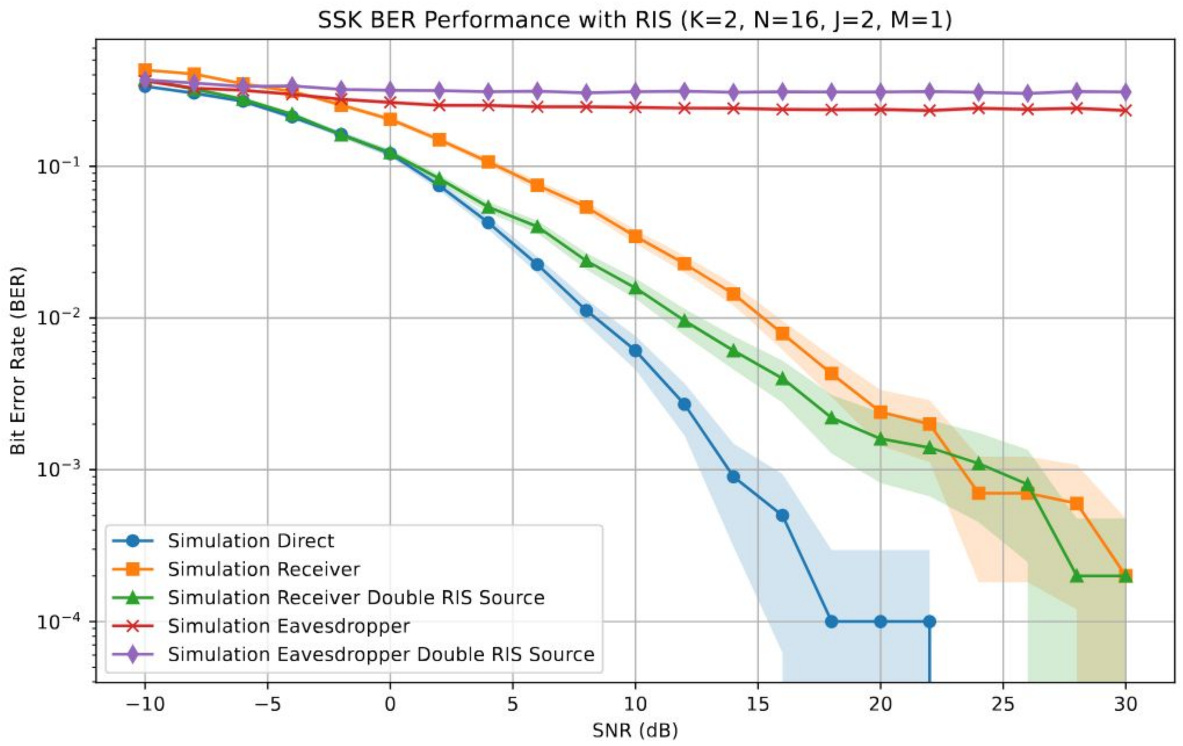


From the reference paper

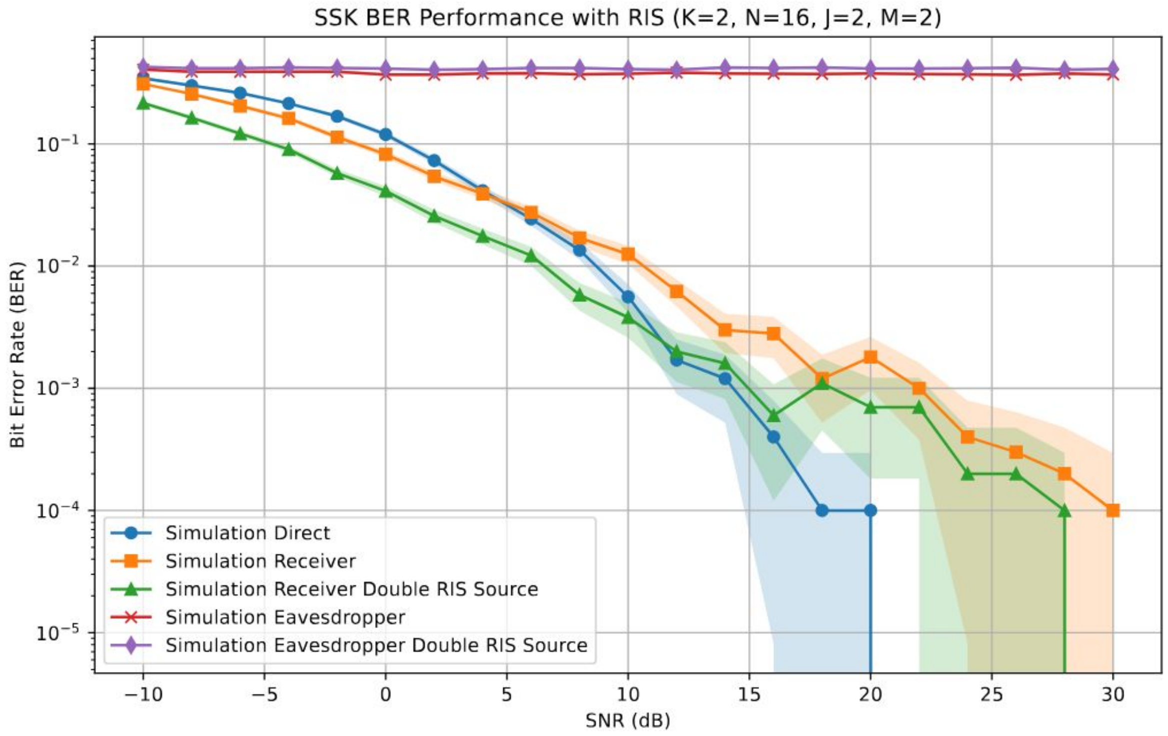
1-2 RIS, 1 users

Bit Error Rate (BER) simulations

1-2 RIS, 2 users



2-4 RIS, 2 users



Realistic channel model

$$\nu^2 = \frac{\tau\xi}{1+\tau} \qquad \sigma^2 = \frac{\xi}{2(1+\tau)} \qquad \Xi \sim C(\tfrac{\nu}{\sqrt{2}}, \sigma)$$

$$e_r(\Omega) = \frac{1}{\sqrt{n_r}} \begin{bmatrix} 1 \\ exp(-j2\pi\Delta\Omega) \\ exp(-j2\pi 2\Delta\Omega) \\ \vdots \\ exp(-j2\pi(n_r-1)\Delta\Omega) \end{bmatrix}$$

$$\boldsymbol{H} = \Xi \odot \sqrt{n_t n_r} exp(-j2\pi d/\lambda) e_r(\Omega_r) e_t(\Omega_t)^H$$

$$PL = ((4\pi/\lambda)^2 d^k)^{-\frac{1}{2}} \qquad y = PL_B \cdot \boldsymbol{B}x$$

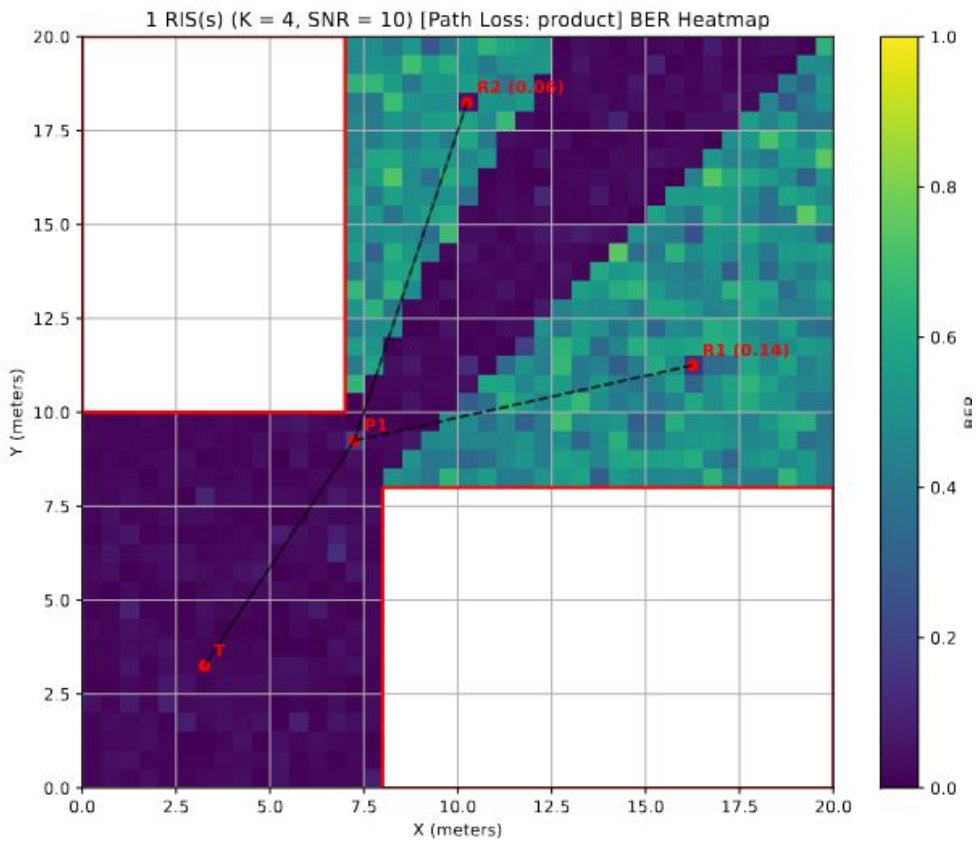
David Tse, Pramod Viswanath,
“Fundamentals of Wireless Communication”

- We generate the fading matrix from a complex distribution using the Shape and Scale parameters
- We calculate the channel gain matrix from the distance and the incidence angle between the antennas arrays
- We use the ideal Free Space path loss

BER Heatmaps - scenario 1

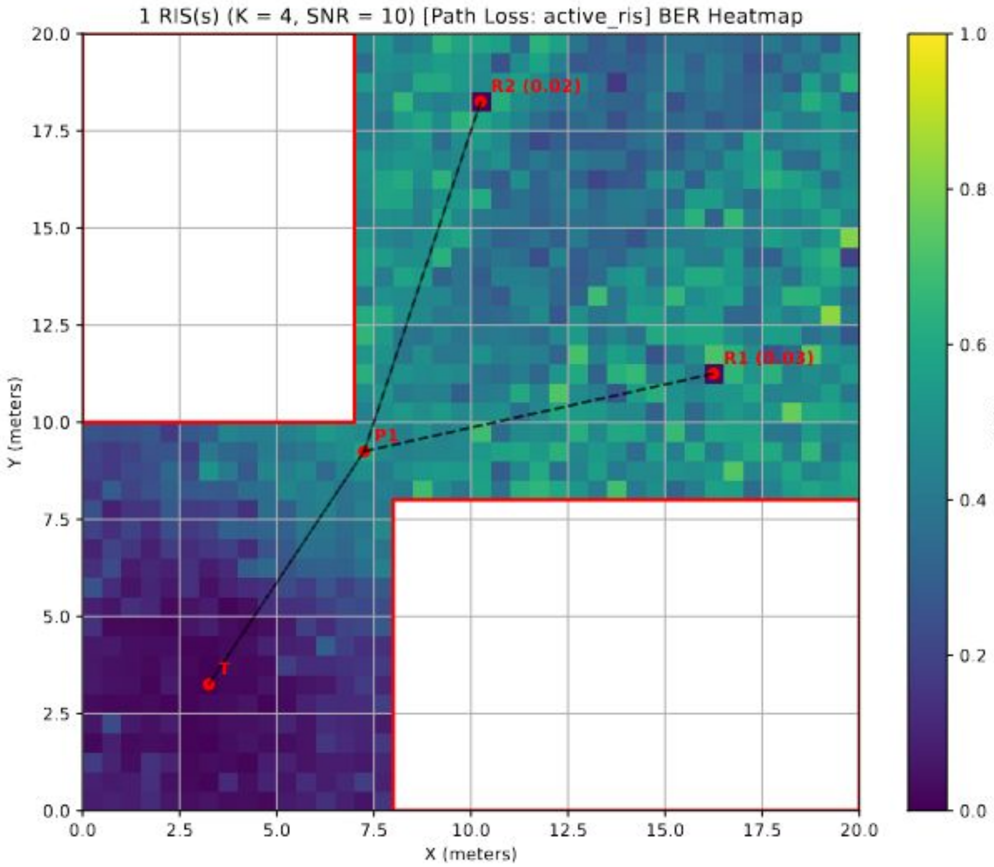
Passive RIS

$$y = PL_G \cdot PL_H \cdot \boldsymbol{GPH}x$$



Active RIS

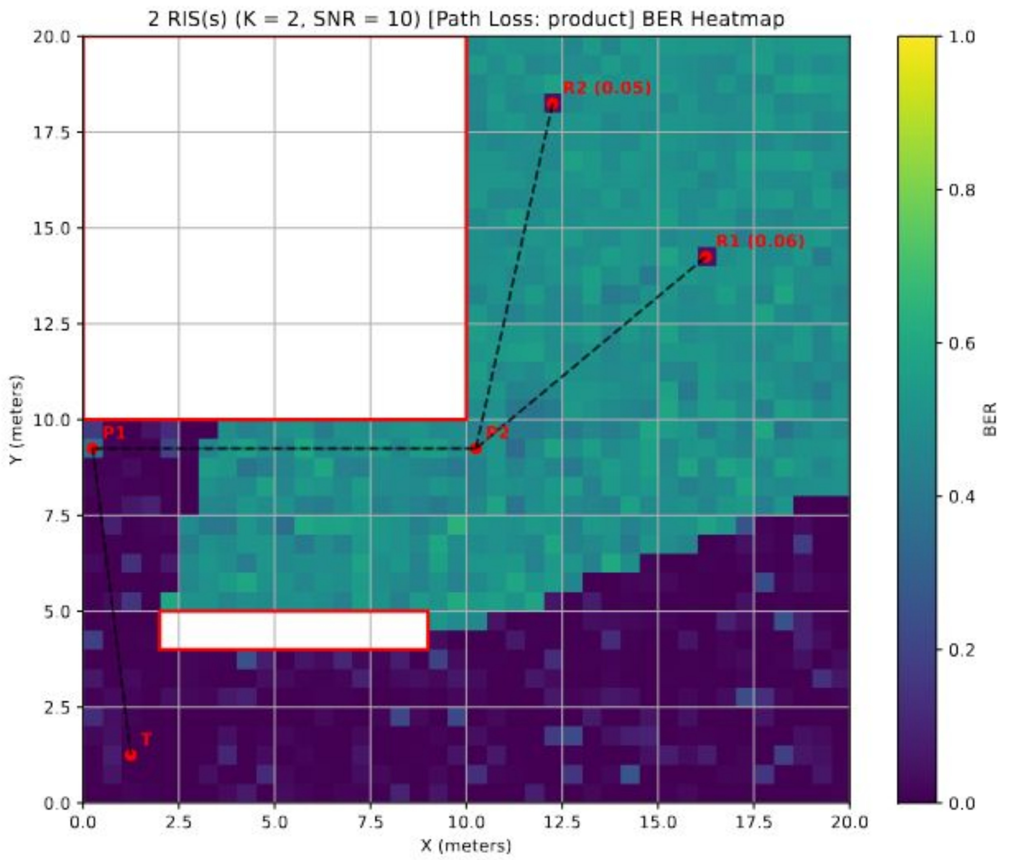
$$y = PL_H \cdot \boldsymbol{GPH}x.$$



BER Heatmaps - scenario 2

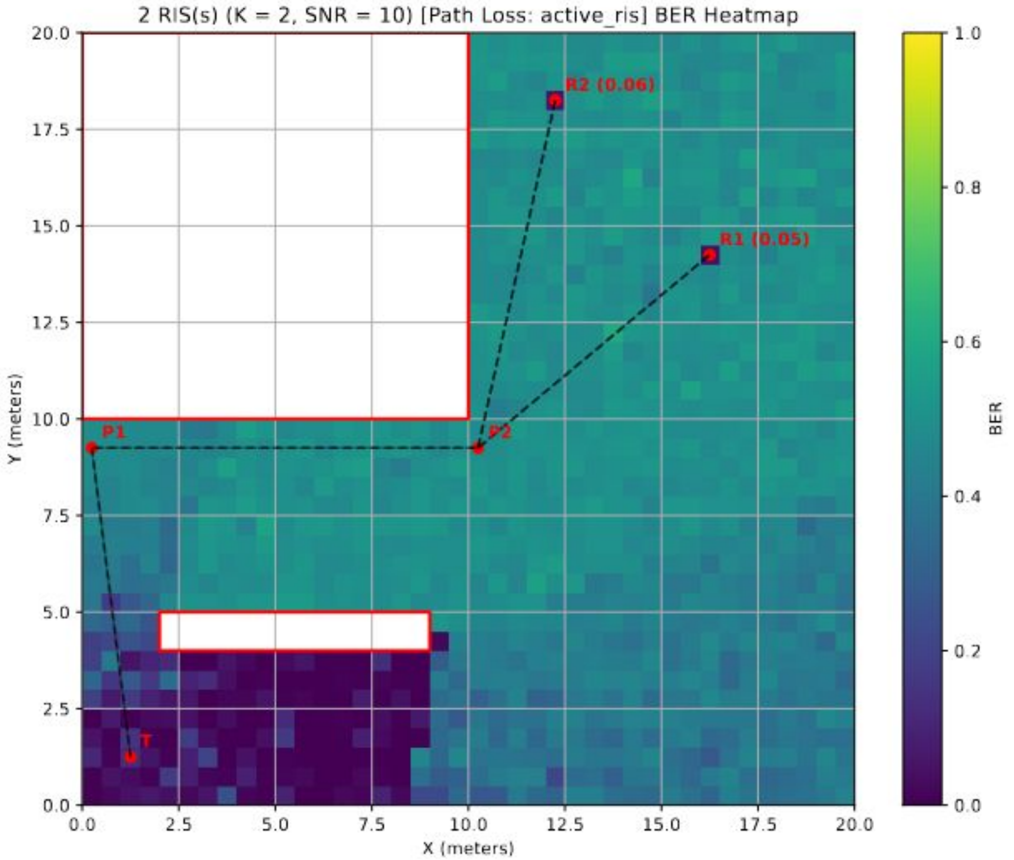
Passive RIS

$$y = PL_G \cdot PL_H \cdot \boldsymbol{GPHx}$$



Active RIS

$$y = PL_H \cdot \boldsymbol{GPH}x.$$



Conclusions and future directions

- We expanded on the work *RECONFIGURABLE INTELLIGENT SURFACE: REFLECTION DESIGN AGAINST PASSIVE EAVESDROPPING*
- We proved the correctness of our contribution
- We validated our solution in realistic scenarios
- Still, the area when the message is received is limited in size

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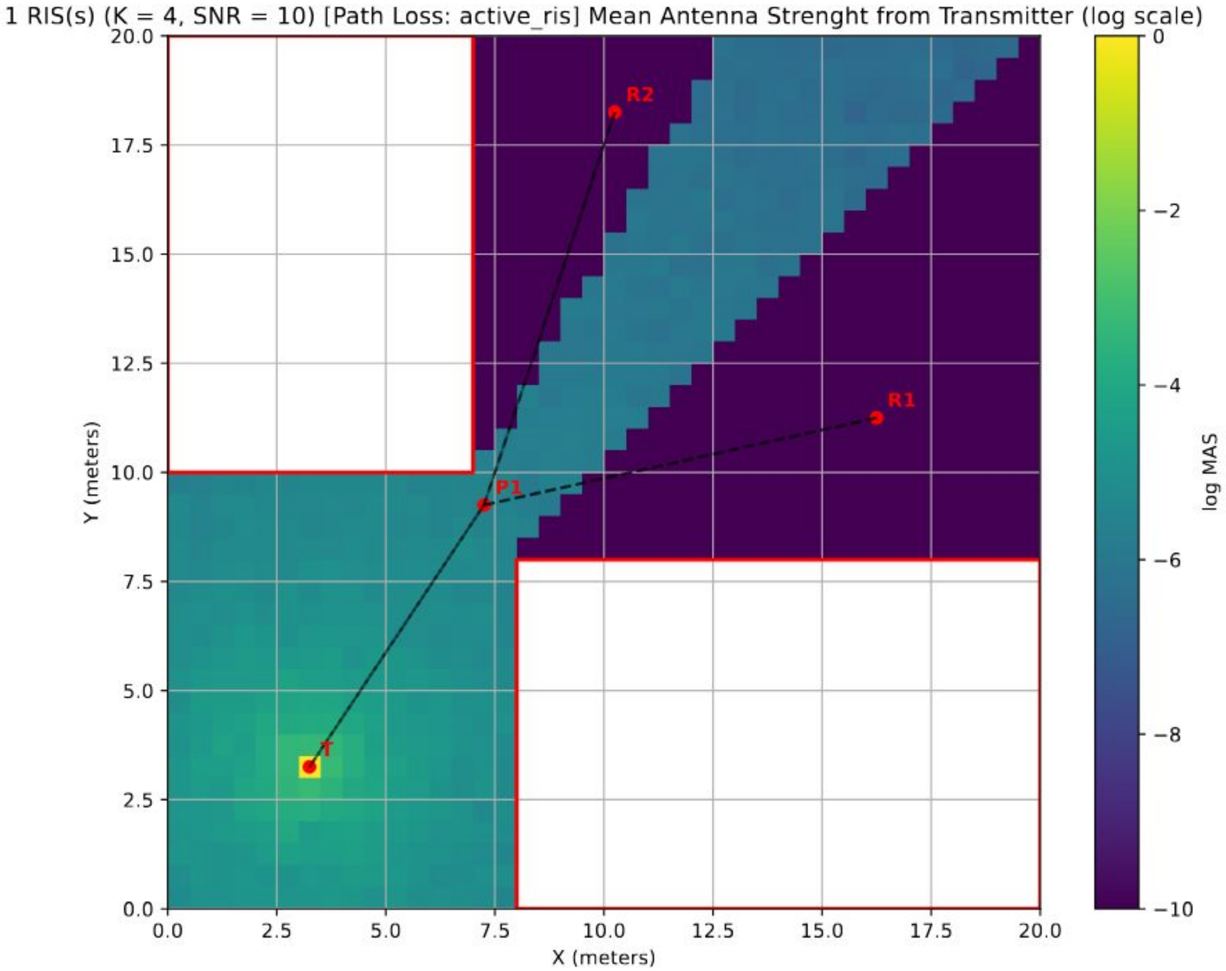
- Future work should be studied in channel gain estimation for moving vehicles
- Low level language implementations should be made to calculate the latency of communication
- Complex schemes that expand on SSK modulation should be considered

Thank you

Questions?

Mean Antenna Strength



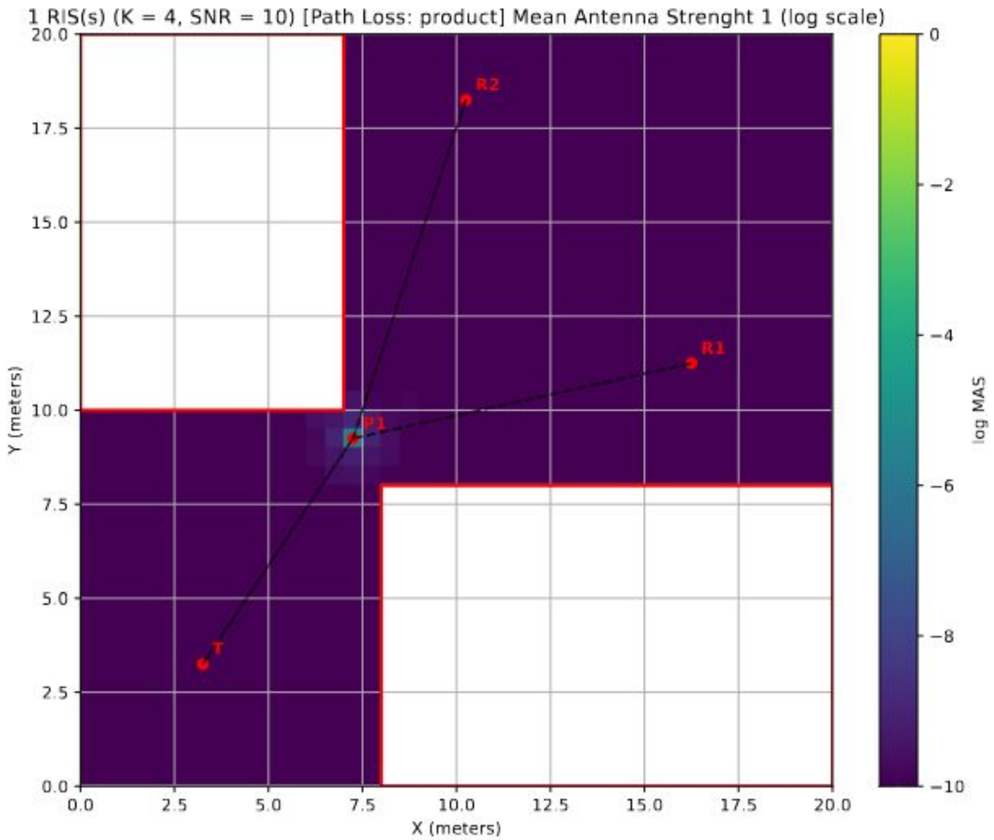
$$MAS_{\boldsymbol{H}} = \sum_{x=1}^{X} ||h_x||^2 \;/\; X$$

$$logMAS_{\boldsymbol{H}} = log_{10}MAS_{\boldsymbol{H}}$$

BER Heatmaps - scenario 1

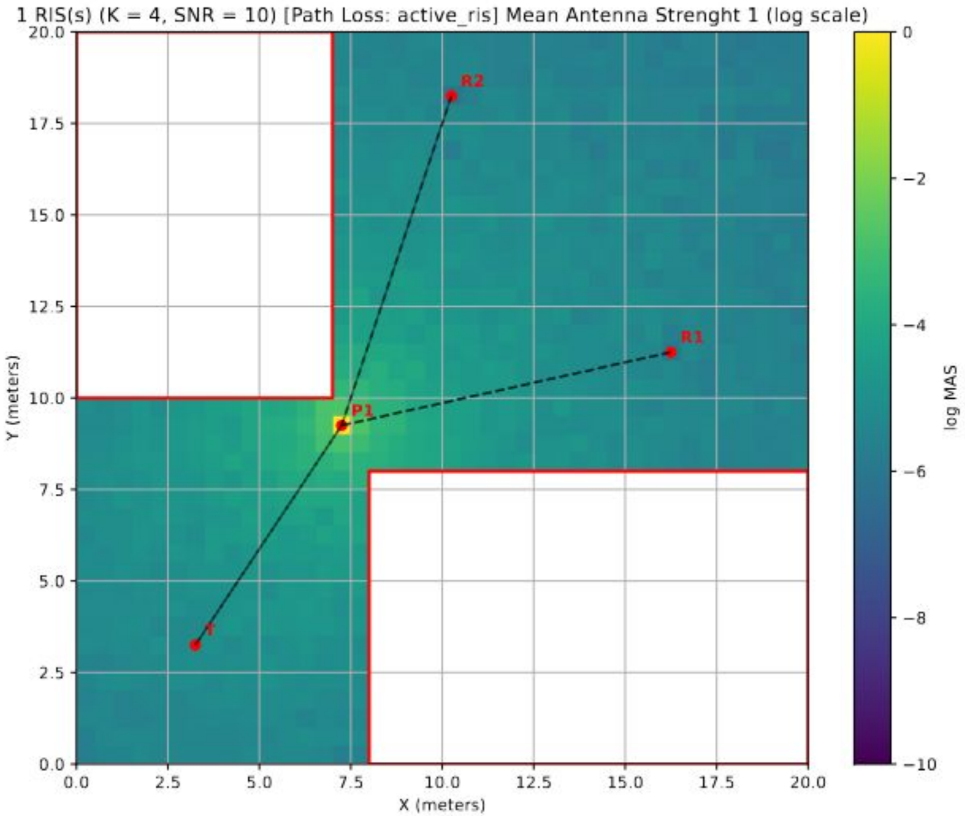
Passive RIS

$$y = PL_G \cdot PL_H \cdot \boldsymbol{GPH}x$$



Active RIS

$$y = PL_H \cdot \boldsymbol{GPH}x.$$



Channel Gain Estimation

- The transmitter communicates to the RIS controller a setup message x′ that it will send to the receiver
- The RIS will set a random P′
- The receiver gets a signal y′ (which will mean nothing), and sends it back to the RIS controller
- Based on x′, y′, P ′ the RIS controller estimates G, H and correctly sets up P
- The transmitter sends x, and the receiver gets y which it can correctly convert back
- If transmitter and receiver are moving, the procedure will start all over. Otherwise, G and H remain the same, and the RIS controller can just create a new P for the next messages

Algorithm 1: JBF-MC algorithm

Input: $\boldsymbol{Y}$, $\boldsymbol{S}$, $\boldsymbol{X}$, prior distributions $p(\boldsymbol{G})$ and $p(\boldsymbol{Z})$

% sparse matrix factorization via BiG-AMP

Initialization: $\forall l,n,t$: generate $g_{l,n}$ from $p(g_{l,n})$, $v^g_{l,n}(1) = \nu_g$, $\hat{z}_{n,t}(1) = \mathbb{E}(z_{n,t})$, $v^z_{n,t}(1) = \lambda\nu_z$, and $\hat{u}_{l,t}(1) = 0$

for $i = 1, \dots, I_{\max}$ % outer iteration

  for $j = 1, \dots, J_{\max}$ % inner iteration

  $\forall l,t$: $\bar{v}^p_{l,t}(i) = \sum_{n=1}^N |\hat{g}_{l,n}(i)|^2 v^z_{n,t}(i) + v^g_{l,n}(i)|\hat{z}_{n,t}(i)|^2$

  $\forall l,t$: $\bar{p}_{l,t}(i) = \sum_{n=1}^N \hat{g}_{l,n}(i)\hat{z}_{n,t}(i)$

  $\forall l,t$: $v^p_{l,t}(i) = \bar{v}^p_{l,t}(i) + \sum_{n=1}^N v^g_{l,n}(i) v^z_{n,t}(i)$

  $\forall l,t$: $\hat{p}_{l,t}(i) = \bar{p}_{l,t}(i) - \hat{u}_{l,t}(i-1)\bar{v}^p_{l,t}(i)$

  $\forall l,t$: $v^b_{l,t}(i) = \sigma^2 v^p_{l,t}(i)/[v^p_{l,t}(i) + \sigma^2]$

  $\forall l,t$: $\hat{b}_{l,t}(i) = v^p_{l,t}(i)[y_{l,t} - \hat{p}_{l,t}(i)]/[v^p_{l,t}(i) + \sigma^2] + \hat{p}_{l,t}(i)$

  $\forall l,t$: $v^u_{l,t}(i) = \left[1 - v^z_{l,t}(l)/v^p_{l,t}(i)\right]/v^p_{l,t}(i)$

  $\forall l,t$: $\hat{u}_{l,t}(i) = \left[\hat{b}_{l,t}(i) - \hat{p}_{l,t}(i)\right]/v^p_{l,t}(i)$

  $\forall l,n$: $v^q_{l,n}(i) = \left[\sum_{t=1}^T |\hat{z}_{n,t}(i)|^2 v^u_{l,t}(i)\right]^{-1}$

  $\forall l,n$: $\hat{q}_{l,n}(i) = \hat{g}_{l,n}(i)\left[1 - v^q_{l,n}(i)\sum_{t=1}^T v^z_{n,t}(i) v^u_{l,t}(i)\right] + v^q_{l,n}(i)\sum_{t=1}^T \hat{z}^*_{n,t}(i)\hat{u}_{l,t}(i)$

  $\forall n,t$: $v^r_{n,t}(i) = \left[\sum_{l=1}^L |\hat{g}_{l,n}(i)|^2 v^u_{l,t}(i)\right]^{-1}$

  $\forall n,t$: $\hat{r}_{n,t}(i) = \hat{z}_{n,t}(i)\left(1 - v^r_{n,t}(i)\sum_{l=1}^L v^g_{l,n}(i) v^u_{l,t}(i)\right) + v^r_{n,t}(i)\sum_{l=1}^L \hat{g}^*_{l,n}(i)\hat{u}_{l,t}(i)$

  $\forall l,n$: $\hat{g}_{l,n}(i+1) = \mathbb{E}\{g_{l,n}|\hat{q}_{l,n}(i), v^q_{l,n}(i)\}$

  $\forall l,n$: $v^g_{l,n}(i+1) = \mathbb{Var}\{g_{l,n}|\hat{q}_{l,n}(i), v^q_{l,n}(i)\}$

  $\forall n,t$: $\hat{z}_{n,t}(i+1) = \mathbb{E}\{z_{n,t}|\hat{r}_{n,t}(i), v^r_{n,t}(i)\}$

  $\forall n,t$: $v^z_{n,t}(i+1) = \mathbb{Var}\{z_{n,t}|\hat{r}_{n,t}(i), v^r_{n,t}(i)\}$

  if *a certain stopping criterion is met*, **stop**

  end for

  $\forall l,n,t, \hat{g}_{l,n}(i) = \hat{g}_{l,n}(i+1), \nu^g_{m,n}(i) = \nu^g_{l,n}(i+1)$, $\hat{z}_{n,t}(i) = \hat{z}_{n,t}(1), \nu^z_{n,t}(i) = v^z_{n,t}(1)$

end for

$\hat{\boldsymbol{G}} \leftarrow \hat{\boldsymbol{G}}(i+1)$, $\hat{\boldsymbol{Z}} \leftarrow \hat{\boldsymbol{Z}}(i+1)$

% matrix completion via RGrad

Initialization: $\boldsymbol{A}(0) = \boldsymbol{0}$

for $k = 1, \dots, K_{\max}$

  $\boldsymbol{Q}(k) = \boldsymbol{S}^* \odot (\hat{\boldsymbol{Z}} - \boldsymbol{A}(k))$

  $\alpha(k) = \frac{\|\mathcal{P}_{\mathcal{S}(k)}(\boldsymbol{Q}(k))\|_F^2}{\|\boldsymbol{S}^* \odot (\mathcal{P}_{\mathcal{S}(k)}(\boldsymbol{Q}(k)))\|_F^2}$

  $\boldsymbol{W}(k) = \boldsymbol{A}(k) + \alpha_k \mathcal{P}_{\mathcal{S}(k)}(\boldsymbol{Q}(k))$

  $\boldsymbol{A}(k+1) = \mathcal{H}_r(\boldsymbol{W}(k))$

  if *a certain stopping criterion is met*, **stop**

end for

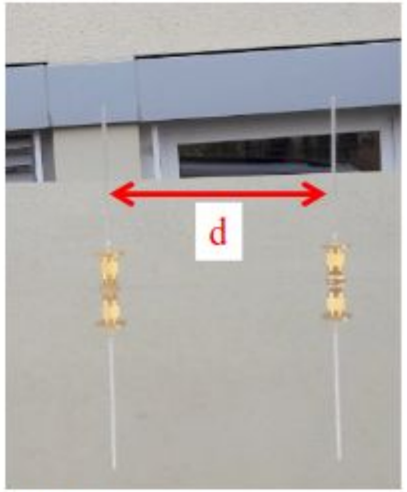
$\hat{\boldsymbol{H}} \leftarrow \hat{\boldsymbol{A}}\boldsymbol{X}^\dagger$ with $\hat{\boldsymbol{A}} = \boldsymbol{A}(k+1)$

Output: $\hat{\boldsymbol{G}}$ and $\hat{\boldsymbol{H}}$

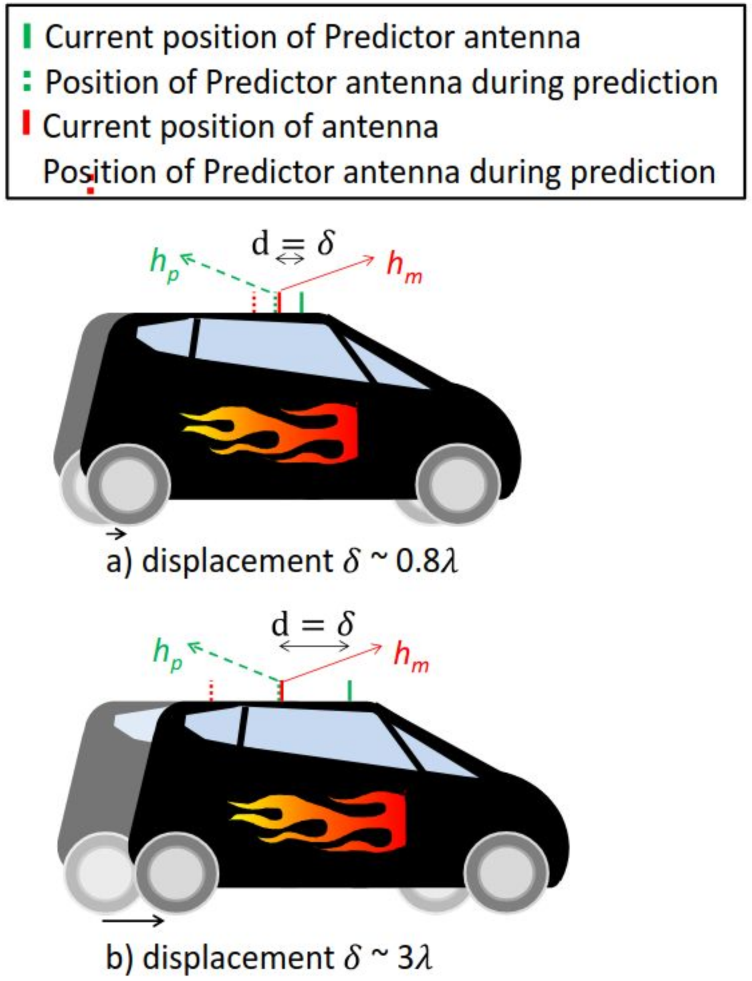
https://ieeexplore.ieee.org/document/8879620

Channel Gain Estimation for Vehicles

a) Car with mounted metallic plane



b) Monopole antennas
on the metallic plane



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Generalized Space Shift Keying Modulation

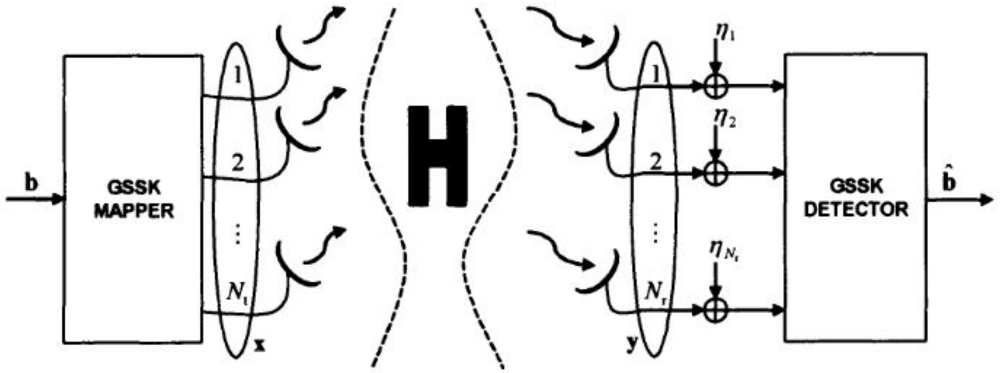


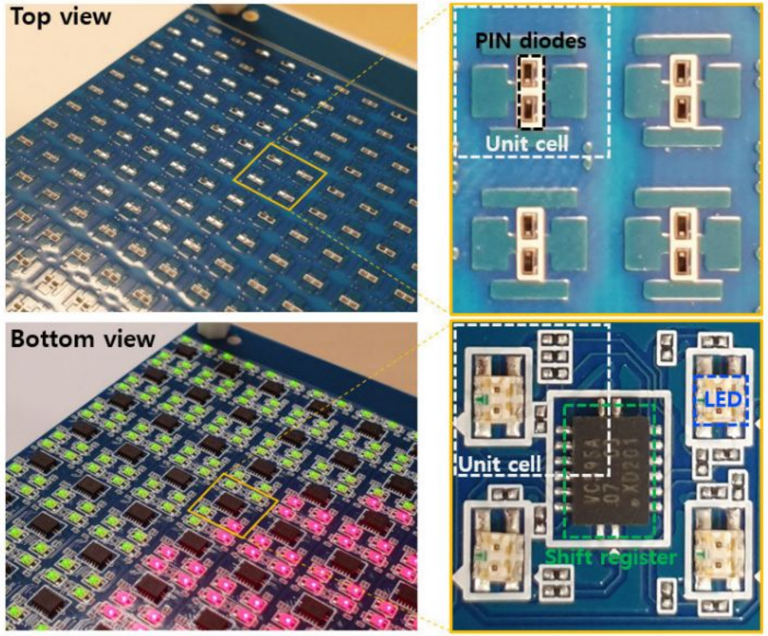
TABLE I

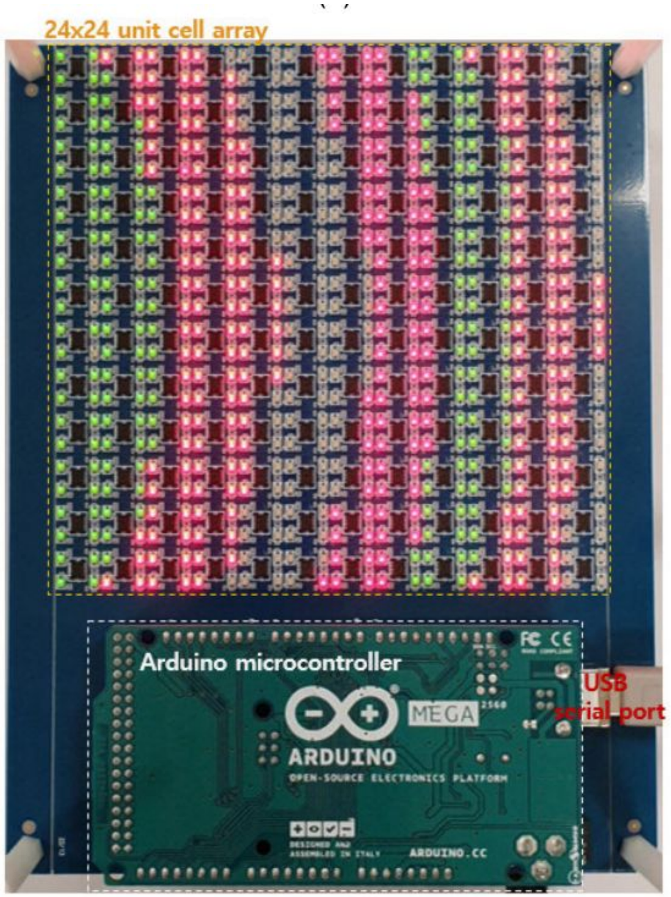
EXAMPLE OF THE GSSK MAPPER RULE.

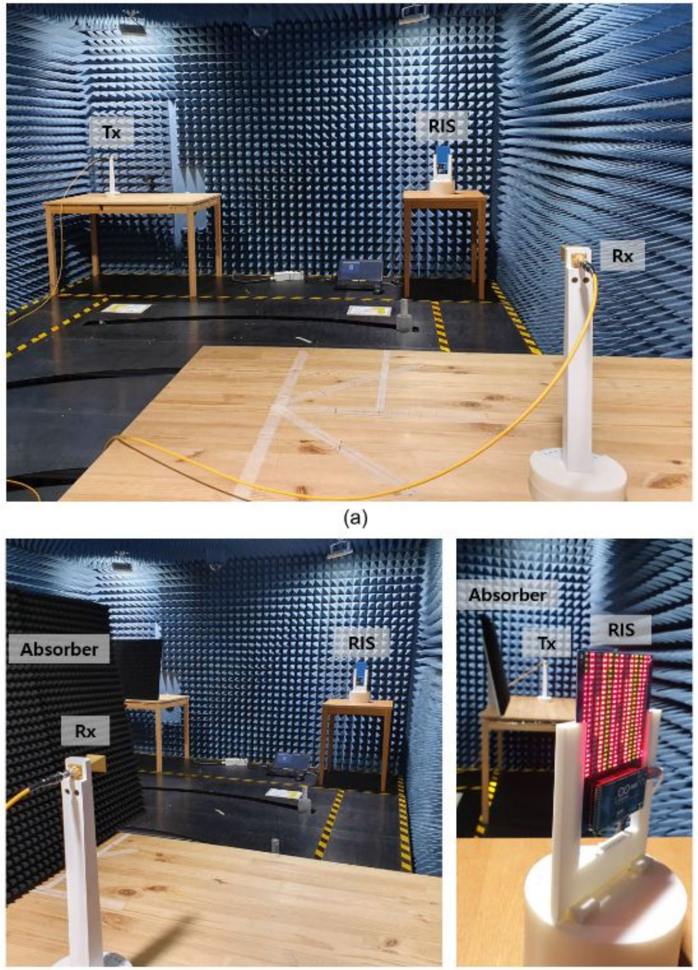
$\mathbf{b} = [b_1 \quad b_2 \quad b_3]$	$\mathbf{j}$	$\mathbf{x} = [x_1 \quad x_2 \quad \cdots \quad x_5]^T$
$[0 \quad 0 \quad 0]$	$(1,2)$	$\left[\frac{1}{\sqrt{2}} \quad \frac{1}{\sqrt{2}} \quad 0 \quad 0 \quad 0\right]^T$
$[0 \quad 0 \quad 1]$	$(1,3)$	$\left[\frac{1}{\sqrt{2}} \quad 0 \quad \frac{1}{\sqrt{2}} \quad 0 \quad 0\right]^T$
$[0 \quad 1 \quad 0]$	$(1,4)$	$\left[\frac{1}{\sqrt{2}} \quad 0 \quad 0 \quad \frac{1}{\sqrt{2}} \quad 0\right]^T$
$[0 \quad 1 \quad 1]$	$(1,5)$	$\left[\frac{1}{\sqrt{2}} \quad 0 \quad 0 \quad 0 \quad \frac{1}{\sqrt{2}}\right]^T$
$[1 \quad 0 \quad 0]$	$(2,3)$	$\left[0 \quad \frac{1}{\sqrt{2}} \quad \frac{1}{\sqrt{2}} \quad 0 \quad 0\right]^T$
$[1 \quad 0 \quad 1]$	$(2,4)$	$\left[0 \quad \frac{1}{\sqrt{2}} \quad 0 \quad \frac{1}{\sqrt{2}} \quad 0\right]^T$
$[1 \quad 1 \quad 0]$	$(2,5)$	$\left[0 \quad \frac{1}{\sqrt{2}} \quad 0 \quad 0 \quad \frac{1}{\sqrt{2}}\right]^T$
$[1 \quad 1 \quad 1]$	$(3,4)$	$\left[0 \quad 0 \quad \frac{1}{\sqrt{2}} \quad \frac{1}{\sqrt{2}} \quad 0\right]^T$

J. Jeganathan, A. Ghrayeb, L. Szczecinski
"Generalized Space shift keying modulation for MIMO channels,"

RIS implementations







(a)

(b) (c)

https://ieeexplore.ieee.org/document/9881509