ELLIIT Focus Period – Linköping 2026

Fluid Antenna Systems for Localization

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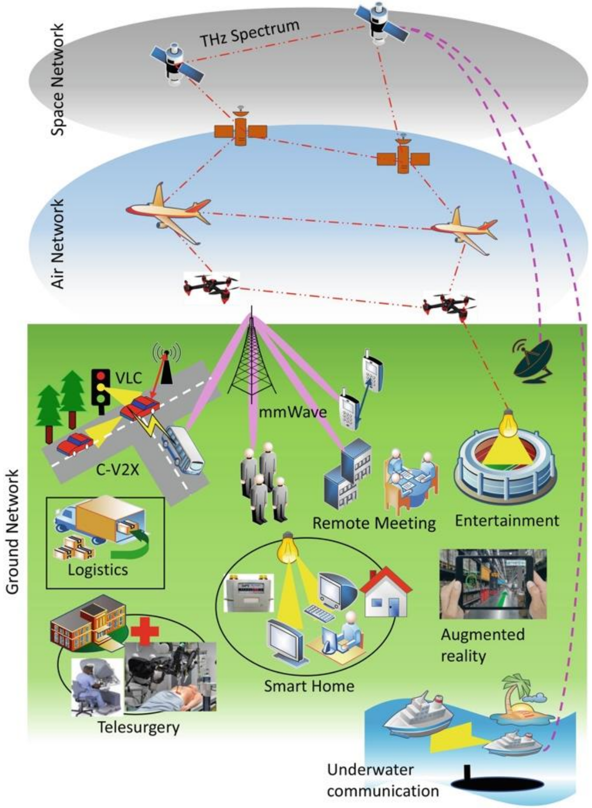
Motivation

- Next-generation wireless networks are expected to support:
  - Massive connectivity
  - Low-latency and high data-rate communications
  - High-accuracy localization
- Multiple-Input Multiple-Output (MIMO) and massive MIMO deployments will remain at the core of future wireless systems.
- To meet these requirements, increasingly large antenna arrays are needed, leading to new scalability and deployment challenges.

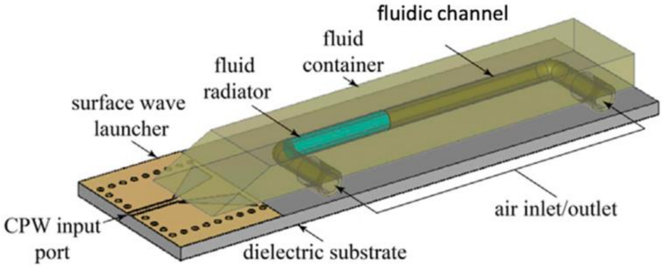


[1] N. Saxena, E. Rastogi, and A. Rastogi, “6G use cases, requirements, and metrics,” in 6G Mobile Wireless Networks, Y. Wu et al., Eds. Cham, Switzerland: Springer, 2021, ch. 2. doi: 10.1007/978-3-030-72777-2_2.

Fluid Antenna Systems

What if we could increase the degrees of freedom in a multi-antenna system without increasing the number of antennas?

- "Fluid antenna represents any radiating structure based on software-controllable fluidic, conductive, or dielectric element that can alter their shape, size, and/or position to reconfigure the polarization, operating frequency, radiation pattern, and other characteristics" [2]
- Other definitions restrict the term fluid antennas to liquid-based reconfigurable designs [3].

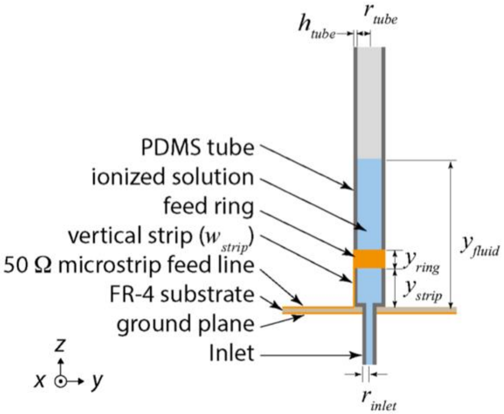


[2] K.-K. Wong, K.-F. Tong, Y. Shen, Y. Chen, and Y. Zhang, "Bruce Lee-Inspired Fluid Antenna System: Six Research Topics and the Potentials for 6G," Front. Commun. Netw., vol. 3, Mar. 2022, doi: 10.3389/frcmn.2022.853416.
[3] L. Zhu, W. Ma, B. Ning and R. Zhang, "Movable-Antenna Enhanced Multiuser Communication via Antenna Position Optimization," in *IEEE Transactions on Wireless Communications*, vol. 23, no. 7, pp. 7214-7229, July 2024, doi: 10.1109/TWC.2023.3338626.

Types of Fluid Antennas

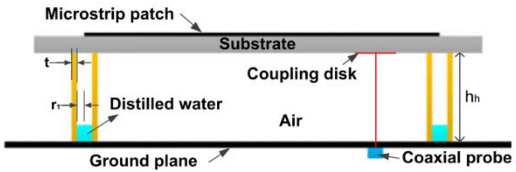
Frequency

e.g. fluid monopole [4]



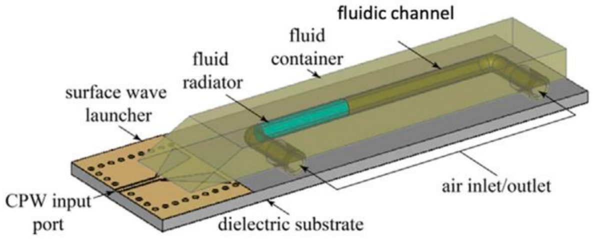
Polarization

e.g. water-loaded microstrip antenna [5]



Gain Pattern

e.g. surface wave–based [2]



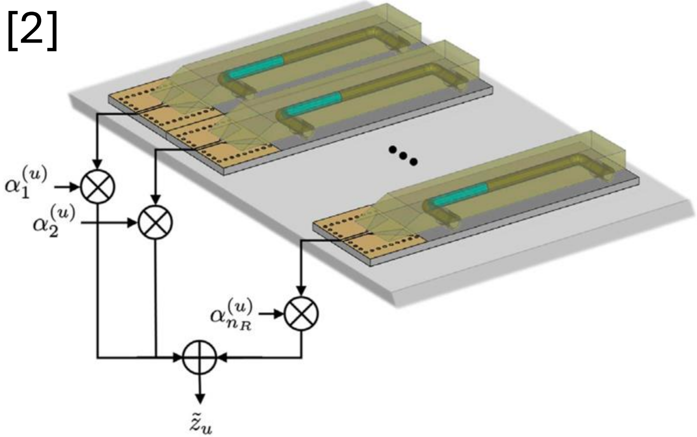
[4] C. Borda-Fortuny, L. Cai, K. F. Tong and K. -K. Wong, "Low-Cost 3D-Printed Coupling-Fed Frequency Agile Fluidic Monopole Antenna System," in *IEEE Access*, vol. 7, pp. 95058-95064, 2019, doi: 10.1109/ACCESS.2019.2928683.
[5] Y. -H. Qian and Q. -X. Chu, "A Polarization-Reconfigurable Water-Loaded Microstrip Antenna," in *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2179-2182, 2017, doi: 10.1109/LAWP.2017.2703821.

Types of Fluid Antennas: Gain Pattern Reconfiguration

Gain Pattern

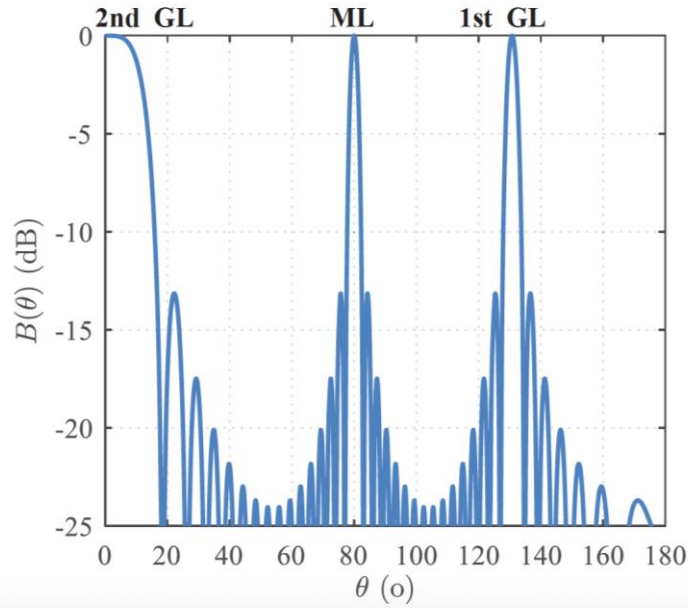
- By moving the antennas, different radiation patterns can be generated.
- Analogous to movable antennas, with mathematically equivalent behavior.
- More antennas, higher gain:
  - Additional spatial degrees of freedom.
  - Enhanced spatial resolution.
  - Increased channel capacity.
- Multiple fluid antennas.

[2]



Some Examples of Fluid Antenna Applications

- Fluid antennas at the base station.
- We can generate grating lobes at desired (controlled) directions [6]:
  - Allows covering two directions simultaneously.
  - e.g. Two users, one user and one reconfigurable intelligent surface, …



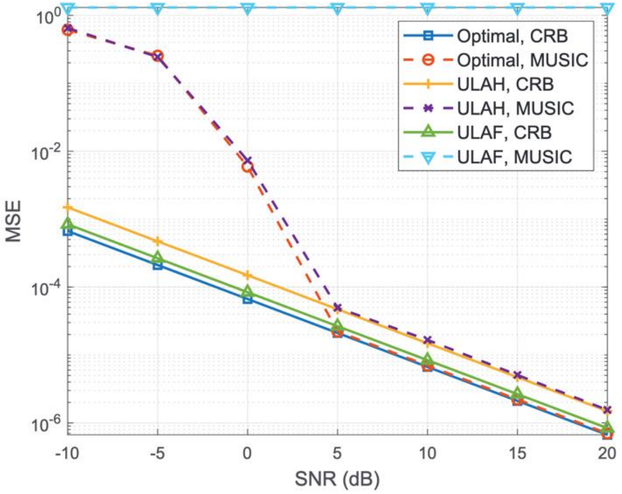
[6] J. Chen, Y. Xiao, J. Zhu, Z. Peng, X. Lei and P. Xiao, "Low-Complexity Beamforming Design for RIS-Assisted Fluid Antenna Systems," 2024 IEEE International Conference on Communications Workshops (ICC Workshops), Denver, CO, USA, 2024, pp. 1377-1382, doi: 10.1109/ICCWorkshops59551.2024.10615877.

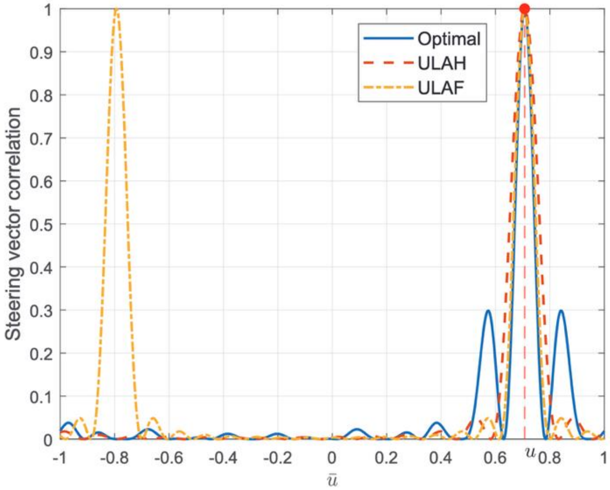
Some Examples of Fluid Antenna Applications

- Fluid antennas at the user equipment.
- Improve angle-of-arrival (AoA) estimation [7]:

Higher estimation accuracy

Lower correlation between steering vectors



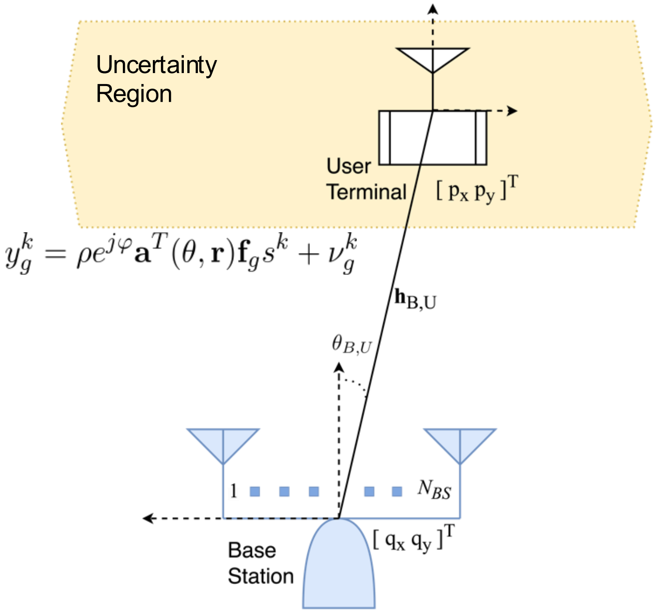


[7] W. Ma, L. Zhu and R. Zhang, "Movable Antenna Enhanced Wireless Sensing via Antenna Position Optimization," in *IEEE Transactions on Wireless Communications*, vol. 23, no. 11, pp. 16575-16589, Nov. 2024, doi: 10.1109/TWC.2024.3443293.

Fluid Antenna Systems for AoD Estimation

- Inspired by [7], we studied the problem of angle-of-departure (AoD) estimation using fluid antennas at the base station.

Find the optimal position of the antennas to minimize the worst-case Cramér-Rao Bound (wCRB) for AoD within the uncertainty region of the user terminal [8].



[8] L. Pallarés-Rodríguez *et al.*, "Optimal Placement of Movable Antennas for angle-of-departure Estimation under User Location Uncertainty," *2026 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Barcelona, Spain, 2026, pp. 22627-22631, doi: 10.1109/ICASSP55912.2026.11461519.

Fluid Antenna Systems for AoD Estimation

- Best estimation performance occurs when the antennas are placed at the array extremes [7] → Maximum Variance (MaxVar) solution.

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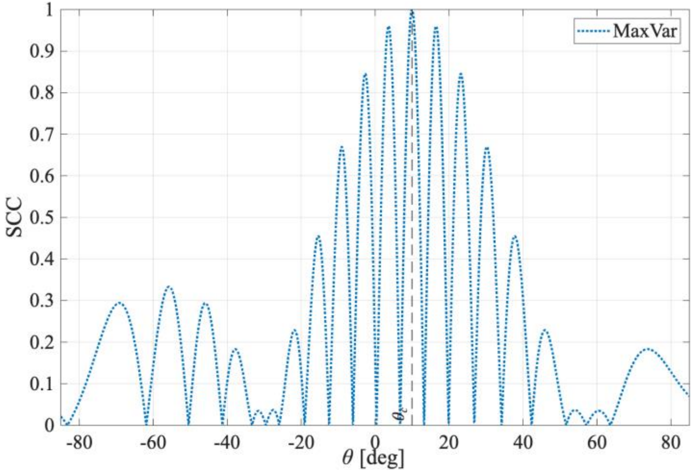
Fluid Antenna Systems for AoD Estimation

- Best estimation performance occurs when the antennas are placed at the array extremes [7] → Maximum Variance (MaxVar) solution.
- This solution generates high side-lobes that affect estimation performance:

Spatial correlation coefficient (SCC):

$$\mathrm{SCC}(\theta_i, \theta_j, \mathbf{r}) = \frac{\mathbf{a}^H(\theta_i, \mathbf{r})\,\mathbf{a}(\theta_j, \mathbf{r})}{||\mathbf{a}(\theta_i, \mathbf{r})||\;||\mathbf{a}(\theta_j, \mathbf{r})||}$$



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Fluid Antenna Systems for AoD Estimation

- To contemplate that, we limit the maximum SCC in the uncertainty region.
- A simplified version of the problem (ignoring additional constraints):

$$\min_{\mathbf{r}} \max_{\theta \in \mathcal{P}} \text{CRB}\left(\theta, \mathbf{r}\right) \quad \text{s.t.} \quad \max_{\theta_i, \theta_j \in \mathcal{P}} \text{SCC}(\theta_i, \theta_j, \mathbf{r}) \leq \kappa$$

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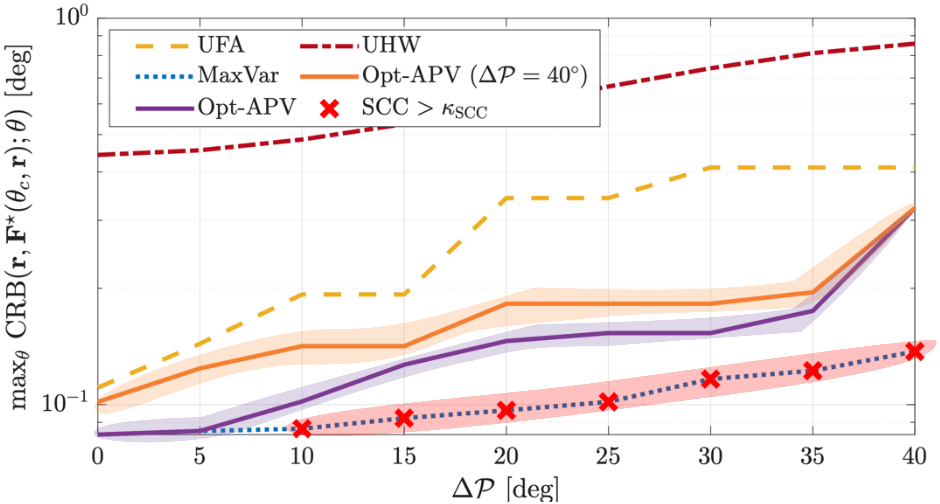
Results: worst-case CRB

Linear Array with 6 antennas; $D_{\text{max}} = 10\lambda$, $d_{\text{min}} = \lambda/2$, $\kappa = 0.5$ [8]

wCRB vs. Uncertainty Region Size ($\Delta\mathcal{P}$)



MaxVar solution does not satisfy the SCC constraint for $\Delta\mathcal{P} > 5°$.

Largest-region optimal vector is not optimal for smaller uncertainty regions.

Optimal performance by adapting antenna positions to each region.

[8] L. Pallarés-Rodríguez *et al.*, "Optimal Placement of Movable Antennas for angle-of-departure Estimation under User Location Uncertainty," *2026 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Barcelona, Spain, 2026, pp. 22627-22631, doi: 10.1109/ICASSP55912.2026.11461519.

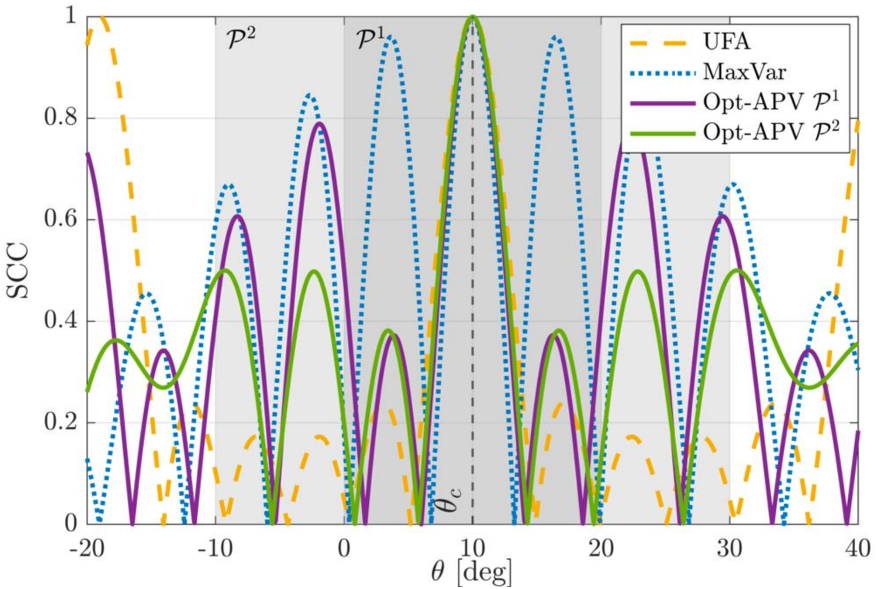
Results: SCC

Linear Array with 6 antennas; $D_{\max} = 10\lambda, d_{\min} = \lambda/2, \kappa = 0.5$ **[8]**

SCC ; $\Delta\mathcal{P}^1 = 20°$ and $\Delta\mathcal{P}^2 = 40°$

Opt-APV $\mathcal{P}^1$ and Opt-APV $\mathcal{P}^2$ have slightly better SCC than UFA.

Opt-APV $\mathcal{P}^1$ and Opt-APV $\mathcal{P}^2$ maintain SCC below 0.5 within their respective regions.



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Conclusion & Future Work

Fluid antennas can **improve angular estimation** performance while **reducing correlation** between steering vectors.

Complete the theoretical analysis by **incorporating AoD estimation results.**

Under user location uncertainty, optimal placement of fluid antennas **improves worst-case AoD estimation** performance and **reduces angular ambiguity.**

Multi-user scenarios: Extend the analysis to scenarios with **multiple uncertainty regions.**

Thank you for your attention !

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