International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 3 [March. 2025] PP: 185-188

Fluid Antenna Systems: An Insight

Akaa A. Eteng
Department of Electrical/Electronic Engineering
Faculty of Engineering University of Port Harcourt Rivers State, Nigeria

Abstract
Multiple-input multiple-output (MIMO) systems provide significant diversity and multiplexing gain enhancements for wireless communications in multipath-rich environments. These performance gains are based on having multiple antennas at fixed locations at the receiving and transmitting terminals. In contrast, fluid antenna systems attempt to replicate the robustness to fading conditions by having a single antenna instantaneously move to any one of fixed locations over a finite length in order to provide diversity at the terminal. In array-based fluid antenna systems, the concept also expands to the ability to adapt the intrinsic electromagnetic properties of each array element to channel conditions, while maintaining their positional dynamism. This paper explores techniques employed to provide this dynamism, namely through continuous fluid- or switchable pixel-based antenna implementations. The article also discusses challenges in fluid antenna systems and proposes areas of further research interest.
Keywords: *Antennas, multiple-input multiple-output, diversity gain, next-generation multiple access, fluid antenna, next-generation wireless networks*

Date of Submission: 16-03-2025 Date of acceptance: 31-03-2025

I. Introduction

Mitigating the impact of the adversarial aspects of the wireless channel is, perhaps, the most critical aspect of wireless communication system design. Free-space line-of-sight propagation represents an ideal condition, characterized by a clear signal path between a pair of linked transceivers, devoid of obstacles and instigators of anomalous propagation conditions. However, the more realistic propagation environment is characterized by objects along signal paths, giving rise to signal blockage, reflection, diffraction and scattering. In addition to a loss in signal strength, these phenomena give rise to multipath-induced fading conditions, where signal components arriving at the receiver via different paths and with different phase orientations, interfere with one another and cause signal outages.

Antenna diversity schemes are an established means for combating the debilitating effects of multipath. However, the birth of multiple-input multiple-output (MIMO) wireless technology over three decades ago [1], [2] provided a revolutionary approach, which rather exploits the presence of multipath conditions to significantly boost channel capacity. Leveraging on the diversity provided by multipath signals at antennas independently experiencing fading, the MIMO technique employs multiple transmitting and receiving antennas to provide spatial multiplexing of data so that more data is transmitted over the wireless channel. The original MIMO concept has given rise to various contemporary techniques for enhancing capacity, such as cell-free massive MIMO [3] and near-field MIMO [4].

The benefits of MIMO are realized when the spatial correlation between antennas at a transceiver is minimal in order to preserve the orthogonally of the data streams. This independence is often preserved by maintaining a half-wavelength spatial separation between antennas. However, this arrangement may not always be workable in devices with tight footprint restrictions. Although studies have shown that deep fade conditions can be surmounted with antenna spacing below the half-wavelength criterion [5], mitigating the mutual coupling between antennas within such tight spaces is a complicated endeavour. This challenge has provided the impetus for the conceptualization of dynamic antenna systems, where a single antenna can instantaneously switch positions within a linear or planar space in order to combat fading. One of such dynamic antenna realizations is the *fluid antenna system*, which "*represents any software-controllable fluidic, conductive, or dielectric structure that can alter its shape and position to reconfigure the gain, radiation pattern, operating frequency, and other characteristics*." [6]

The goal of this paper is to present a concise insight into fluid antenna systems as an approach to mitigate fading in wireless channels. First, it highlights the relationship between fluid antenna systems and other flexible antenna technologies. Subsequent sections discuss the two general categories of fluid antenna systems. First, spatially-reconfigurable fluid antenna systems are presented under the banner of the two general methods for implementing them – continuous fluid systems and pixelated systems. Next, electromagnetically-reconfigurable fluid antenna systems are described. Lastly, this paper examines challenges associated with the implementation of this technology, and discusses an outlook for further development towards mainstreaming this technology.

1. Relationship With Other Flexible Antenna Systems

Traditionally, *flexible antennas* in the research literature denotes antennas that are structurally malleable, for example, bendable antennas [7]. R*econfigurable antennas*, on the other hand, usually refer to those whose operational features can be altered while in use, for instance frequency-reconfigurable antennas [8]. A recent observable trend is the development of antenna systems that employ some levels of positional flexibility to provide reconfigurability. It is necessary to comment on fluid antennas within the context of such dynamic antenna systems.

Early research in fluid antennas largely presented them as synonymous with *liquid antennas*, signifying the idea of implementation using liquid metals or dielectrics [9], [10], [11]. Since then, various prototypes of fluid antenna systems have been developed, such that the contemporary use of the term '*fluid'* encompass all mechanisms to enable flexibility in the antenna shape and position, including continuous fluid [12] or pixel-based implementations [13]. *Movable antennas*, on the other hand, originally referred to antennas whose position or orientation could be adjusted in response to control signals using external mechanical actuators such as micro-electromechanical system (MEMS) actuators or step motors [14]. Contemporary research, though, suggests a convergence of fluid and movable antennas, and the traditional distinctions between both antenna implementations are no longer stark [15], [16]. Yet, a distinct flexible antenna paradigm has recently emerged in the research community – *pinching antenna systems* [17]. This is a variation of movable antenna systems not targeted towards device integration, and provides much greater latitude for instantaneous movement and positioning.

2. Spatially-Reconfigurable Fluid Antenna Systems

The basic concept of a spatially-reconfigurable fluid antenna system is that there are a number of fixed locations, also known as ports, evenly distributed along a linear space of fixed length. The position of the antenna can be switched instantaneously to any port with the strongest received signal. By so doing, fading effects are mitigated by providing a form of spatial diversity without generating mutual coupling, since only one antenna is present in the system. A theoretical study of this idealized model in [5] demonstrates the potential for achieving an arbitrarily small outage probability regardless of how tight the linear footprint of the system is. Two practical approaches for implementing such spatially-reconfigurable fluid antenna systems are through the use of continuous fluid mechanisms and pixelated systems, and are highlighted below.

2.1. Continuous Fluid-Based Antennas

Continuous fluid systems employ radiating fluids that can be moved within designated spaces to provide spatial diversity. Shen et al. [18] provide an example of a surface-wave-based fluid antenna system. The operation of the antenna is based on the diffraction of a propagating surface wave by the fluid radiating element, thereby creating a beam-pattern at that location. Changing the position of the fluid radiating element leads to a change in the direction and location of the resulting beam-pattern. With fine-control of the fluid element, the antenna system achieves a high level of spatial resolution.

This example highlights some key elements for implementing a continuous fluid-based system namely, the fluid radiating element, the fluid channel or container, and the actuating system. Liquid metals, ionized solutions or water can serve as the fluid radiating element. Typical liquid metals used for this purpose include mercury [19], eutectic gallium-indium [20] and galistan liquid metal alloy, among others [21]. Ionized solutions and water lend themselves to dielectric resonator-type antenna implementations. Fluid channels, on the other hand can be implemented using photolithographic techniques. Alternatively, 3D printing can be used to additively fabricate a resin container for the fluid flow. Lastly, the actuating system consists of a microcontroller connected to a micro- or nano-pump to provide the pressure necessary for fluid flow into or out of the microchannels in the fluid container. The microcontroller provides the control signaling to activate the pump in accordance with programmed logic.

2.2. Pixelated Antennas

Pixel-based reconfigurable antennas realize the desired adaptability of a fluid antenna system through the use of radio-frequency (RF) switches, rather than physical movement of a fluid. An example of the adoption of such structures for fluid antenna systems is provided in [13]. This design is based on the premise that changes in antenna position and orientation are equivalent to beam-pattern reconfiguration. The developed prototype consists of 12 ports spanning across a half-wavelength and operates at 2.5 GHz. This geometry provides fine-spatial sampling of the wireless channel. The antenna structure consists of an E-slot patch that is probe-fed through its ground plane. A second substrate, consisting of metallic pixels printed on its top surface, is placed as an upper layer above the E-slot patch layer, with an air-gap separating both layers. The E-slot patch is the radiation source for the upper pixel substrate. Six RF switches are strategically placed among 60 internal ports in order to electronically switch between pixels, thereby varying the antenna configuration at microsecond speeds.

This proposal lays out the key components of a pixelated fluid antenna systems. First is the radiating element, which serves as a radiation source for the pixelated the main radiator. RF switches are required to alter the flow of surface current on the pixelated structure, so that specific pixels can be activated as required for the reconfiguration. A field programmable gate array (FPGA) or microcontroller provides the control signals to activate and deactivate switches according to the programmed logic.

3. Electromagnetically-Reconfigurable FAS

In contrast with spatially-reconfigurable implementations which focus on antenna orientation and position, electromagnetically-reconfigurable fluid antenna systems focus on adapting the intrinsic electromagnetic radiation properties of the antenna, such as frequency, gain or bandwidth. Borda-Fortuny et al. [23] provide an example of an electromagnetically-reconfigurable fluid monopole antenna system consisting of a radiating fluid in a tube. The effective length of the antenna is varied by adjusting the amount of radiating fluid within the tube, thereby enabling control over the resonant frequency. This antenna can be employed in cognitive radio applications, where frequency-agile transceivers are required to switch their operating frequencies in response to frequency availability or priorities.

Electromagnetic reconfigurability can provide an added dimension of flexibility to the spatial dynamism of an array-based fluid antenna system. This is illustrated in the fluid antenna design for an array element proposed in [21]. The front layer of this three-layer structure contains independently controlled and reconfigurable parasitic fluid metal channels. In this case, the liquid metals are encapsulated within transparent polyethylene terephthalate (PET) substrates and polymethyl methacrylate (PMMA). The middle layer comprises a planar monopole antenna with two metallic layers, which is fed through an SMA connector. The back layer contains an additional set of parasitic fluid metal channels, which are also independently controlled and reconfigurable. This layout assigns the role of the primary radiating element to the planar monopole antenna middle layer. The fluid channels in the front and back layers sandwiching the monopole antenna act as directors and reflectors, respectively. Having these two layers in place is necessary to have a good directivity and front-to-back ratio performance. Independent control of each fluid channel in both the front and back layers enables the dynamic adjustment of the antenna element beam pattern. Exploiting N channels in each of both layers can potentially provide reconfigurable states.

4. Challenges and Outlook

Although a number of significant insights have been gained from theoretical studies, electromagnetic simulations and proofs-of-concept, research in fluid antenna systems is still in its infancy. There are a number of challenges that require concerted attention in order to bring this technology to maturity.

The first is the problem of selecting the optimal port in spatially-reconfigurable fluid antenna systems. Performance gains realized by using such systems are predicated on being able to instantly switch to the best port to maintain favourable communication conditions. The authors in [6] draw a contrast between slow and fast port selection strategies. Single-user fluid systems exhibit slow selection in the sense that a port selection is altered only when channel conditions change. On the other hand, fast selection re-selects ports whenever an instantaneous interference signal in the multipath environment changes. Be that as it may, port selection requires that the transceiver has access to measurements of the signal quality at each port, which becomes daunting as the number of ports increases. It is necessary to work out algorithms to infer port conditions in real time, probably through learning-learning based methodologies.

Another area of concern lies in the physical implementation of these systems. While pixelated antenna realizations have an edge in speed due to the switching times provided by electronic switches, the achievable reconfigurable states are limited. Systems implemented using fluidic channels may provide greater flexibility in implementing intermediate states. However, fluidic channels have fixed dimensions and layouts, which ultimately restrict the range of reconfigurability. It would be interesting to investigate finer-grained pixel implementations, without compromising the elimination of mutual coupling between elements. For fluidic channel implementations, methods to deploy liquid metals without the need for pre-defined pathways would extend the adaptability of such systems. Also, it would be interesting to have prototypes of array-based fluid antenna systems, where electromagnetic-reconfigurability of each antenna element is combined with spatial-reconfigurability of the whole system.

Lastly, going by the trajectory provided by MIMO research, it is expected that multiple-antenna implementations of fluid antenna systems would likely provide performance enhancements significantly beyond what is predicted for current single-antenna systems. Also, extending the operation of these systems to millimetre wave (mm-wave) bands could provide bandwidths, speeds and spectral efficiencies in excess of what is obtainable at lower microwave frequencies.

II. Conclusion

This paper has provided an overview of fluid antenna systems as a novel device antenna paradigm to combat fading-induced outages in multipath rich environments. The two major categories of fluid antenna systems have been discussed, namely spatially-reconfigurable and electromagnetically reconfigurable systems. The paper has noted that that spatial-reconfigurability can be achieved either using continuous fluid antenna systems or pixelated antenna systems, while electromagnetic-reconfigurability focuses on adapting the intrinsic qualities of the antenna to the channel conditions. The paper ends by highlighting three areas of potential further research, namely optimal selection of ports in real-time, hardware implementation of reconfigurable structures and the extension of the concept to fluid multi-antenna systems.

References

[1]. G. J. Foschini and M. J. Gans, “On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas”.

[2]. S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998, doi: 10.1109/49.730453.

[3]. S. Elhoushy, M. Ibrahim, and W. Hamouda, “Cell-free massive MIMO: A survey,” *IEEE Commun. Surv. Tutor.*, vol. 24, no. 1, pp. 492–523, 2021.

[4]. X. Hou, E. Björnson, N. Lee, and R. W. Heath, “Guest Editorial: Near-Field MIMO Technologies Toward 6G,” *IEEE Commun. Mag.*, vol. 63, no. 1, pp. 20–21, 2025.

[5]. K.-K. Wong, A. Shojaeifard, K.-F. Tong, and Y. Zhang, “Fluid Antenna Systems,” May 23, 2020, *arXiv*: arXiv:2005.11561. doi: 10.48550/arXiv.2005.11561.

[6]. 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, p. 853416, Mar. 2022, doi: 10.3389/frcmn.2022.853416.

[7]. S. G. Kirtania *et al.*, “Flexible antennas: A review,” *Micromachines*, vol. 11, no. 9, p. 847, 2020.

[8]. S. T. Al-Hadeethi, T. A. Elwi, and A. A. Ibrahim, “A Printed Reconfigurable Monopole Antenna Based on a Novel Metamaterial Structures for 5G Applications,” *Micromachines*, vol. 14, no. 1, p. 131, Jan. 2023, doi: 10.3390/mi14010131.

[9]. Y. Huang, L. Xing, C. Song, S. Wang, and F. Elhouni, “Liquid antennas: Past, present and future,” *IEEE Open J. Antennas Propag.*, vol. 2, pp. 473–487, 2021.

[10]. A. Diebold *et al.*, “Electrowetting-actuated liquid metal for RF applications,” *J. Micromechanics Microengineering*, vol. 27, no. 2, p. 025010, 2017.

[11]. Y. Shen, K.-F. Tong, and K.-K. Wong, “Radiation pattern diversified double-fluid-channel surface-wave antenna for mobile communications,” in *2022 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, IEEE, 2022, pp. 085–088.

[12]. C. Psomas, P. J. Smith, H. A. Suraweera, and I. Krikidis, “Continuous fluid antenna systems: Modeling and analysis,” *IEEE Commun. Lett.*, vol. 27, no. 12, pp. 3370–3374, 2023.

[13]. J. Zhang *et al.*, “A novel pixel-based reconfigurable antenna applied in fluid antenna systems with high switching speed,” *IEEE Open J. Antennas Propag.*, 2024.

[14]. A. Zhuravlev, V. Razevig, S. Ivashov, A. Bugaev, and M. Chizh, “Experimental simulation of multi-static radar with a pair of separated movable antennas,” in *2015 IEEE International Conference on Microwaves, Communications, Antennas and Electronic Systems (COMCAS)*, IEEE, 2015, pp. 1–5.

[15]. B. Ning *et al.*, “Movable Antenna-Enhanced Wireless Communications: General Architectures and Implementation Methods,” Aug. 08, 2024, *arXiv*: arXiv:2407.15448. doi: 10.48550/arXiv.2407.15448.

[16]. L. Zhu and K.-K. Wong, “Historical Review of Fluid Antenna and Movable Antenna”.

[17]. Z. Yang *et al.*, “Pinching Antennas: Principles, Applications and Challenges,” Jan. 18, 2025, *arXiv*: arXiv:2501.10753. doi: 10.48550/arXiv.2501.10753.

[18]. Y. Shen, K.-F. Tong, and K.-K. Wong, “Reconfigurable surface wave fluid antenna for spatial MIMO applications,” in *2021 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, IEEE, 2021, pp. 150–152.

[19]. Y. Kosta and S. Kosta, “Realization of a microstrip-aperture-coupled-passive-liquid patch antenna,” in *2008 IEEE International RF and Microwave Conference*, IEEE, 2008, pp. 135–138.

[20]. G. J. Hayes, J.-H. So, A. Qusba, M. D. Dickey, and G. Lazzi, “Flexible liquid metal alloy (EGaIn) microstrip patch antenna,” *IEEE Trans. Antennas Propag.*, vol. 60, no. 5, pp. 2151–2156, 2012.

[21]. R. Wang *et al.*, “Electromagnetically Reconfigurable Fluid Antenna System for Wireless Communications: Design, Modeling, Algorithm, Fabrication, and Experiment,” Mar. 01, 2025, *arXiv*: arXiv:2502.19643. doi: 10.48550/arXiv.2502.19643.

[22]. L. N. Pringle *et al.*, “A reconfigurable aperture antenna based on switched links between electrically small metallic patches,” *IEEE Trans. Antennas Propag.*, vol. 52, no. 6, pp. 1434–1445, 2004.

[23]. C. Borda-Fortuny, K.-F. Tong, A. Al-Armaghany, and K.-K. Wong, “A low-cost fluid switch for frequency-reconfigurable Vivaldi antenna,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 3151–3154, 2017.