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Views & Comments

Fluid MIMO: A Timely MIMO Upgrade

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1. Introduction

Wireless systems are entering an era of unprecedented complexity. Beyond the traditional pursuit of ever-higher spectral efficiency, networks must simultaneously deliver stringent energy efficiency and hyper-reliable low-latency communication (HRLLC) [1–3], while supporting new service paradigms such as integrated sensing and communication (ISAC) [4–6] and mobile edge computing (MEC) [7–9]. These capabilities will not be add-ons; they will be native requirements driven by heterogeneous devices, dense deployments, and highly dynamic environments. A particularly strong driver is the rapid emergence of robots—across factories, warehouses, hospitals, homes, and low-altitude platforms [10,11]—that demand continuous high-rate uplink and downlink connectivity, tight control-loop latency, and reliable perception-grade links for cooperation and safety. Such mobility-intensive applications have also stimulated growing interest in waveform designs tailored for rapidly time-varying channels, including orthogonal time frequency space (OTFS) modulation [12] and its variants such as orthogonal delay-Doppler division-multiplexing modulation (ODDM) [13] and affine frequency-division multiplexing (AFDM) [14]. In many such scenarios, robots operate in cluttered, mobility-rich, and blockage-prone settings in which conventional cellular architectures, built around fixed antenna apertures with limited spatial degrees of freedom (DoFs), may struggle to provide the combination of throughput, robustness, and responsiveness required at scale.

Multiple-input multiple-output (MIMO) technology [15,16] has been the workhorse underpinning modern cellular evolution, and the prevailing trajectory toward massive and even extra-large MIMO systems continues to bet on scaling antenna counts to unlock more spatial DoFs [17]. Yet, this direction is approaching practical limits. As arrays grow, channel acquisition and tracking become increasingly burdensome, since pilot overhead, feedback, calibration, and channel state information (CSI) latency all scale unfavorably. Moreover, precoding/combining design imposes substantial computational complexity and stringent real-time requirements. These challenges are compounded by hardware and energy costs: More radio-frequency (RF) chains, higher baseband throughput, and tighter synchronization translate directly into higher power consumption and reduced system efficiency. Furthermore, the "infrastructure-centric" nature of MIMO precoding assumes a capable coordinator (e.g., a base station (BS)) with global CSI and centralized processing, which is often unavailable in emerging scenarios such as device-to-device links, machine-to-device interactions, and massive Internet-of-Things (IoT) swarms. In these distributed settings, where coordination is limited, nodes are power-constrained, and channels are highly dynamic, classical large-array MIMO technology becomes difficult to deploy and, in many cases, ill-suited as the primary path to meet next-generation connectivity demands.

These limitations motivate a complementary paradigm that increases spatial capability without blindly scaling hardware complexity: the fluid antenna system (FAS) [18,19]. Rather than treating the antenna array as a fixed aperture, FASs elevate antenna reconfiguration to a first-class physical-layer resource, allowing a compact device or infrastructure node to adapt its effective spatial sampling by selecting (or continuously adjusting) antenna ports/positions within a confined region [20–25]. In doing so, FASs convert the spatial fading field, often viewed as an impairment, into an exploitable resource, enabling users to seek favorable channel states, suppress interference [26], and shape spatial correlation in a controllable manner. This opens a path to "next-level MIMO," where spatial DoFs are obtained through reconfigurable sampling rather than ever-larger numbers of always-on RF chains, thereby reducing the channel-estimation burden, lowering power consumption, and making spatial processing viable even in decentralized settings (e.g., robot-to-robot connectivity and massive IoT). In short, FASs provide a hardware-agnostic system concept that can extend the benefits of MIMO technology to emerging scenarios where conventional array scaling is no longer the most practical—or even feasible—solution.

Although the FAS is a system-level concept, tangible progress has been made toward its practical realization. Representative implementations include mechanically movable antennas [27], liquid-based antennas [28,29], reconfigurable pixel-based radiating structures [30–32], and metamaterial-/metasurface-enabled platforms [33,34]. These prototypes demonstrate that "antenna

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fluidity" can be instantiated through multiple hardware routes, each with distinct trade-offs in switching speed, control granularity, losses, and integration complexity. A recent article by Tong et al. [35] provides a timely overview of these practical challenges and offers a comparative discussion of emerging FAS prototypes, helping to clarify the implementation landscape and the key bottlenecks toward deployment.

This article focuses on fluid MIMO, also referred to as MIMO-FAS [36], where FASs are deployed at both the BS and user equipment (UE). We highlight its performance advantages over conventional MIMO technology with fixed-position antennas (FPAs). Instead of pursuing ever-larger arrays, fluid MIMO exploits high-resolution spatial sampling within compact apertures: By reconfiguring ports/positions on demand, it adapts the effective transmit/receive geometry to the instantaneous propagation environment. This allows the system to preferentially operate on more favorable channel realizations, thereby enhancing the desired link strength and interference conditions, without proportionally increasing the number of active RF chains. Hence, fluid MIMO offers a fundamentally different pathway for improving spatial resource utilization and provides a promising route to alleviating key scalability bottlenecks of conventional MIMO architectures.

2. Fundamentals of fluid MIMO

The FAS was originally introduced by Wong et al. [18,19], inspired by the notion that an antenna can be "shapeless like fluid"—that is, capable of reconfiguring its effective radiating position, and more generally its radiation characteristics, within a given aperture. Under this paradigm, the antenna location is no longer a fixed hardware attribute; instead, it becomes an adaptable physical-layer resource that can be tuned to the propagation environment, thereby creating additional DoFs for signal processing and system design. When such spatial reconfigurability is extended to multi-antenna transmission and reception, it naturally leads to the concept of fluid MIMO.

Unlike conventional MIMO, in which the available spatial DoFs are largely determined by the number and fixed geometry of FPAs, fluid MIMO can adapt its effective transmit/receive geometry by selecting (or combining) ports within the accessible region. In doing so, it effectively reshapes the channel statistics and instantaneous channel realizations, enhancing desired links and/or improving interference conditions through spatial reconfiguration rather than through brute-force scaling of antennas and RF chains. This mechanism is fundamentally different from the conventional route to MIMO gains, which relies on increasing the array size and associated hardware complexity. In contrast, fluid MIMO targets performance gains via high-resolution spatial utilization without requiring a proportional increase in RF chains. A concise comparison between fluid MIMO and conventional MIMO is provided in Table 1, and these distinguishing characteristics are elaborated in the next section. It is worth mentioning that, although fluid MIMO shares the general objective of improving wireless performance through additional reconfigurability, it differs fundamentally from several related technologies that have recently attracted significant attention, such as antenna selection, reconfigurable intelligent surfaces (RISs), and dynamic metasurface antennas (DMAs). To clarify the differences, a comparison of these technologies is summarized in Table 2.

3. Benefits of fluid MIMO

In this section, we highlight the key advantages of fluid MIMO over conventional MIMO from a system-level perspective. We focus on three representative aspects. For each, we summarize supporting evidence from recent studies and present illustrative simulation results, demonstrating how fluid MIMO translates spatial reconfigurability into tangible performance gains under practical operating conditions.

3.1. Enhanced spatial DoFs and performance gains

Traditional MIMO systems exploit spatial DoFs through a finite number of antennas, whereas fluid MIMO systems provide a much higher spatial resolution by enabling a large number of candidate ports within a confined physical region. This characteristic allows fluid MIMO to access a richer set of spatial channel realizations and achieve significantly higher performance gains under the same resource conditions, which is one of its key advantages. For example, in Ref. [37], this benefit of enhanced spatial resolution using fluid MIMO is demonstrated in near-field fluid MIMO systems. Compared with conventional FPA systems, both the average rate and the energy efficiency have been significantly improved by deploying FASs. The performance gain becomes more pronounced as the number of available ports increases, highlighting the role of spatial reconfigurability in improving the effective channel quality. The advantage of fluid MIMO is even more evident in multiuser systems [38,39]. In Ref. [38], the continuous movement capability of the FAS introduces additional optimization dimensions in both antenna positioning and beamforming. This in turn enables the system to achieve the same quality-of-service (QoS) requirements with significantly less transmit power. Moreover, as the number of users increases, the performance gain becomes more substantial, indicating that the additional spatial DoFs can be effectively exploited to manage multiuser interference. Notably, it has been shown that, even within a very limited spatial region, FASs can identify near-optimal positions that provide considerable performance improvements, directly reflecting the high spatial resolution offered by fluid MIMO. In addition, the performance benefits of fluid MIMO extend to more specialized scenarios such as secure communications. As Ref. [39] shows, the additional spatial DoFs provided by fluid antennas can be utilized to improve secrecy

Table 1
Comparison between conventional MIMO and fluid MIMO systems.

Item	Aspects							
	Antenna structure	Spatial distribution	RF-chain requirement	Hardware and energy cost	Utilization of spatial DoFs	Interference management	Deployment mode	Implementation flexibility
Conventional MIMO (i.e., MIMO-FPA)	Fixed antenna positions	Limited by antenna spacing	Usually one RF chain per antenna	High	Usually beamforming	Beamforming-based suppression	Fixed arrays at BS and UE	Static array geometry
Fluid MIMO (a.k.a. MIMO-FAS)	Reconfigurable spatial ports	Dense spatial sampling within aperture	Many fewer RF chains than available ports	Low	Beamforming + port selection or position optimization	Adaptation via port selection	Flexible deployment	Adaptive spatial configuration

Table 2
Comparison between fluid MIMO and related reconfigurable wireless technologies.

Item	Aspects				
	Source of reconfigurability	Location of adaptation	RF-chain requirement	Scalability	Main practical deployment challenges
Fluid MIMO	Port selection/position and shape adaptation	Transmitter or receiver	Fewer RF chains than available ports	Flexible spatial adaptation	Port control and switching overhead
Antenna selection	Antenna subset selection	Transmitter or receiver	Fewer RF chains than antennas	Limited by fixed array geometry	Selection complexity
RIS	Phase control of the reflected waves	External reflecting surface	No RF chains	Limited by channel estimation and surface size	Cascaded CSI acquisition
DMA[a]	Electromagnetic response	Transmitter or receiver	Fewer RF chains than metasurface elements	Limited by hardware control complexity	Hardware integration and real-time tuning

[a] DMA is one kind of reconfigurable antenna technology that is attractive in terms of power consumption. As FAS is hardware agnostic, DMA is naturally included under the FAS framework when DMA is used for wireless system design.

performance while maintaining low complexity, further demonstrating its versatility.

Fig. 1 illustrates the average sum rate versus the number of candidate ports N in a multiuser downlink system consisting of $U = 4$ UEs, where U denotes the number of UEs. The BS employs $M = U = 4$ RF chains, where M denotes the number of active BS antenna ports and corresponding RF chains. For the fluid MIMO scheme, both the BS and UEs are equipped with a two-dimensional (2D)-FAS offering N ports over a fluid antenna aperture size $W = 4\lambda \times 4\lambda$, where λ represents the carrier wavelength. Port selection is performed based on the method reported in Ref. [36]. Each UE activates L ports and performs signal combining (i.e., with L RF chains, where L denotes the number of activated ports (and RF chains) per UE), while the BS selects M ports accordingly. As a benchmark, the conventional FPA-MIMO system adopts fixed antenna positions, where each UE is equipped with a fixed number of antennas $L^{\mathrm{FPA}} = L$, and the BS antenna number $M^{\mathrm{FPA}} = M = 4$. Three scenarios with different parameters are considered. It is observed that the fluid MIMO scheme consistently outperforms the FPA-MIMO benchmark, and its performance improves monotonically with N. Furthermore, the gain becomes more pronounced at a higher signal-to-noise ratio (SNR). These results indicate that, within the same limited physical region, fluid MIMO introduces additional spatial DoFs through port reconfiguration, leading to significant performance gains.

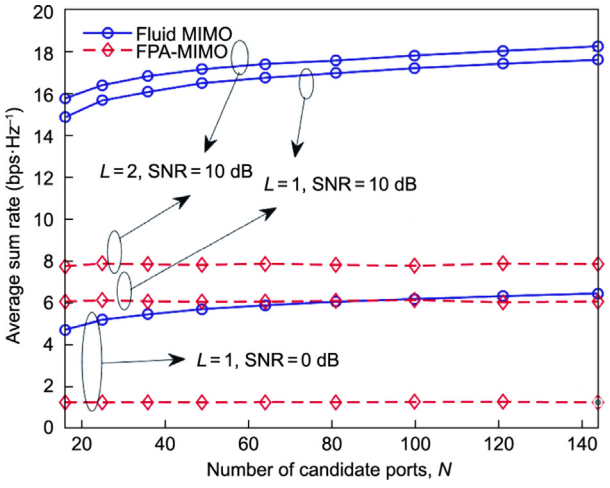

Fig. 1. The average sum rate versus the number of candidate ports N in a multiuser MIMO system under three different scenarios. bps: bits per second; SNR: signal-to-noise ratio; L: the number of activated ports (and RF chains) per UE.

3.2. Hardware, energy, and spatial utilization efficiency

Fluid MIMO fundamentally decouples the utilization of spatial resources from the hardware limitations. In conventional FPA-MIMO systems, each activated antenna element typically requires a dedicated RF chain, leading to increased hardware cost, power consumption, and circuit complexity as the array size grows. In contrast, fluid MIMO exhibits strong robustness under hardware impairments. For instance, Ref. [40] considers a multiuser system with non-ideal hardware. In this case, the FAS was demonstrated to be effective in mitigating the impact of impairments through spatial resource reconfiguration. This result highlights the energy and hardware efficiency of fluid MIMO, as performance improvements are achieved through spatial flexibility rather than increased hardware resources. From the perspective of spatial utilization, FASs are able to provide significant performance gains within a highly constrained physical aperture. In Ref. [41], after jointly optimizing the antenna positions and beamforming, simulation results show that even a small movable region can provide near-optimal performance, indicating that spatial resources are utilized with excellent efficiency. This observation also reinforces the high spatial resolution property discussed in the previous section, where densely distributed candidate ports enable fine-grained channel adaptation and improved performance. A representative example that clearly illustrates these advantages is the compact ultra-massive antenna array (CUMA) proposed in Ref. [42] and further developed in Refs. [43–45]. In CUMA, a massive number of ports are selected and activated to enhance signal quality with a concise method, while each UE operates with only one or two RF chains and without requiring complex signal processing, precoding, or interference cancellation. This design breaks the conventional scaling relationship between antenna count and hardware complexity, demonstrating that large spatial apertures can be effectively utilized with minimal RF resources.

Fig. 2 shows the average sum rate versus the number of UEs U under different numbers of candidate ports N in a downlink multiuser MIMO system, where the fluid antenna aperture size is fixed at $W = 4\lambda \times 4\lambda$ and the system operates in the interference-dominated environment in the downlink. The CUMA scheme in Ref. [42] is applied. The BS is deployed with $M = U$ FPAs, and each UE is deployed with one 2D-FAS configured with one RF chain (CUMA) or two RF chains (2RF-CUMA), as indicated in Fig. 2. The benchmark FPA adopts fixed antenna positions, where each UE is equipped with one antenna. It can be observed that, for the conventional FPA-MIMO system, increasing the number of users does not lead to any noticeable improvement in the sum rate, which is due to the rapidly increasing interference caused by the growing number of UEs. In contrast, the proposed CUMA scheme exhibits

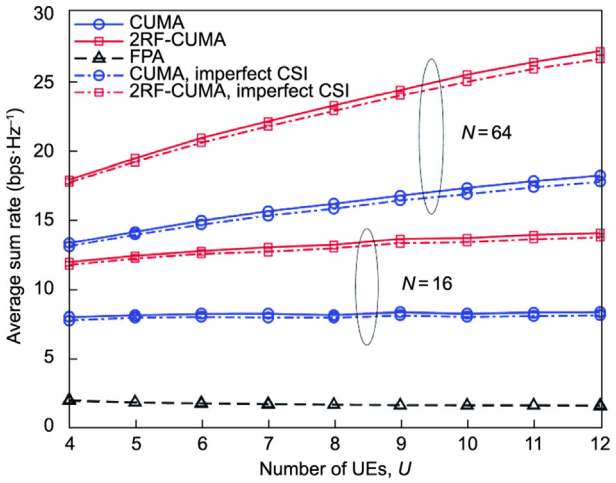

Fig. 2. Average sum rate versus number of UEs U with different numbers of candidate ports N in a downlink multiuser MIMO system.

a clear growth in the sum rate with respect to U, and this gain becomes more significant as the number of candidate ports N increases. This result demonstrates that CUMA is capable of effectively exploiting the additional spatial resources provided by a large number of fluid antenna ports, even with a very small number of RF chains.

To further evaluate its robustness under practical CSI errors, we model CSI as follows:

$$\widehat{\boldsymbol{h}} = \sqrt{1-\tau_{\mathrm{CSI}}^2}\boldsymbol{h} + \tau_{\mathrm{CSI}}\boldsymbol{e}$$

where $\boldsymbol{h}$ and $\widehat{\boldsymbol{h}}$ represent the real and estimated channels, respectively. Also, $\boldsymbol{e}$ denotes the error channel with the same distribution as $\boldsymbol{h}$. The imperfect CSI parameter is set as $\tau_{\mathrm{CSI}} = 0.2$. It can be observed from Fig. 2 that only a negligible performance loss is incurred compared with the perfect-CSI case, indicating that the proposed scheme is relatively insensitive to channel estimation errors. This further demonstrates that the performance gains of CUMA mainly stem from its effective utilization of the additional spatial DoFs provided by the FAS, rather than relying on highly accurate CSI. These results confirm that fluid MIMO increases the utilization of spatial resources, enabling scalable performance gains without necessarily increasing hardware complexity.

3.3. Flexibility and scalability

Unlike conventional MIMO systems, whose antenna configurations are fixed once deployed, fluid MIMO introduces an additional degree of flexibility through spatial resource reconfigurability, which provides a new dimension for system design and optimization with scalability. Depending on the target application, fluid antennas can be deployed at the UE side [46–48], the BS side [45], or both [36] and can operate in either uplink or downlink transmission modes. UE-side deployment is particularly attractive for uplink-oriented systems and distributed networks, in which reducing the CSI acquisition and signal-processing burden at the BS is desirable. BS-side deployment is more suitable for interference-limited multiuser systems, where spatial adaptation can be exploited to improve interference management and resource allocation. Joint BS–UE deployment offers the greatest flexibility and performance potential, making it attractive for high-capacity communication scenarios. This flexibility enables the system to be designed for diverse design objectives, such as low energy cost or high stability. Another important aspect of this flexibility lies in the associated channel knowledge requirements. Existing fluid MIMO schemes span a wide range of CSI assumptions. Some designs rely on instantaneous CSI to perform joint optimization of antenna positions and beamforming, achieving high performance through adaptation to channel variations [49–51]. On the other hand, information-theoretic frameworks based on statistical CSI demonstrate that substantial performance gains can still be obtained without requiring instantaneous channel knowledge [36,52]. An even more scalable design is proposed in Ref. [53] that shifts the adaptation process to the UE side. The local CSI is exploited to guide port selection at each UE without any channel knowledge at the BS. This ability to trade channel knowledge for spatial reconfigurability is particularly valuable in large-scale systems, where the feedback of full CSI for many UEs becomes prohibitively expensive. It should be noted that the large number of candidate ports in an FAS may increase the overhead associated with channel acquisition. Nevertheless, extensive research has been conducted to address this issue. Several low-overhead CSI acquisition schemes have been proposed that exploit the strong spatial correlation among nearby ports and reconstruct the CSI of all candidate ports from measurements obtained at only a small subset of ports [54,55]. As a result, the CSI acquisition overhead can be significantly reduced while preserving most of the spatial adaptation gain offered by fluid MIMO.

Such architectural diversity naturally leads to strong scalability. In dense multiuser and multi-cell networks, conventional MIMO techniques often rely on centralized optimization, full CSI, and complex signal processing, which quickly become impractical as the system size grows. In contrast, fluid MIMO provides a more scalable alternative by reducing the reliance on global CSI and high-complexity processing. For example, in Ref. [56], by equipping users with FASs and shifting interference mitigation to the UE side, the system significantly reduces the CSI requirement and antenna burden at the BS, thereby improving the scalability of cell-free networks. Another example is the uplink CUMA-based design in Ref. [45], which enables efficient multiuser communication without requiring inter-cell CSI, while maintaining competitive performance through simple aggregation mechanisms. Furthermore, recent developments such as scalable FAS architectures highlight how the spatial configuration itself can be dynamically adapted—including the effective aperture size and port density—according to system requirements [51]. This introduces an additional level of scalability that is fundamentally different from conventional array designs, where the geometry is typically fixed. Overall, fluid MIMO enables a flexible and scalable system design, making it particularly attractive for future wireless networks with massive connectivity and heterogeneous service requirements.

Fig. 3 illustrates the average sum rate versus the number of UEs U in an uplink multiuser MIMO system, where each user is equipped with a 2D-FAS. The fluid antenna aperture size is fixed to $W = 4\lambda \times 4\lambda$, the SNR is set to 10 dB, and the BS is equipped with a fixed number of 32 FPAs. In this setup, only the UE side has access to CSI. The fluid MIMO scheme adopts the codebook-based port selection and combining (CPSC) method reported in Ref. [53]. With this scheme, each user only needs a single RF chain, and the number of activated ports is fixed at $K = 16$. The conventional FPA-MIMO serves as the benchmark. Its BS deployment is the same as that of fluid MIMO, but each user has 16 FPAs equipped with a single RF chain. By varying the number of candidate ports N, we observe that fluid MIMO consistently achieves significantly higher sum rates than its FPA counterpart. Moreover, the performance improves as the number of users increases, in contrast to conventional systems under similar constraints. This result demonstrates that fluid MIMO can effectively exploit spatial resources even with limited CSI. In addition, increasing the number of candidate ports

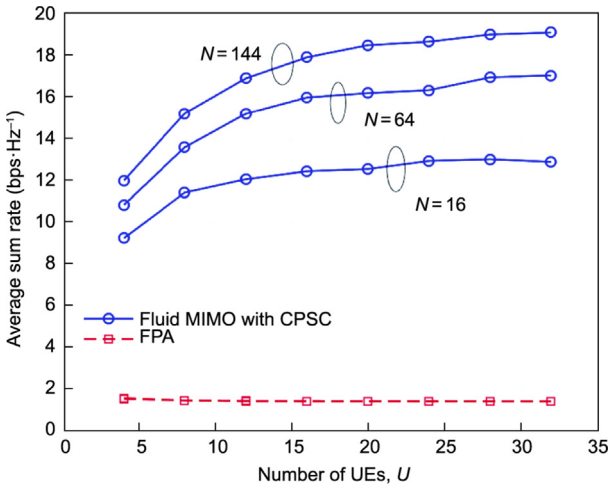

Fig. 3. The average sum rate versus the number of UEs U with different candidate ports N in an uplink multiuser MIMO system.

can further improve performance gains, confirming that fluid MIMO naturally supports scalable system design by using additional spatial DoFs without any extra hardware device.

4. Conclusions

Fluid MIMO technology establishes a fundamentally new paradigm for wireless communications by exploiting spatial resources through antenna reconfigurability, rather than by continually scaling array hardware or relying on increasingly complex precoding and coding. As discussed in this article, fluid MIMO can deliver clear advantages over conventional fixed-antenna MIMO in terms of spatial utilization, hardware and energy efficiency, and overall system flexibility—attributes that are especially valuable in future large-scale, heterogeneous networks. Looking ahead, realizing the full potential of fluid MIMO will hinge on advances in low-overhead operation under imperfect or limited channel knowledge, scalable multiuser architectures and control, and practical high-speed hardware implementations that translate reconfigurability into reliable field performance. At the same time, challenges such as port-selection overhead, real-time reconfiguration capability, and hardware control complexity must be carefully addressed to enable efficient large-scale deployment.

CRediT authorship contribution statement

Chenguang Rao: Writing – original draft, Validation, Software, Methodology, Investigation. **Kai-Kit Wong:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Hyundong Shin:** Supervision, Project administration, Funding acquisition, Conceptualization. **Ross Murch:** Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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