One6G Open Lectures

Advancements in Fluid Antenna Systems for MIMO Communication: A Path to Enhanced Wireless Connectivity

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20th June 2024

Outline

I. Introduction

Background and framework

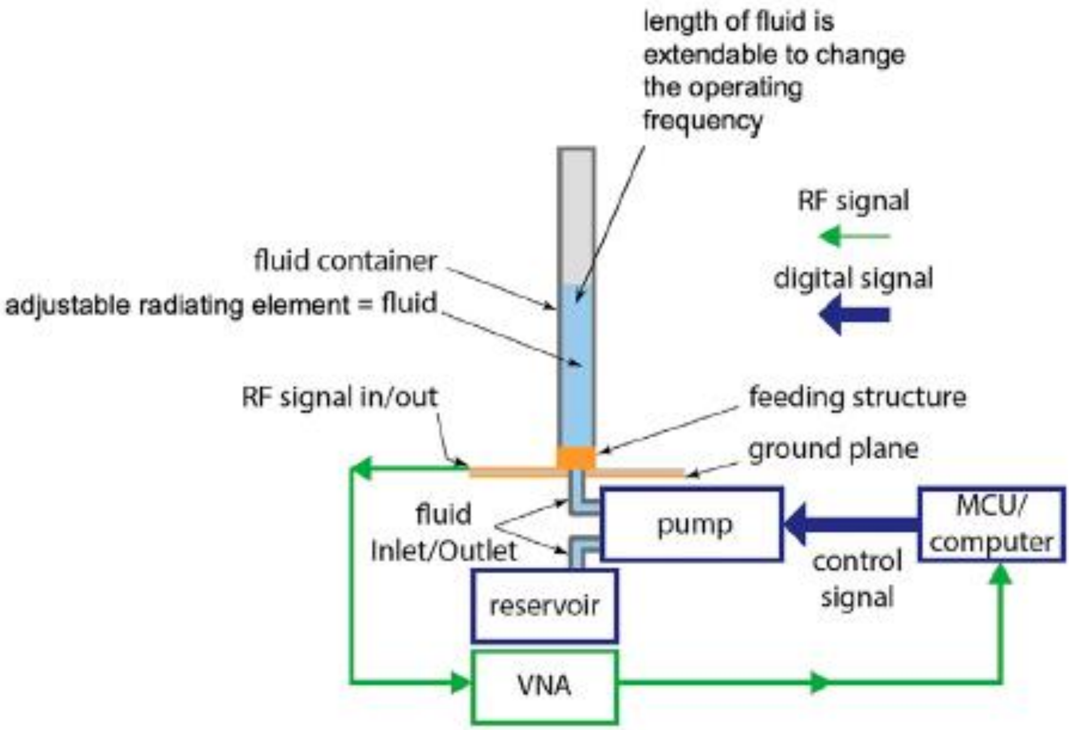
- Increasing connectivity demands (6G means from 30 to 100x capacity demand)
- Channel estimation overheads and complex precoding matrix for massive MIMO
- Scalability problems (today 64 antenna ports, up to 16 layers, 8 multiplexed UEs)
- NOMA (not 5G tech) imposes complexity on the UE side

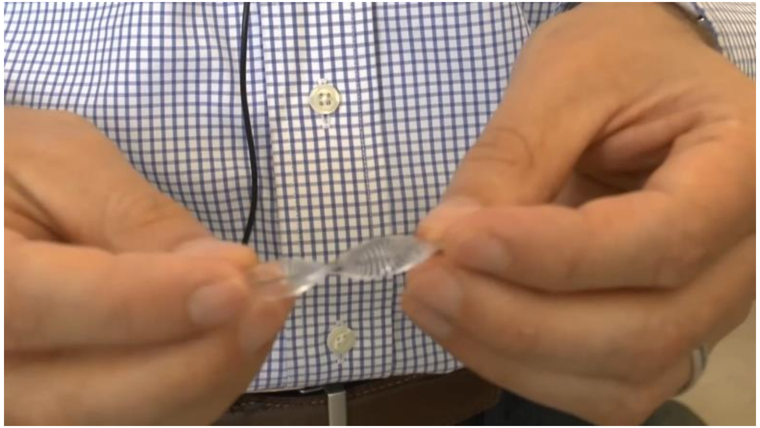
I. Introduction

Could Fluid Antenna Systems be the answer?

- Diversity and multiplexing gains
- No CSI acquisition overheads
- No precoding complexity
- “Simple” interference management

II. Principles of fluid antenna systems

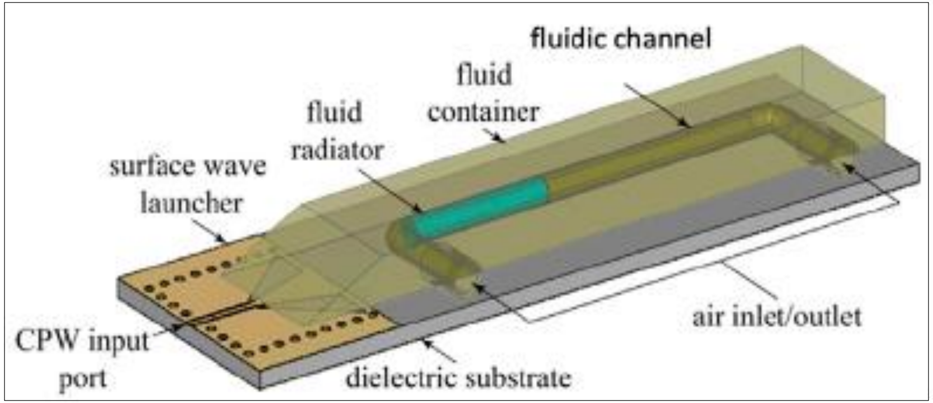




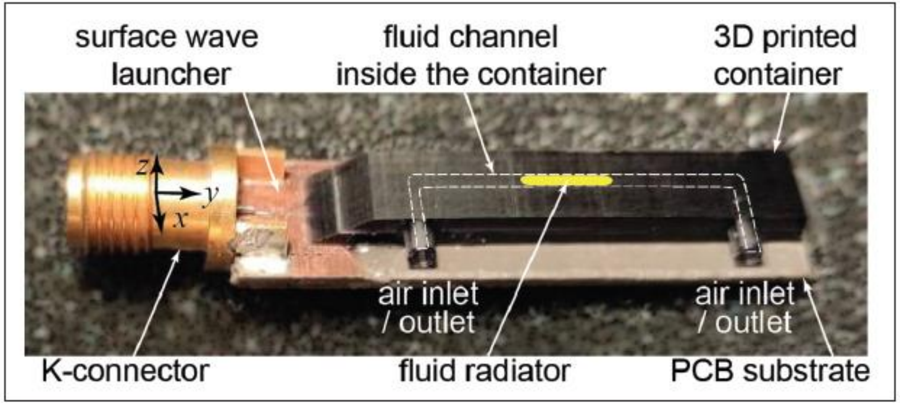
eutectic gallium-indium (eGaIn)

Wong, K. K., Tong, K. F., Shen, Y., Chen, Y., & Zhang, Y. (2022). Bruce Lee-inspired fluid antenna system: Six research topics and the potentials for 6G. *Frontiers in Communications and Networks*, *3*, 853416.

II. Principles of fluid antenna systems



A surface wave–based fluid antenna



Prototype manufactured by UCL, containing the geometry of the surface wave-based fluid antenna.

Wong, K. K., Tong, K. F., Shen, Y., Chen, Y., & Zhang, Y. (2022). Bruce Lee-inspired fluid antenna system: Six research topics and the potentials for 6G. *Frontiers in Communications and Networks, 3,* 853416.

J. O. Martínez, J. R. Rodríguez, Y. Shen, K. -F. Tong, K. -K. Wong and A. G. Armada, "Toward Liquid Reconfigurable Antenna Arrays for Wireless Communications," in *IEEE Communications Magazine*, vol. 60, no. 12, pp. 145-151, December 2022, doi: 10.1109/MCOM.001.2200392.

II. Principles of fluid antenna systems

Reconfigurability

Dynamic tuning of shape, position, polarization, and radiation patterns.

Compact & Lightweight

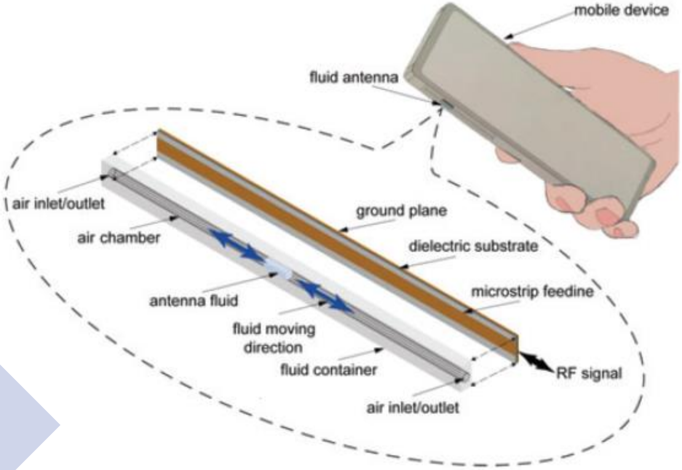
Ideal for mobile and portable devices.

Enhanced Performance

Improved signal quality and higher efficiency.

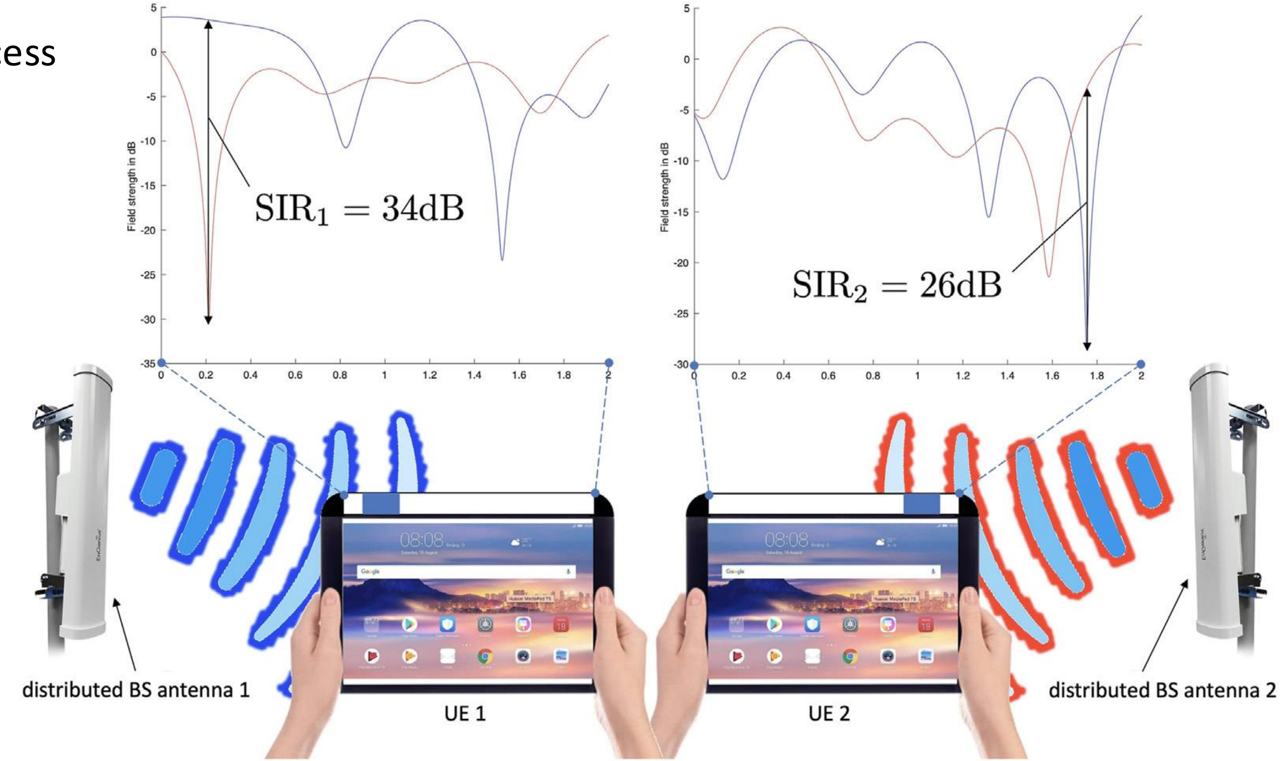
Interference inmunity

Interference can be avoided by switching ports.



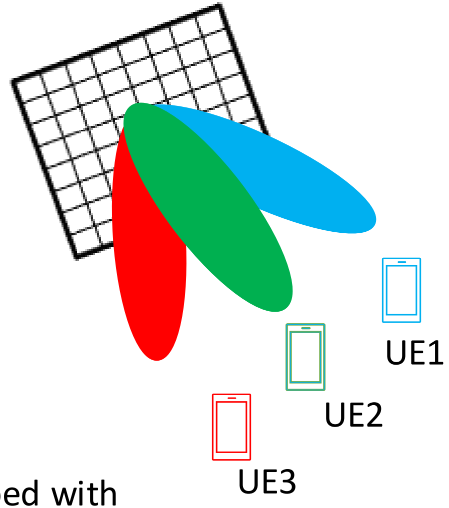
Wong, K. K., Tong, K. F., Zhang, Y., & Zhongbin, Z. (2020). Fluid antenna system for 6G: When Bruce Lee inspires wireless communications. *Electronics Letters*, *56*(24), 1288-1290.

Fluid Antenna Multiple Access



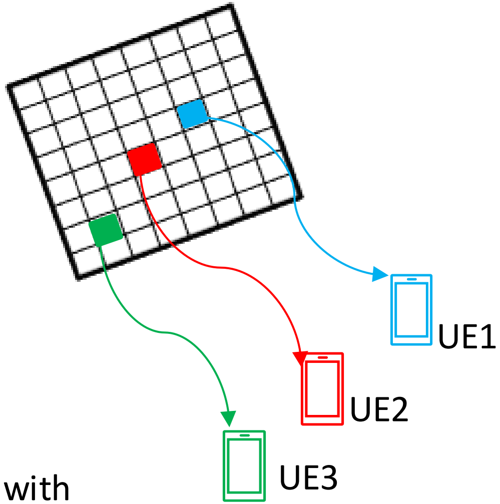
III. Integration of FAS in MIMO systems

- BS is equipped with a fixed MIMO antenna array



- UEs are equipped with fixed MIMO arrays

- BS is equipped with a fixed MIMO antenna array



- UEs are equipped with fluid antenna systems

- Having N-antenna array at BS, K UEs could be served simultaneously, being K considerably smaller than N in practice.
- With fluid antennas, multiple access (FAMA) could be achieved at the UE side, so each BS antenna could transmit to a different UE simultaneously, i.e, $N = K$.

III. Integration of FAS in MIMO systems

Capacity expression:

Being N and M the number of transmit and receive antennas, C_t y C_r square regions where transmit and receive antennas can freely move and $t_n = \left[x_{t,n}, y_{t,n}\right]^T \in \mathcal{C}_t$ and $r_m = \left[x_{r,m}, y_{r,m}\right]^T \in \mathcal{C}_r$ the antennas' coordinates…

$$\tilde{\boldsymbol{t}} = [\boldsymbol{t}_1, \boldsymbol{t}_2, \ldots, \boldsymbol{t}_N] \in \mathbb{R}^{2\times N}$$
$$\tilde{\boldsymbol{r}} = [\boldsymbol{r}_1, \boldsymbol{r}_2, \ldots, \boldsymbol{r}_M] \in \mathbb{R}^{2\times M}$$

$$\boldsymbol{H}(\tilde{\boldsymbol{t}}, \tilde{\boldsymbol{r}}) \in \mathbb{C}^{M\times N}$$

$$\boldsymbol{Q} \triangleq \mathbb{E}\{\boldsymbol{s}\boldsymbol{s}^H\} \in \mathbb{C}^{N\times N}, \boldsymbol{Q} \succcurlyeq \boldsymbol{0}, \boldsymbol{s} \in \mathbb{C}^N, \mathbb{E}\{\|\boldsymbol{s}\|^2\} \leq P \Leftrightarrow \mathrm{Tr}(\boldsymbol{Q}) \leq P$$

$$\boldsymbol{y}(\tilde{\boldsymbol{t}}, \tilde{\boldsymbol{r}}) = \boldsymbol{H}(\tilde{\boldsymbol{t}}, \tilde{\boldsymbol{r}})\boldsymbol{s} + \boldsymbol{z}, \quad \boldsymbol{z} \sim \mathcal{CN}(0, \sigma^2 \boldsymbol{I}_M)$$

$$C(\tilde{\boldsymbol{t}}, \tilde{\boldsymbol{r}}) = \max_{\substack{\boldsymbol{Q}:\boldsymbol{Q} \succcurlyeq \boldsymbol{0} \\ \mathrm{Tr}(\boldsymbol{Q}) \leq P}} \log_2 \det\left(\boldsymbol{I}_M + \frac{1}{\sigma^2}\boldsymbol{H}(\tilde{\boldsymbol{t}}, \tilde{\boldsymbol{r}})\boldsymbol{Q}\boldsymbol{H}(\tilde{\boldsymbol{t}}, \tilde{\boldsymbol{r}})^H\right)$$

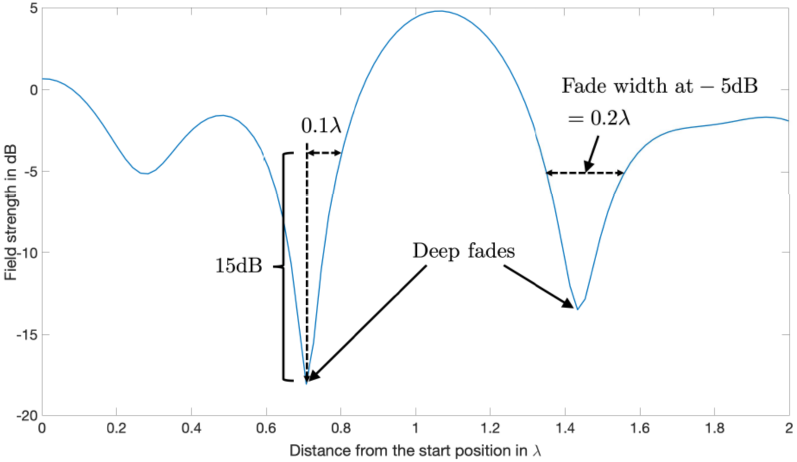
W. Ma, L. Zhu and R. Zhang, "MIMO Capacity Characterization for Movable Antenna Systems," in *IEEE Transactions on Wireless Communications*, vol. 23, no. 4, pp. 3392-3407, April 2024, doi: 10.1109/TWC.2023.3307696.

III. Integration of FAS in MIMO systems

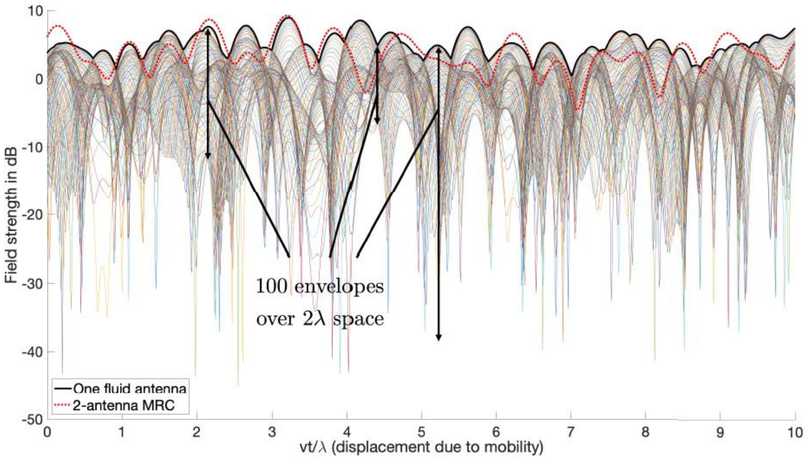
- Fluid Antenna Multiple Access (FAMA): The UE finds and activates the best port for reception and the interference signal will disappear naturally due to fading.

- **Slow FAMA**: each UE activates the port that maximizes the average SINR.

- **Fast FAMA**: each UE chooses the port that maximizes the ratio between the instantaneous desired signal energy and the instantaneous energy of the sum-interference and noise.



(a) A typical received signal across a space of 2λ

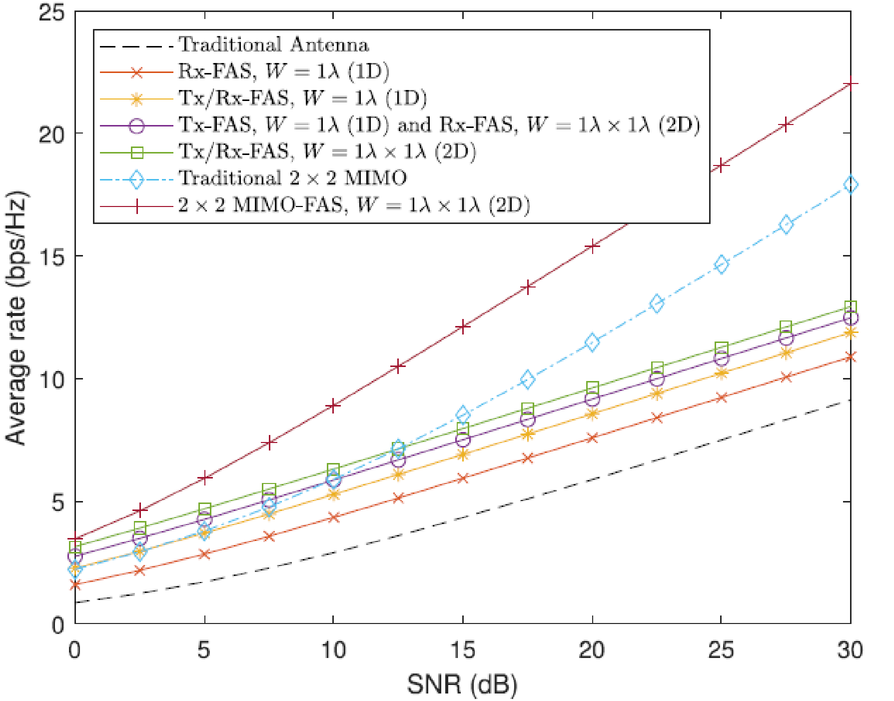


(b) Comparison for a 100-port FAS with 2λ space and MRC at 5GHz at $v = 30$km/h

Examples for the fading envelopes.

K. -K. Wong, A. Shojaeifard, K. -F. Tong and Y. Zhang, "Fluid Antenna Systems," in *IEEE Transactions on Wireless Communications*, vol. 20, no. 3, pp. 1950-1962, March 2021, doi: 10.1109/TWC.2020.3037595.

IV. Some SoA results



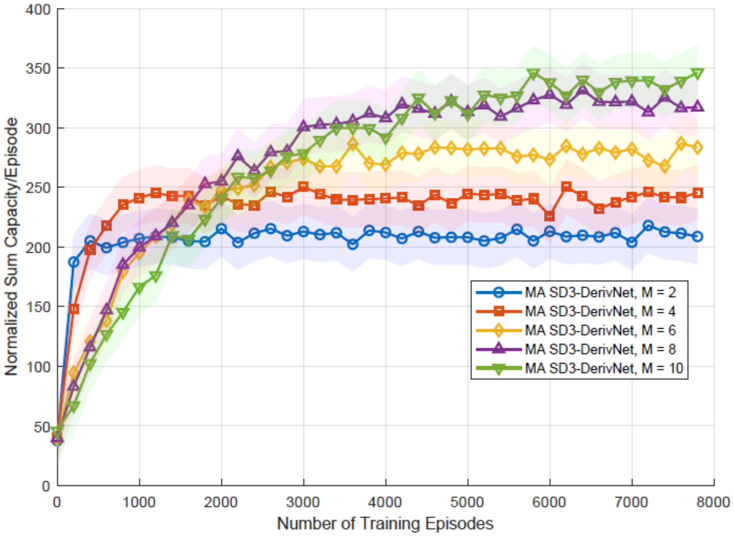
Average rate of SIMO and MIMO FAS against the SNR

K. -K. Wong, W. K. New, X. Hao, K. -F. Tong and C. -B. Chae, "Fluid Antenna System—Part I: Preliminaries," in *IEEE Communications Letters*, vol. 27, no. 8, pp. 1919-1923, Aug. 2023, doi: 10.1109/LCOMM.2023.3284320.

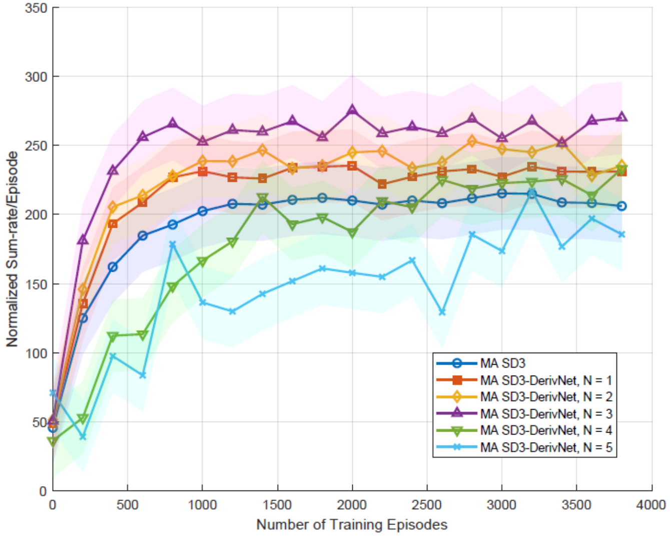
IV. Some SoA results

MA SD3-DerivNet employs the softmax deep deterministic policy gradient (SD3) algorithm in combination with the derivative network for a multi-agent scenario.

M: The total number of users in the system
W: Normalized size of FAS
K: Total number of ports at FAS
N: number of required derivatives



Convergence analysis of the proposed **MA SD3-DerivNet** scheme, exhibiting cumulative system rewards achieved against the number of training episodes for varying M, with $W = 2$, $K = 100$, and $N = 3$.



Convergence analysis of the proposed **MA SD3-DerivNet scheme**, exhibiting cumulative system rewards achieved against the number of training episodes for varying N, with $W = 2$, $K = 100$, and $M = 6$.

N. Waqar, K. -K. Wong, C. -B. Chae, R. Murch, S. Jin and A. Sharples, "Opportunistic Fluid Antenna Multiple Access via Team-Inspired Reinforcement Learning," in *IEEE Transactions on Wireless Communications*, doi: 10.1109/TWC.2024.3387855.

V. Challenges

VI. Research Opportunities

VII. Conclusions

Simplified Management and Enhanced Capacity

FAMA simplifies the operation and management of massive connections and adds dimensions to MIMO at base stations, accommodating more users and easing antenna optimization.

Innovative Antenna Solutions

Fluid MIMO introduces single RF-chained multiple antennas in mobile devices, improving interference immunity and offering highly flexible, quickly responsive antennas with high frequency agility, diversity, and multiplexing gains.

Improved Efficiency and Security

Learning-based methods enable efficient port selection for mobile communications, while fluid antenna technologies reduce latency and enhance security in mobile networks.

Thank you

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