Towards arrays of liquid antennas - the next MIMO paradigm?

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(joint work with Javier Otero and Javier Rodriguez from UC3M)

What 6G would we like?

- Profitable
  - Verticals, industry, automotive
- Inclusive, for all
  - Coverage, low complexity options
- Sustainable
  - Energy efficiency
- For people
  - People's communications needs (immersive)

- **Al this calls for higher data rates and higher user density at an affordable complexity**

6G KPIs (ITU vision beyond 2030)

Spectrum availability -> operating carrier frequency to unprecedently high values -> amplification and RF impairments are more severe …

- Throughput/data rate up to 1 Tbit/s (x50 5G)
- User-experienced data rate of 1 Gbit/s (x10 5G),
- End-to-end latency less than 1 ms
- Vehicle speeds of up to 1,000 km/h
- Localization precision equal to 1 cm in three dimensions
- Etc …

We cannot only trust on spectrum availability, we still need a strong multiplexing capability

Multiplexing and Multiple access

- From FDMA, TDMA, CDMA to OFDMA
- SDM and SDMA through (MU-)MIMO
- Massive MIMO
- Hybrid beamforming
- Network-MIMO (CoMP) and Cell-Free Massive MIMO
- What is next? …
  - Ultra-large massive MIMO
  - Reconfigurability

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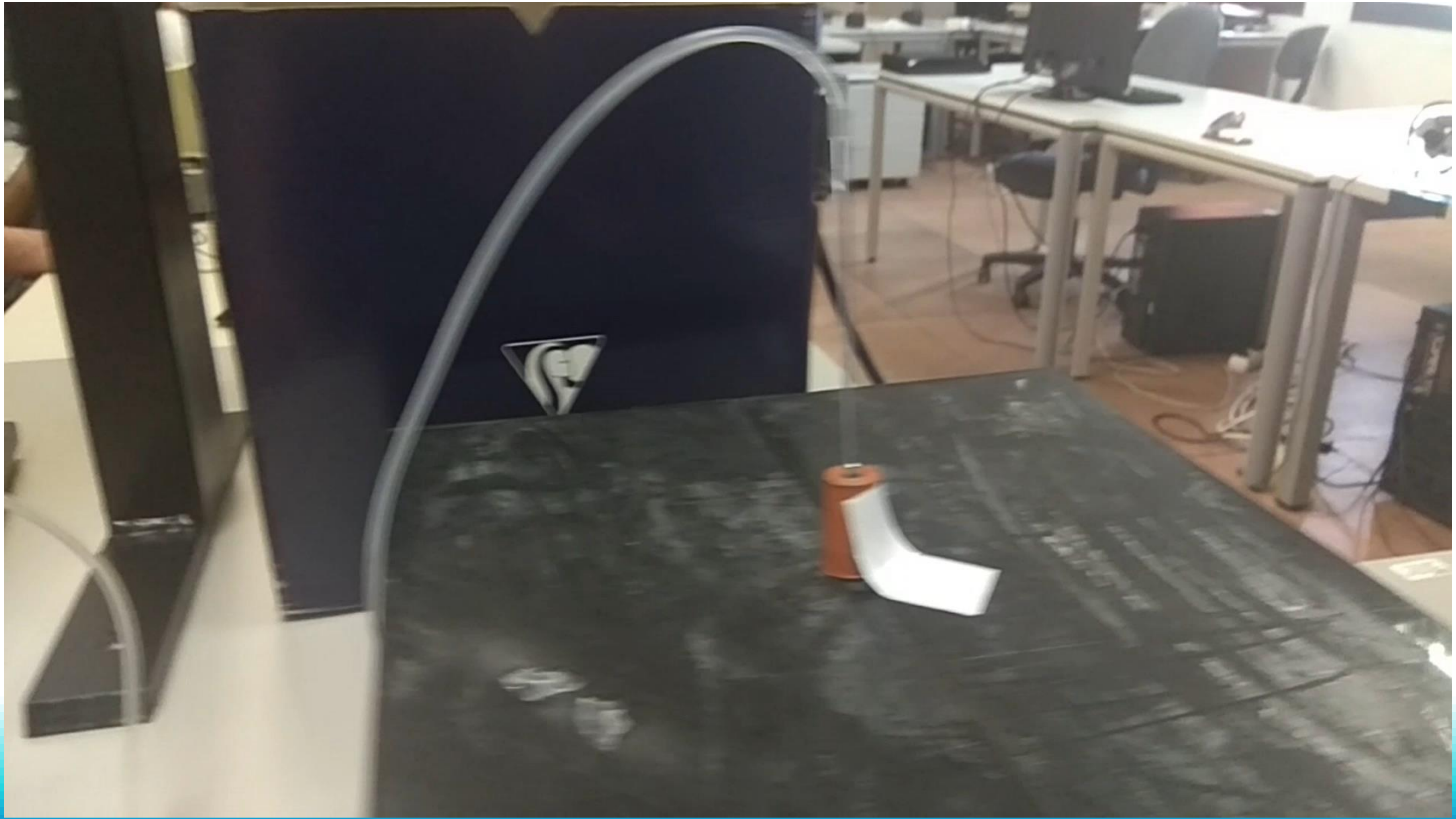
Liquid antennas - Introducing reconfigurability at the Tx/Rx end

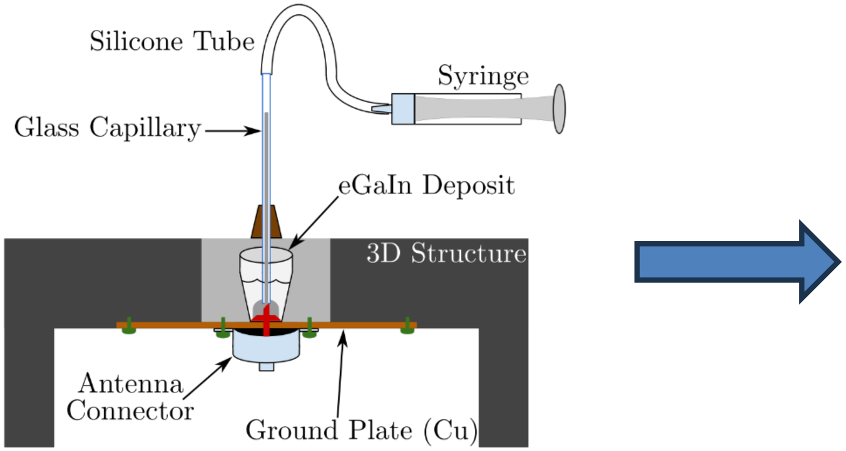
- The term “fluid antenna” was first used in 2010 when aqueous solutions were studied as potential materials for an antenna.
- Reconfigurable fluid antennas have emerged in recent years.
- **Eutectic Gallium-Indium (EGaIn)** is an alloy that is liquid at room temperature; gallium-based alloys present a conductivity just an order of magnitude less than that of copper.
- There are several works in the antenna community showing (mature) antenna designs with EGaIn.

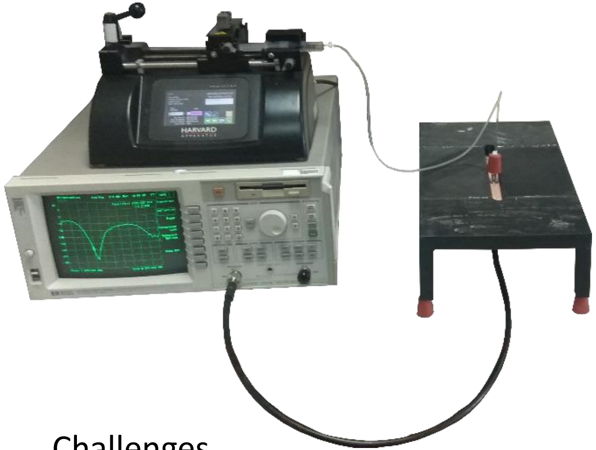
What could we achieve if we can arbitrarily shape the antenna? Is it feasible?

Our first prototype



Liquid antennas – a communications perspective





J. Otero Martínez, J. R. Rodríguez, Y. Shen, K.-F. Tong, K.-K. Wong, and A. G. Armada, "Toward Liquid Reconfigurable Antenna Arrays for Wireless Communications," *IEEE Communications Magazine*, vol. 60, no. 12, pp. 145–151, Dec. 2022.

<u>Challenges</u>

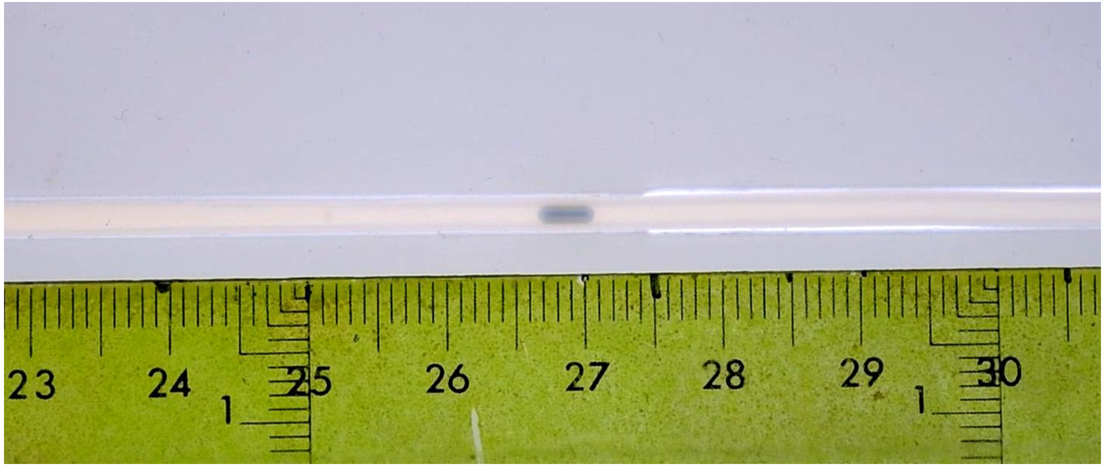
- Mechanical pumping
- Communications use cases and architectures
- Realistic assumptions

First challenge - Moving eGaIn without pumping

Use of small voltages to move a drop of EGaIn.

Real-time reconfiguration of the drop using electric signals

Working on it!



Response to 1V sinusoidal excitation. Slow motion x4 time scale. Experiments performed in UC3M 2024

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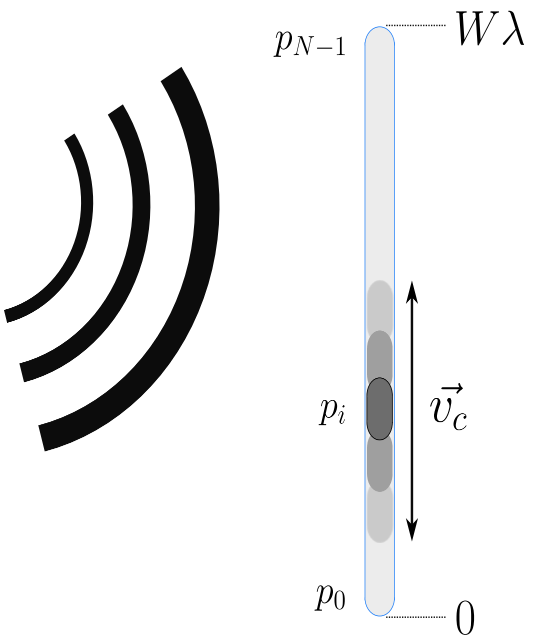
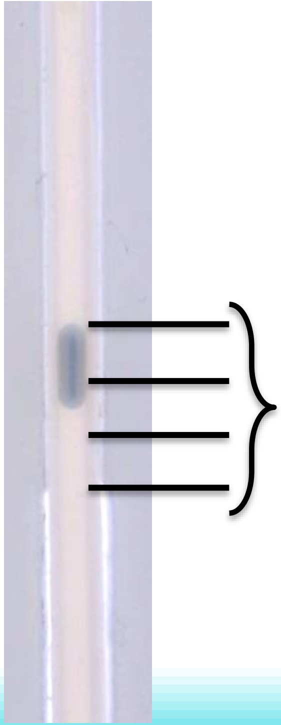
Using eGaIn for communications





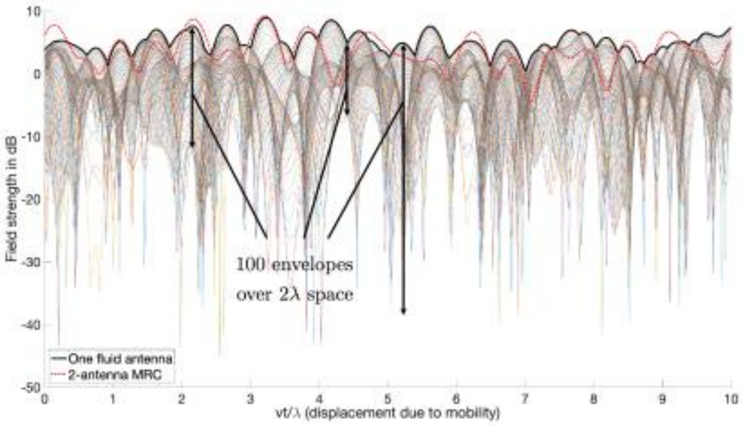
Change the EGaIn antenna element position to get diversity

Different configurations - antenna ports

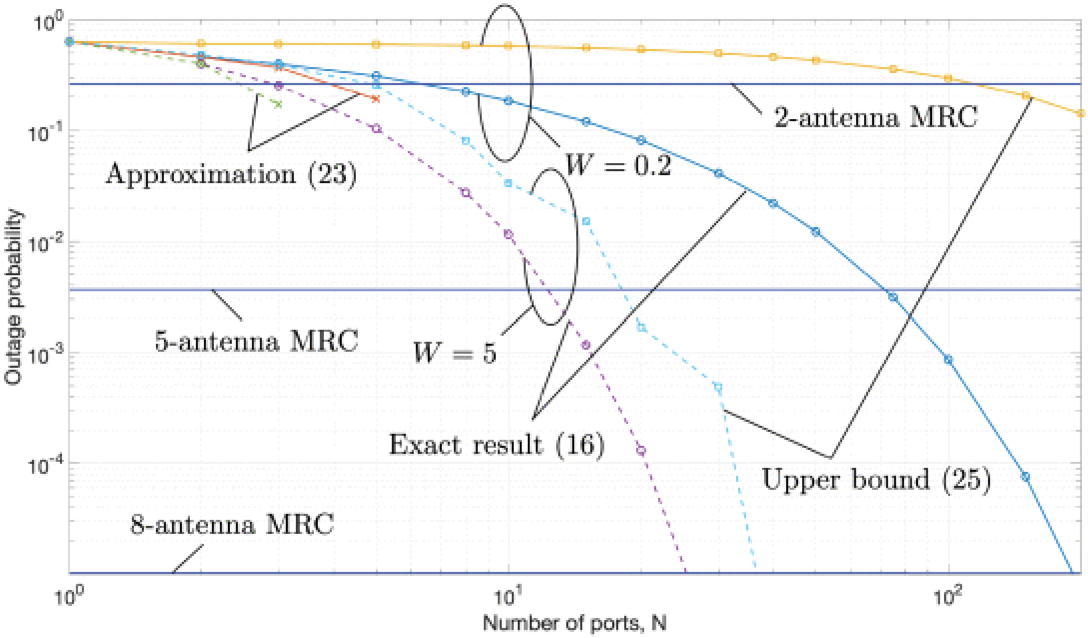
These positions are close to each other hence received signals are heavily correlated

K.-K. Wong, A. Shojaeifard, K.-F. Tong, and Y. Zhang, “Fluid Antenna Systems,” *IEEE Trans. Wireless Commun.*, vol. 20, no. 3, pp. 1950–1962, Mar. 2021.

FAS outperforming MRC



(b) Comparison for a 100-port FAS with 2λ space and MRC at 5GHz at $v = 30$km/h



massive diversity is available in a tiny space

K.-K. Wong, A. Shojaeifard, K.-F. Tong, and Y. Zhang, "Fluid Antenna Systems," *IEEE Trans. Wireless Commun.*, vol. 20, no. 3, pp. 1950–1962, Mar. 2021.

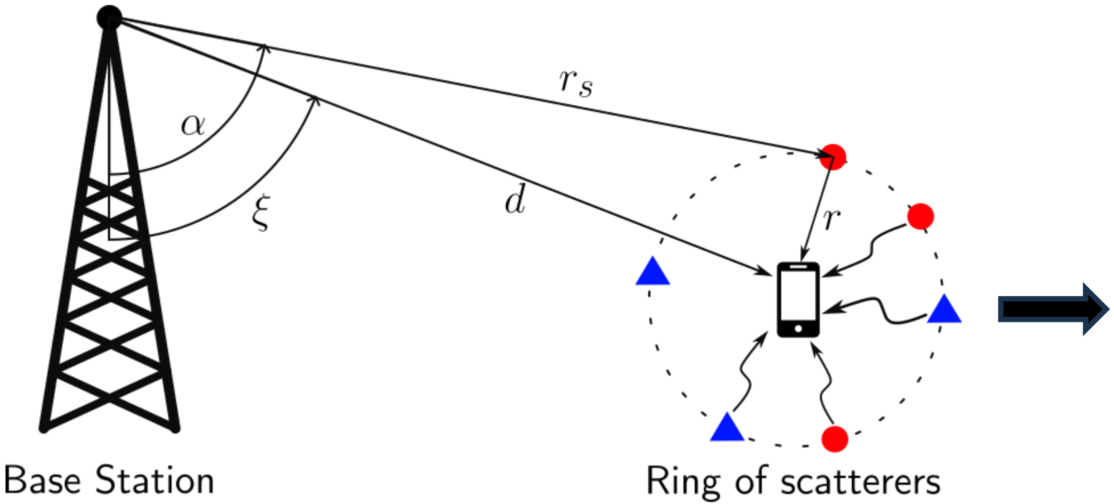
Modelling the Correlation

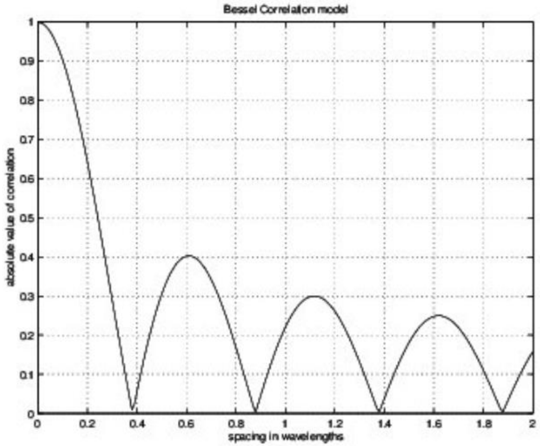
In the SoTA:

1. No correlation was considered
2. Correlation according to Jakes' model

$$r(x) = J_0(2\pi x/\lambda)$$

J_0 is the zero-order Bessel function of the first kind





Receiver far away from emitter, scatterers uniformly distributed over 2π in 2D.

Realistic correlation

Jakes' model does not fit every scenario

Different environments require different correlation scenarios

Generate channel coefficients with a given autocorrelation (defined by the scenario)

Generate a colored rv according to the environment

1. Select correlation scenario.
2. Generate correlation function accordingly.
3. Adjust ARMA filter to match the desired correlation function.
4. Obtain correlated channel coefficients by filtering independent samples (rv).

ARMA filter design

$$y_t = \underbrace{-\sum_{i=1}^{p} a_i y_{t-i}}_{\text{AR}} + \underbrace{\sum_{i=0}^{q} b_i w_{t-i}}_{\text{MA}}$$

$$\hat{S}(\omega) = \left.\frac{\hat{b}(z)\,\hat{b}(z^{-1})}{\hat{a}(z)\,\hat{a}(z^{-1})}\right|_{z=\exp(j\omega)}$$

M. C. Jeruchim, P. Balaban, K. S. Shanmugan, and M. C. Jeruchim, Eds., *Simulation of communication systems: modeling, methodology, and techniques*, 2nd ed. in Information technology--transmission, processing, and storage. New York: Kluwer Academic/Plenum Publishers, 2000.

B. Friedlander and B. Porat, "The Modified Yule-Walker Method of ARMA Spectral Estimation," *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-20, no. 2, pp. 158–173, Mar. 1984.

AR filter design

$$\begin{bmatrix} \mathbf{r}_{1,q+1} & \mathbf{r}_{2,q+1} & \cdots & \mathbf{r}_{p,q+1} \\ \mathbf{r}_{1,q+2} & \mathbf{r}_{2,q+2} & \cdots & \mathbf{r}_{p,q+2} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{r}_{1,N} & \mathbf{r}_{2,N} & \cdots & \mathbf{r}_{p,N} \end{bmatrix} \begin{bmatrix} \mathbf{a}_1 \\ \mathbf{a}_2 \\ \vdots \\ \mathbf{a}_p \end{bmatrix} = \begin{bmatrix} \mathbf{r}_{0,q+1} \\ \mathbf{r}_{0,q+2} \\ \vdots \\ \mathbf{r}_{0,N} \end{bmatrix}$$

$$\mathbf{a} = [R'\, W\, R]^{-1} R'\, W\, r$$

W is a diagonal weighting matrix

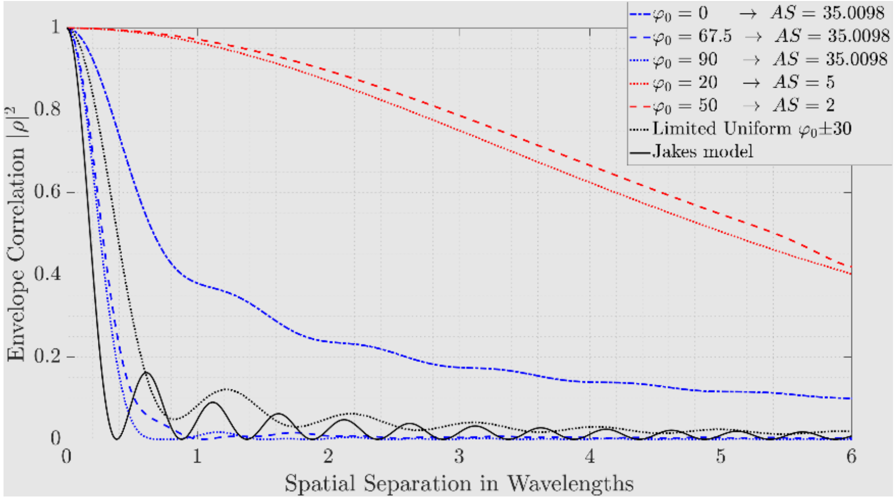
All r are values of the desired autocorrelation

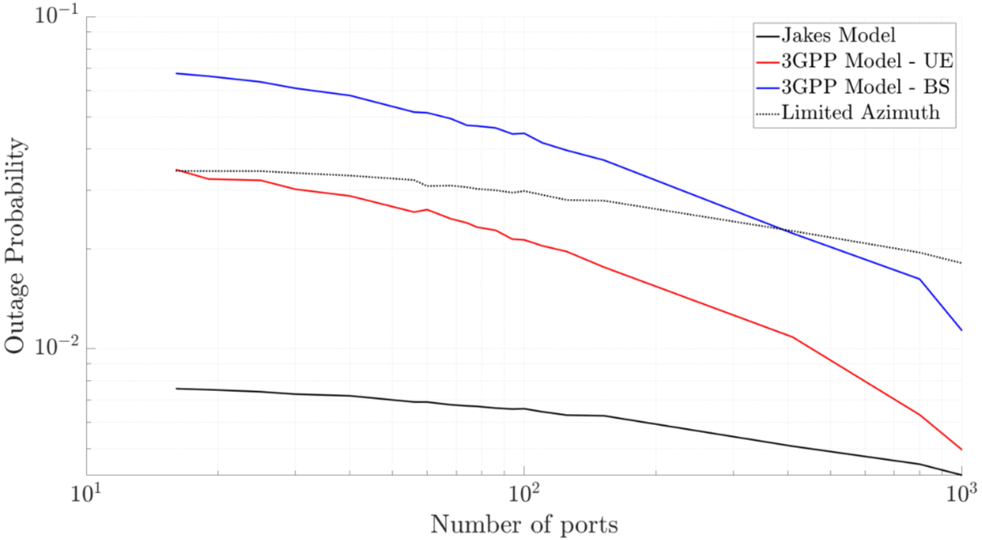
Minimum prediction error according to:

$$\hat{\varepsilon} = R_{\mathrm{XX}}(0) + \sum_{k=1}^{p} a_k\, R_{\mathrm{XX}}(-k)$$

S. M. Kay and S. L. Marple, "Spectrum analysis—A modern perspective," *Proc. IEEE*, vol. 69, no. 11, pp. 1380–1419, 1981, doi: 10.1109/PROC.1981.12184.

Results strongly depend on the Correlation





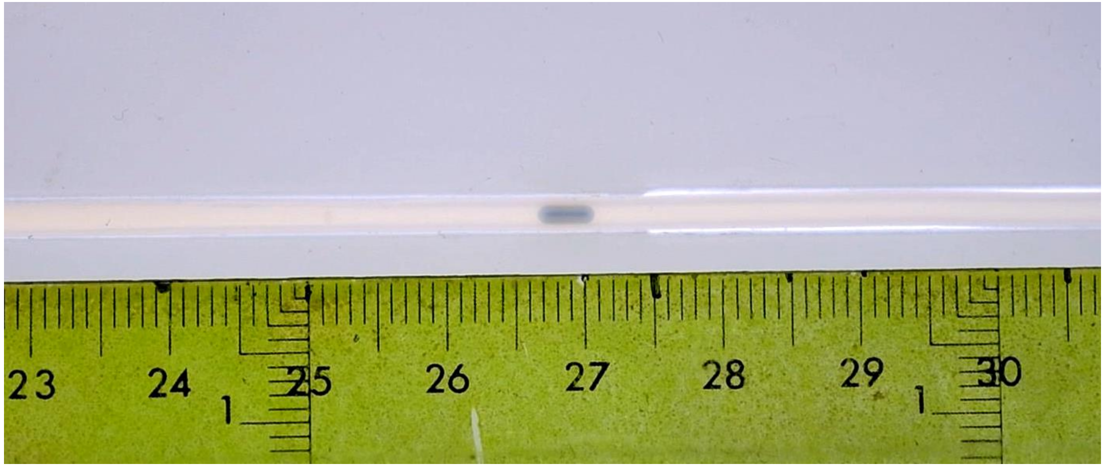
J. Otero Martinez and A. G. Armada, “Realistic Correlation Modeling for Fluid Antenna Systems,” in *2024 IEEE International Conference on Communications Workshops (ICC Workshops)*, Jun. 2024, pp. 1371–1376. doi: 10.1109/ICCWorkshops59551.2024.10615574.

Let’s get back to the dynamic environment and consider the movement of the EGaIn drops

Use of small voltages to move a drop of EGaIn.

Real-time reconfiguration of the drop using electric signals

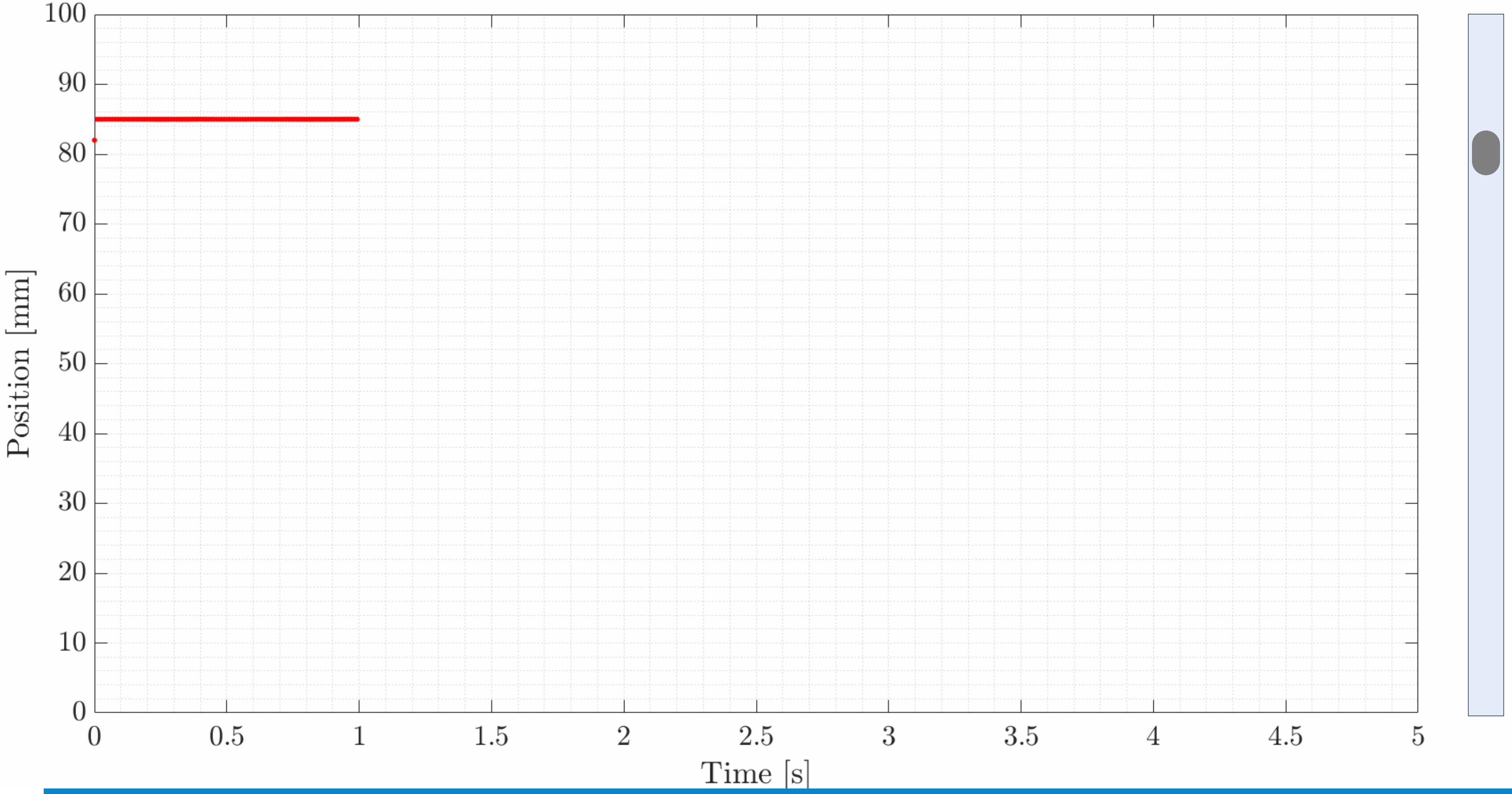
Working on it!



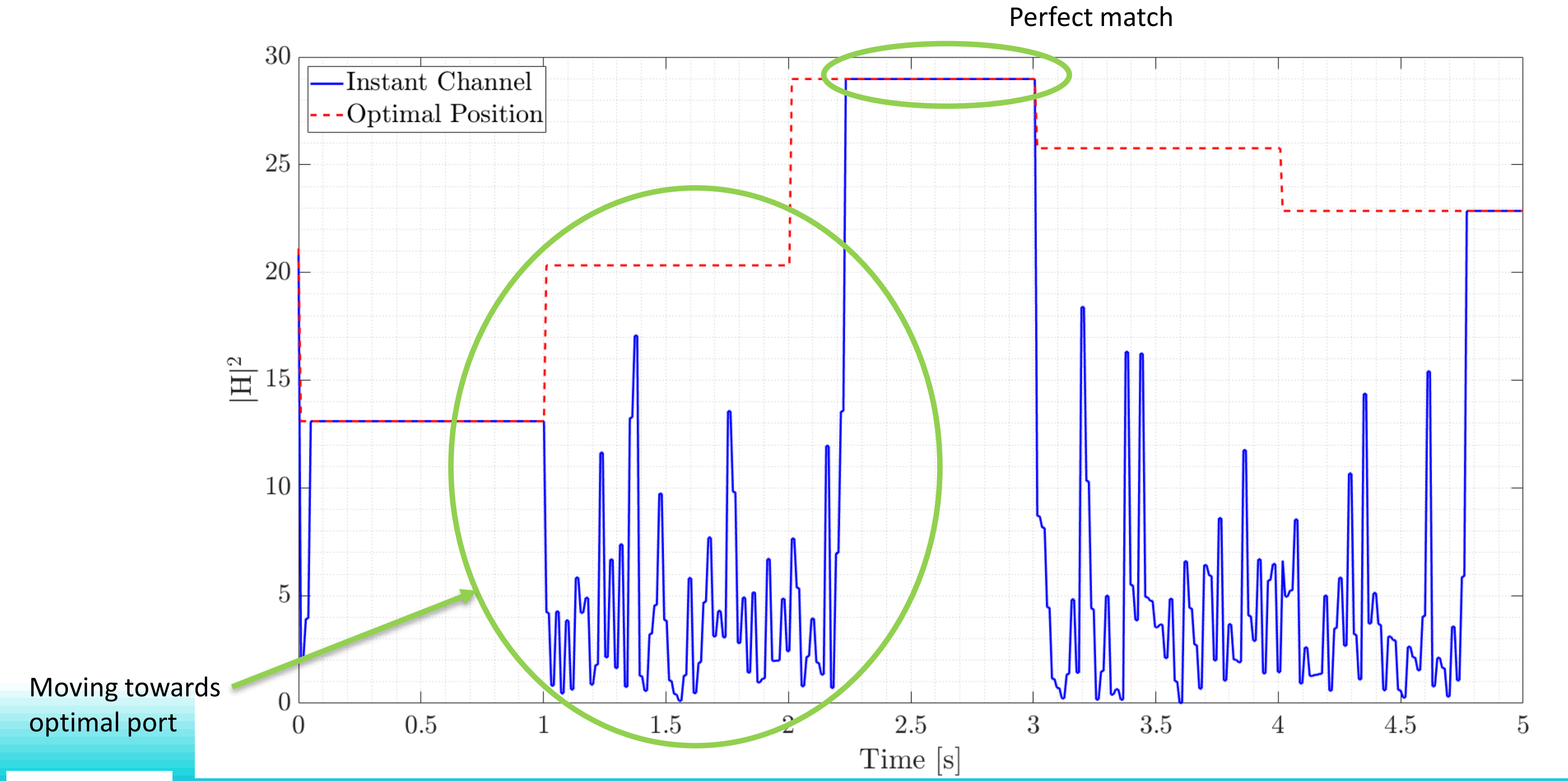
Response to 1V sinusoidal excitation. Slow motion x4 time scale. Experiments performed in UC3M 2024

Reconfiguration time

Losses when the position is not optimal

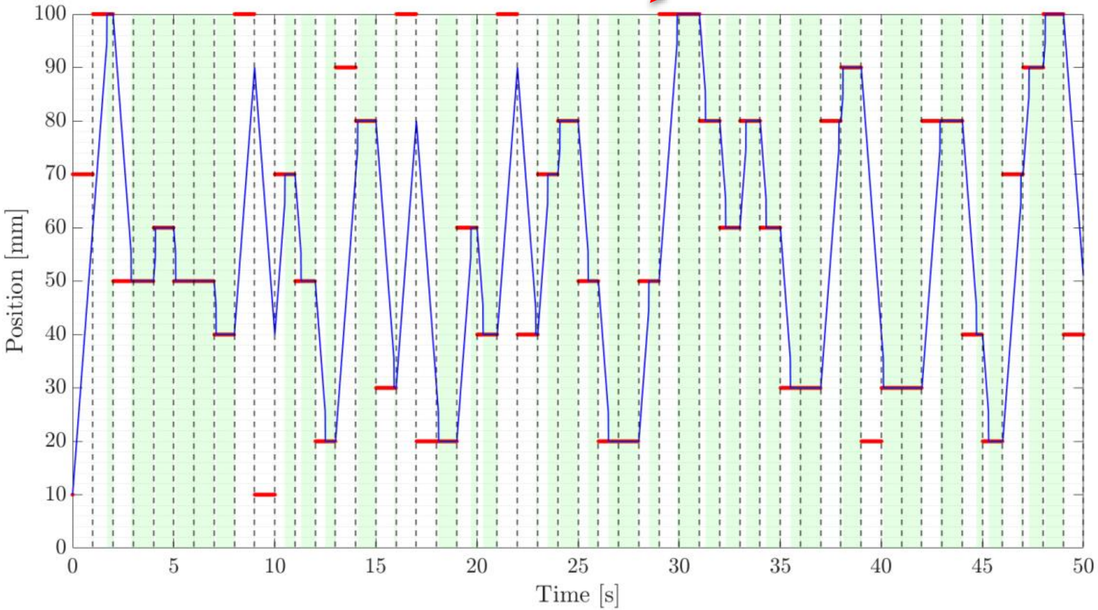


Reconfiguration time



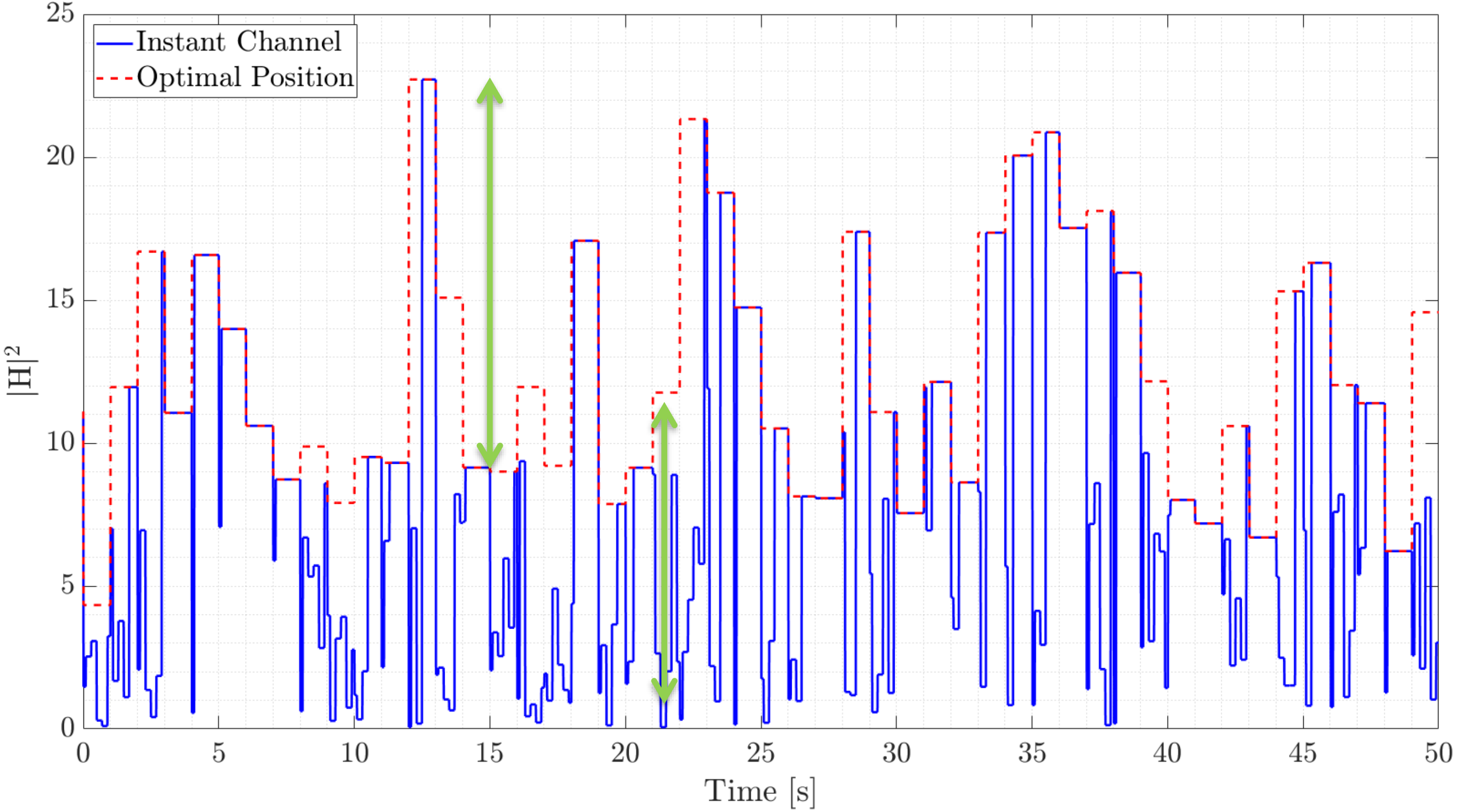
Reconfiguration time

Channel Sampling every 1s (channel assumed to change at that speed)

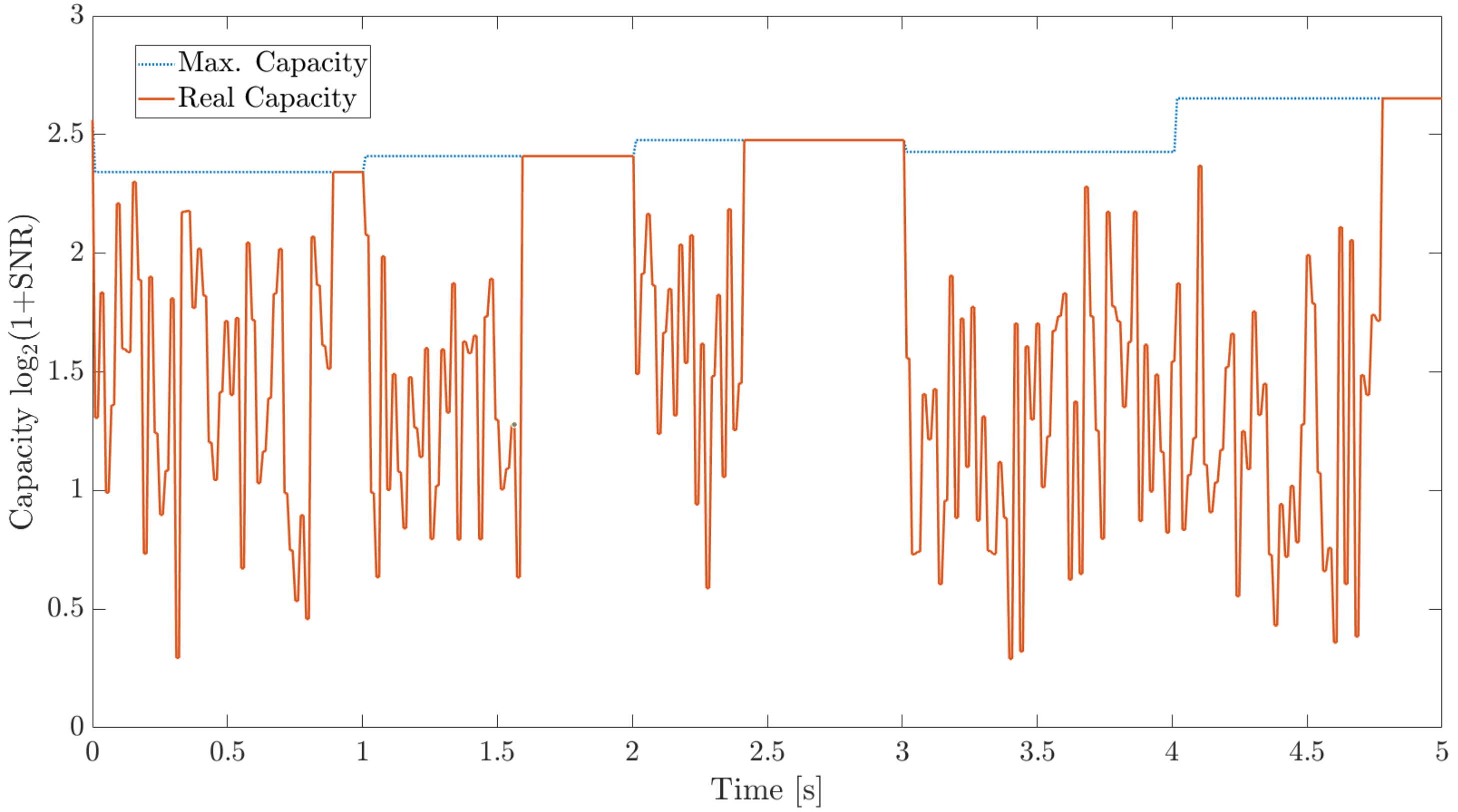


Channel parameters should be changed to model different scenarios.

Reconfiguration time



Achievable rate



What is next?

- We have an understanding of the drop dynamics and the channel correlation
- Algorithms to find the best antenna port
- Building a prototype for validation
- Fluid Antenna Systems (FAS) are much more general


go raibh maith agat
мерси
koszonom
malondo
asante
dhanyavad
rahmet
hvala
najis tuke
mochchakkeram
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ngiyabonga
kia ora
mamnun
gracias
sobodi
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grazie
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thank you
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dankon
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diolch
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謝謝