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SURVEY

A Survey on Fluid Antenna Multiple Access for 6G: A New Multiple Access Technology That Provides Great Diversity in a Small Space

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ABSTRACT In recent times, a fluid antenna system (FAS) has gained attention as a potential contender for 6G wireless networks. Fluid antenna multiple access (FAMA) is a new technology that allows each user to constantly move to the position with the strongest signal-to-interference ratio (SIR) by means of a single RF-chain port fluid antenna. Research works in FAMA mainly focus on propose models and solutions linked to the enhancement of FAMA from several aspects, including FAS system, enhancing orthogonal and non-orthogonal multiple access, channel modeling, diversity gain, artificial intelligence (AI) techniques, FAMA with other emerging technologies for 6G such as intelligent reflecting surface (IRS), multiple-input multiple-output (MIMO), terahertz (THz) communication, etc. There is no survey which covers all these important aspects of FAMA. Based on several concerns, a comprehensive taxonomy of FAMA has been presented in this study. First, FAS system is discussed. Then, FAMA mechanism is presented with its channel modeling and diversity gain. After that, FAMA is investigated with other emerging technologies such as IRS, MIMO, THz communication, etc. AI approaches to enhance FAMA are provided. In the end, we cover the potential research directions for further study in all areas. When designing and enhancing the FAS system, facilitating communication via FAMA, and integrating it with other cutting-edge technologies for 6G, this article may serve as a reference or guidance.

INDEX TERMS AI, FA, FAS, FAMA, IRS, multiple access, MIMO, THz communication, 6G.

I. INTRODUCTION

While the fifth generation (5G) is expected to improve our lives over the next ten years, sixth generation (6G) will surely require even higher energy and spectrum efficiency in order to provide consumers a plethora of new services and experiences wherever they may be. Many technologies, including resource allocation, advanced coding and signal processing, and most notably massive multiple-input multiple-output (MIMO), have already been implemented in 5G to salvage some stability from the wireless medium. It is certain that 6G will be based on more disruptive technologies that open the door to yet another revolution. Artificial intelligence (AI), intelligent reflecting surface (IRS), terahertz (THz) communications, MIMO, and many more exciting applications may be integrated with the fluid antenna system (FAS), which has recently become a viable choice for 6G [1]. Any software-controllable fluidic, dielectric, or conductive structure that may alter its form and location to reorganize the channel is stated to as a fluid antenna (FA). Therefore, all types of flexible antennas, both moveable and immobile, fall within FA. In recent years, industry and academics have created a variety

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of FA prototypes, mostly because to the advancements in the use of liquid metals and radio frequency (RF) switchable pixels for antennas [2], [3]. One RF chain as well as N preset points, or ports, dispersed across a certain region make up the most basic FA [4], [5], [6], [7], [8], [9], [10].

MIMO technology, which uses multiple antennas to create bandwidth from space independent of frequency and time resources, has revolutionized the world of mobile communications. For point-to-point communication networks, the significant diversity and multiplexing advantages given by spatially independent channels in many antennas have produced exceptional performance. Because multi-user MIMO multiplex users are totally in the spatial domain and offer a network capacity that scales with the number of antennas between base stations (BS) and/or user equipment (UE), it may provide an even bigger contribution [11]. With multi-user MIMO, the BS primarily handles signal processing and coding, making it simpler for the UEs to maintain communication. This is because BSs often have far larger processing capacities, but it also implies that the processing demands of many users might overload BSs very fast. By using a high number of antennas in the base station, massive MIMO significantly reduces the complexity of processing multi-user signals via the law of large numbers [12], [13], [14]. However, massive MIMO faces some challenges, such as availability of sufficient physical space to place a large number of antennas in the BS, complexity of connections between antennas, energy consumption of antennas, cost of antennas, etc. Fluid antenna multiple access (FAMA) technology has the potential to overcome the bandwidth limitations faced by MIMO systems thanks to its ability to dynamically change the physical positions of antennas. By optimizing the location of antenna elements according to channel conditions and traffic demand, FAMA can use the available bandwidth more efficiently. Besides, traditional mobile networks require each user to have a separate antenna. However, FAMA technology allows a single antenna to serve multiple users. This causes mobile devices to consume less energy and emit less radiation. Additionally, FAMA allows mobile devices to transfer data faster and more reliably.

Nowadays, rapid developments in wireless communications require greater spectrum efficiency and multiplexer gain to meet the increasing data traffic demand. Traditional multiple access systems, on the other hand, involve extensive signal processing and coordination to share spectrum resources, which has drawbacks such as high cost, latency, and power consumption. As a result, novel and effective multiple access strategies are an essential area of research. FAMA employs a FAS, a novel technique that may physically replace a single antenna in a specific region [15], [16], [17], [18], [19], [20]. Fluid antennas can dynamically vary their radiating properties by adjusting their form and size. Fluid antennas can leverage the deep attenuation moments of interference to find a channel state that is appropriate for the desired signal. Thus, FAMA does not need complicated signal processing and may effectively decrease multiple access conflicts.

This article provides a survey on FAMA, a new technology in which the antenna can change its physical position in a designated area. FAMA provides multiple access with a single liquid antenna, using deep attenuation moments of interference to obtain a suitable channel state for the desired signal, without requiring complex signal processing. First, FAS system is explained with mentioning advantages and challenges. Then, FAMA mechanism is discussed with its types, enhancing orthogonal and non-orthogonal multiple access, channel modeling and diversity gain. After that, FAMA integration with other emerging technologies such as IRS, MIMO, THz communication, etc. are investigated. AI approaches to enhance FAMA are provided. Finally, the potential research directions for further study in all areas are covered.

The rest of the paper is organized as follows: In Section II, FASs are described. In Section III, FAMA system is presented. In Section IV, FAMA with other emerging technologies for 6G are evaluated. In Section V, Artificial Intelligence for FAMA is discussed. In Section VI, future research directions are indicated. In Section VII, the results are summarized and.

II. FLUID ANTENNA SYSTEMS (FAS)

In this section, FAS technology along with its advantages and challenges are discussed. The FAS is a concept that employs flexible antenna systems that can reposition the antenna. As in the classic selection diversity approach, one can freely move to any of N places on a fixed-length line field to obtain the strongest signal. This allows for unprecedented spatial diversity. Furthermore, the ability to access an apparently continuous fading envelope in the spatial domain allows for numerous accesses without requiring sophisticated optimization and processing. The proper execution of FAS is dependent on activating the most appropriate port to ensure optimal channel conditions for wireless communications [19], [20]. A general FAS is shown in Figure 1. The idea of a potential implementation on a UE where conductive fluid is put on a structure resembling a tube and the fluid is allowed to circulate around within is depicted in Figure 1. The UE receiver can browse through the fading envelopes in space for capacity and diversity benefits by allowing the radiating element to alter positions. The FAS system allows the antenna's physical location to be freely switched between one of N positions or ports on a fixed-length line field. This allows the antenna location to be altered to get the strongest signal. The FAS system adjusts to the characteristics of the wireless channel by modifying the position and form of the antennas. Therefore, when the antenna functions as a transmitter (Tx) or receiver (Rx), it can continually analyze the channel's fading envelope and determine the optimal antenna position and form. As a result, it can take full use of the channel's spatial diversity.

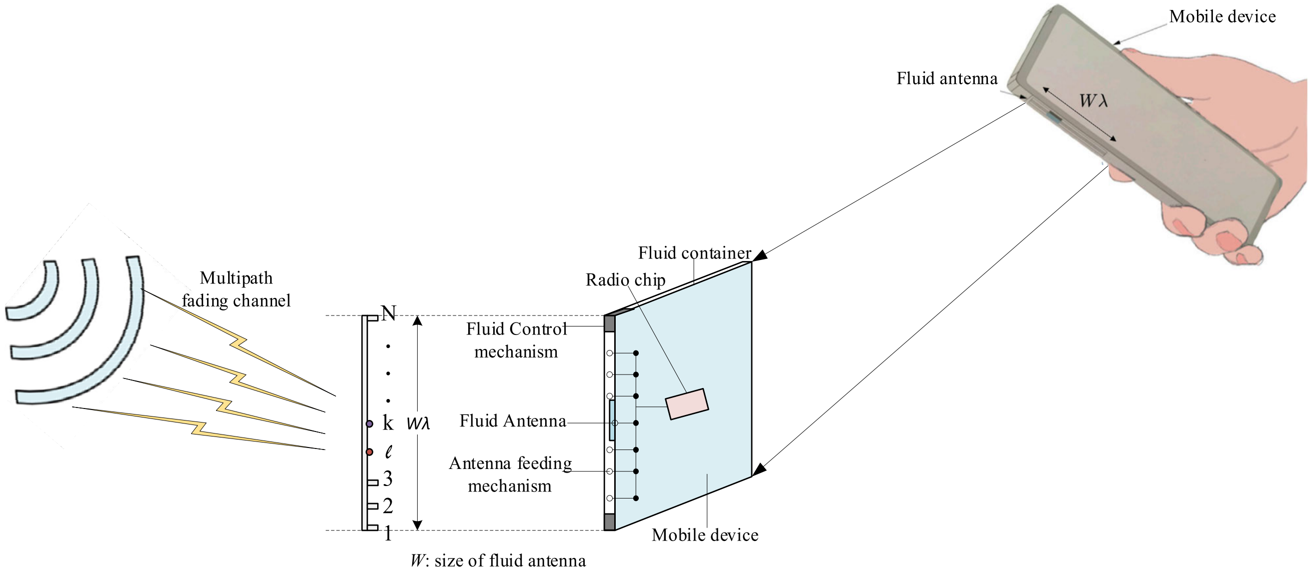

FIGURE 1. A depiction of FAS.

TABLE 1. Comparison of FAMA advantages and challenges.

Advantages	Challenges
FAMA can support a large number of users, regardless of the size of the fluid antenna.	FAMA requires sufficient time to change the position of the antenna.
FAMA, like traditional selection diversity, can choose the position of the antenna to receive the strongest signal.	FAMA uses a complex double integral formula to calculate the outage probability in channels with random Rayleigh fading.
When combined with deep learning, FAMA can intelligently learn to optimize the position of the antenna.	FAMA requires a mechanical or electrical mechanism to change the position of the antenna.

A. FAS TECHNOLOGY

The FAS system is a revolutionary communication technology that employs flexible antenna layouts that can change the location and form of the antenna. This allows for great diversity and interference-free communication gains that are impossible to attain with typical antenna setups. The FAS system allows the antenna's physical location to be freely switched between one of N spots on a fixed-length line field. This allows the antenna location to be altered to get the strongest signal, similar to the old selection diversity technique. Furthermore, varied antenna layouts allow for changes to the form of the antenna. The FAS system adjusts to the characteristics of the wireless channel by modifying the position and form of the antennas. As a result, when the antenna functions as a receiver or transmitter, it can continually analyze the channel's fading envelope and determine the optimal antenna position and form. As a result, it can take full use of the channel's spatial variety. The FAS system can employ a variety of techniques to modify the location and form of the antenna. Flexible antenna topologies, such as reconfigurable RF pixel-based antennas, liquid-based antennas, and stepper motor-based antennas, can be utilized to vary the antenna location. Antenna designs with variable geometry, size, polarization, or direction can be utilized to vary the form of the antenna. Materials that can vary the location and form of an antenna and have appropriate electrical and mechanical qualities can be used to make it acceptable for flow in the FAS system. These materials can be liquid, solid, gas, or a combination of these. Materials suitable for the FAS system include liquid metal, liquid crystal, ferro liquid, polymer, carbon nanotube, graphene, silicon, copper, gold, and silver.

B. ADVANTAGES

FAS allows for great diversity and interference-free communication gains that standard antenna systems do not provide. FAS has a low complexity since it only employs one antenna and requires a simple algorithm for antenna selection. This means less processing power and energy usage than MIMO systems. The benefits of FAS are outlined below:

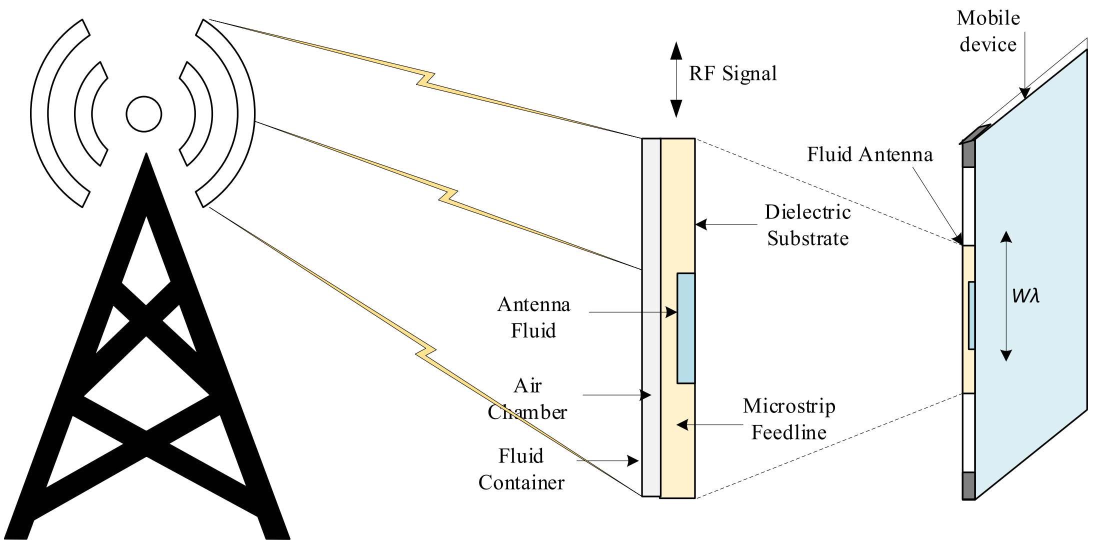

FIGURE 2. An illustration of FAMA.

- ➢ High diversity: By adjusting the position and form of the antenna, FAS may take full use of the channel's spatial variety. This can continually evaluate the channel's fading envelope and determine the best antenna position and form. This results in a system that is responsive to channel circumstances.
- ➢ Multiple access diversity: FAS allows users to take use of a shared pool of space variety in multi-user environments. This lowers interference between users while increasing efficiency.
- ➢ Flexibility and compatibility: FAS may be used as a performance parameter to compare different antenna designs. Additionally, FAS delivers analytical and numerical findings for various channel and antenna motion models. This exhibits the flexibility of FAS to various wireless communication circumstances.
- ➢ Compatibility with the 6G: FAS is a technology that can give a next-generation breakthrough at a time when research into 6G mobile communications is ramping up. FAS can work along with other enabled technologies to achieve 6G requirements. FAS, for example, has applications in the internet of things (IoT), AI, big data, smart cities, cloud computing, and virtual reality.

C. CHALLENGES

The proper execution of FAS is dependent on activating the most appropriate port to ensure optimal channel conditions for wireless communications. This illustrates some of FAS's issues. The challenges of FAS are outlined below.

- ➢ Channel estimate and signal reception: FAS can continually monitor the channel's fading envelope and pick the ideal antenna location and shape by changing the antenna's position and form. However, because FAS resolution may be quite high, this may place a significant load on channel estimate and signal reception. As a result, FAS channel estimate and signal reception algorithms must be designed to be modest in complexity but high in accuracy.
- ➢ MIMO optimization: When FAS is integrated with MIMO systems, co-optimization of the chosen ports and beamforming is necessary. This is a crucial aspect in improving the performance of FAS. However, because to the high resolution of FAS and the large scale of MIMO, this optimization problem may be difficult to solve. As a result, effective and adaptive optimization techniques for FAS-MIMO systems should be studied.
- ➢ 6G compliance: FAS is a technology that potentially give a next-generation breakthrough at a time when research on 6G mobile communications is ramping up. FAS can work along with other enabled technologies to achieve 6G requirements. However, issues about how to incorporate FAS into these sectors, as well as how to manage and safeguard it, remain unaddressed. Thus, more study is required to make FAS compatible with 6G.

III. FLUID ANTENNA MULTIPLE ACCESS (FAMA)

In this section, firstly, FAMA technology is described with its categories. Then, how FAS performs better than traditional antenna systems (TAS) is explained. After that, channel modeling and diversity gain, capacity and energy efficiency, and multiplexing gain of FAMA are discussed. The FAMA is a new technology in which a single fluid antenna can change its physical position within a designated area. FAMA uses the deep fading of the interference to obtain an appropriate channel state for the desired signal, without the need for complex signal processing. Figure 2 shows an illustration of a FAMA. The FAMA is able to navigate through the fading envelope at each time instant. This allows the system to avoid deep fades by activating the antenna at a desired position or port, though the resolution will depend on the number of ports available

TABLE 2. Comparisons of slow FAMA and fast FAMA.

Features	Slow FAMA	Fast FAMA
Antenna port replacement timing	When the channel changes	Per symbol
Interference reduction method	Using the initiative's deep fading	Using the initiative's deep fading
Number of users	Can support hundreds of users	Can support dozens of users
Signal processing complexity	Low	Low
Multiple access capability	Significantly higher than traditional MIMO	Significantly higher than traditional MIMO
Difficulty of application	Low	High

at the fluid antenna. A port refers to a physical location at which the fluid antenna can be switched to instantly. Based on port selection, FAMA can be categorized into two types which are slow (s-FAMA) and fast (f-FAMA). In s-FAMA, the port that has been selected remains unchanged until the channel conditions change. In f-FAMA, the port is reselected whenever the instantaneous interference signal changes.

A. FAMA TECHNOLOGY

FAMA allows the antenna to change its physical position in a given area. FAMA is exploring the potential for a single fluid antenna to provide multiple reach points for mobile users. FAMA obtains a suitable channel condition for the desired signal by using the deep fading moments experienced by interference. By calculating the signal-to-interference ratio's outage probability in double integral form, the FAMA network is examined. Subsequently, the FAMA system's upper limit on outage probability and lower bound on average outage rate are determined. This is how the FAMA multiplexing gain is described. The size of the fluid antennas being utilized may be used to determine the number of locations needed to attain the required multiplexing gain of FAMA. FAMA is used to ensure efficient operation of mobile devices. Traditional mobile networks require each user to have a separate antenna. However, FAMA technology allows a single antenna to serve multiple users. This causes mobile devices to consume less energy and emit less radiation. Additionally, FAMA allows mobile devices to transfer data faster and more reliably.

The mathematical model of the FAMA system is based on a multiple access environment in which the positions of fluid antennas change randomly and each user has one fluid antenna. In the system, one user is considered the desired signal source and the other users are considered interference sources. The locations of the fluid antennas are selected from a set of N points that are independent of each other and evenly distributed. These points define the area in which the fluid antenna can move. The positions of the fluid antennas are refreshed at the beginning of each time interval or symbol interval. This means that fluid antennas can operate on slow or fast changing channels.

In the equations, Rayleigh fading model is assumed. These models represent the statistical properties of the wireless channel and are used to model fluctuations in signal strength. As with all wireless communication systems, Additive White Gaussian Noise (AWGN) model is assumed in the equations. This means that the strength of the signal transmitted over the channel is affected by white Gaussian noise. In the FAMA system, the SIR for the desired signal is calculated as:

$$\mathrm{SIR} = \frac{|\, h_d \,|^2}{\sum_{i=1}^{K} |\, h_i \,|^2}. \tag{1}$$

Here, h_d is the channel gain of the desired signal, h_i is the channel gain of the i_{th} interference signal. K is the number of attempts. SIR is a random variable depending on the positions of the fluid antennas. To evaluate the performance of the FAMA system, statistical metrics such as SIR's outage probability and average outage capacity are used.

The outage probability of the SIR is the probability that the SIR will remain below this value for a given threshold value γ. This probability is calculated as

$$P_{\mathrm{out}}(\gamma)=\mathbb{P}(\mathrm{SIR} < \gamma)=\int_0^\infty \left(1-\exp\left(-\frac{\gamma x}{\sigma_d^2}\right)\right)^K f_{|h_d|^2}(x)\mathrm{d}x \tag{2}$$

where, σ_d^2 is the variance of the desired signal, and $f_{|h_d|^2}$ (x) is the probability density function of the square of the channel gain of the desired signal. This function is the exponential distribution, which is a special case of the Rayleigh distribution:

$$f_{|h_d|^2}(x) = \frac{1}{\sigma_d^2} \exp\left(-\frac{x}{\sigma_d^2}\right). \tag{3}$$

SIR's outage probability formula is in the form of a double integral. It is difficult to solve this integral analytically.

Therefore, to simplify this formula, it is possible to obtain an upper bound. This upper limit is given by:

$$P_{\text{out}}(\gamma) \leq \frac{1}{1+\frac{\sigma_d^2}{\gamma}} \left(1+\frac{\gamma}{\sigma_d^2}\right)^{-K} \tag{4}$$

These upper bound expresses the exit probability of the SIR in closed form. In this way, it is possible to analyze the performance of the FAMA system more easily.

1) SLOW FAMA

The s-FAMA considers a scenario where each user with a fluid antenna selects the best port and does not change until the channel conditions change [21]. In the s-FAMA system, there is a base station (BS) and K users. Each user has a fluid antenna. A fluid antenna is an antenna that can change its physical position in a designated area. Assume that the fluid antenna has N ports. Each port represents a specific location of the fluid antenna in space. Each user selects the port with the highest SINR and uses that port until the channel conditions change. This approach is called s-FAMA which capacity can be calculated as

$$C_{slow} = B\log_2\left(1+\frac{P\mid h\mid^2}{N_0+I}\right), \tag{5}$$

where B is the bandwidth, P is the transmitted power, N_0 is the noise power density and I represents the interference power.

2) FAST FAMA

The f-FAMA is a technique that aims to reduce the switching time and latency of the FAMA system by rapidly changing the positions and orientations of fluid antennas. Fast FAMA ensures that 6G networks comply with FAMA's goals of ultra-low latency and ultra-high reliability. Fast FAMA increases the mobility, flexibility and adaptability of fluid antennas. Fast FAMA's methods use various algorithms to position, direct and optimize the switching process of fluid antennas. These algorithms adjust the positions and orientations of fluid antennas according to channel status, traffic density, number of users and quality of service [22], [23]. These algorithms reduce the switching time of fluid antennas from milliseconds to microseconds. Additionally, by increasing the switching frequency of fluid antennas, it increases the multiplexer gain and spectral efficiency of the FAMA system.

Future research directions of Fast FAMA could be to develop more effective, efficient and intelligent algorithms for positioning, routing and optimizing the switching process of fluid antennas. It may also be about designing new protocols, standards, and architectures to enable Fast FAMA to work with other new technologies. Fast FAMA can contribute to the widespread use of FAMA technology in 6G networks. The capacity of f-FAMA can be calculated as

$$C_{fast} = B\log_2\left(1+\frac{P\mid h(t)\mid^2}{N_0}\right), \tag{6}$$

where $h(t)$ is the time-varying channel gain.

B. ENHANCING OMA AND NOMA

To support numerous users, most existing wireless networks employ orthogonal multiple access (OMA). In OMA, the available degrees of freedom are divided into orthogonal sections in order to prevent multi-user interference. When the channel state information at the transmitter (CSIT) is accessible, this strategy isn't the best one, however. Rather to OMA, NOMA that makes use of successive interference cancellation (SIC) and superposition coding may be more effective. In particular, NOMA is a broadcast channel capacity-achieving technique that has been suggested for use in 6G wireless networks to enable huge connections [24]. For instance, NOMA has been suggested for 6G use cases such as space-aerial-terrestrial networks [25], integrated sensing and communications [26]. On the other hand, the SIC decoding order has a significant impact on NOMA's superiority [27]. Specifically, in the downlink, the stronger user's signal must be decoded or subtracted off before decoding the weaker user's signal, and vice versa in the uplink. Hence, in the event that the CSIT is unavailable, NOMA can no longer achieve capacity. When the CSIT is absent, it may sometimes be more efficient to give each user the same amount of freedom and authority.

OMA and NOMA have been separately studied in recent research to support multiple FAS receivers. In [28], the tradeoff between channel estimation and outage probability in large-scale cellular networks was studied by the authors taking into account time-division multiple access (TDMA) and using stochastic geometry. In their most recent work, [29] examined space division multiple access in the uplink and, subject to the necessity for a per-user rate, minimized the overall transmit power via the use of receive beamforming, base station antenna placements, and user power distribution. These programs are thought to be OMA. On the other hand, [30] used NOMA to determine the cooperative FAS receivers' outage probability. Even in the most basic scenario, when the transmitter is outfitted with a traditional antenna (TA) and the receivers are outfitted with a single FA, the effect of FAS on multiple access is still unknown.

Enhancing OMA and NOMA is a new method that aims to improve multiple access performance using a FAS [31]. FAS consists of FA, which, unlike TAS, can change their position in a certain area. In this way, FAS can benefit from additional diversification and multiplexing gains. Enhancing OMA and NOMA uses multiple access schemes to maximize the overall data rate. In particular, it makes traditional multiple access schemes such as TDMA, frequency division multiple access (FDMA), and NOMA compatible with FAS. These systems perform active irradiation selection and power distribution optimization at the base station according to the data rate requirement of each user. It shows that FAS significantly improves the overall data rate of OMA and NOMA compared to TAS. More interestingly, it is found that FAS can surpass CSIT with optimal TAS without CSIT at the transmitter side.

C. CHANNEL MODELING AND DIVERSITY GAIN

Channel modeling and diversity gain uses the field response model of the multipath channel to analyze the performance of the FAMA system. This model takes into account the amplitude, phase and angle of arrival/angle of departure (AoA/AoD) information of the multipath channel under the far-field condition [32]. This model is used to derive important performance indicators of the FAMA system, such as outage probability and diversity gain. It also optimizes parameters such as the number of positions, size and shape of liquid antennas to achieve the optimal design of the FAMA system.

Each user in the system sends a signal at the same frequency and with the same strength. These signals pass through multipath channels with Rayleigh-distributed complex gains. Channel gains vary depending on the positions of the liquid antennas. The statistical properties of channel gains can be described by classical models such as the Jakes model or the Clarke model. These models calculate the correlation of channel gains depending on the distances and angles between the positions of the fluid antennas. The correlation increases as the positions of the fluid antennas get closer together.

The types of diversity provided by FAMA technology are as follows:

- ➢ Spatial Diversity: FAMA can dynamically change the positions of antenna elements. This enables signals from different locations to be combined, reducing negative channel effects such as signal attenuation and ghosting. Spatial diversity improves signal quality, especially by combining signals propagating over multiple paths.
- ➢ Frequency Diversity: FAMA provides frequency diversity by using antennas that can operate in different frequency bands. This offers protection against frequency selective fading effects and improves bandwidth efficiency. Frequency diversity can improve channel capacity by combining signals of different frequencies.
- ➢ Time Diversity: FAMA uses time diversity by changing the positions of the antennas over time. This ensures reliable communication even in rapidly changing channel conditions. Time diversity can increase signal strength by combining signals received at different times.
- ➢ Code Diversity: FAMA can use code diversity by supporting different coding schemes. This provides an extra layer of error correction and data integrity. Code diversity can reduce the error rate by combining signals transmitted using different coding techniques.
- ➢ Polarization Diversity: FAMA can increase diversity by using different polarizations of signals. Polarization diversity can improve signal quality by combining signals with different polarizations at the same frequency.

These types of diversity directly impact the advantages FAMA will provide in 6G wireless communication systems, such as high reliability, low latency, and high data rates. By leveraging these variations, FAMA technology can significantly improve the performance of wireless communication systems and offer a flexible structure to meet future communication needs.

D. CAPACITY AND ENERGY EFFICIENCY

The capacity of the FAMA system is characterized by the probability of SIR outage. The energy efficiency of the FAMA system is measured by the energy consumed per bit. The energy dissipated per bit includes components such as transmit power, circuit power, and antenna switching power. Capacity and energy efficiency are often key performance measures of communications systems [33]. Capacity represents the maximum information transfer capacity of a communication channel. Energy efficiency indicates the amount of energy spent for a certain amount of service or communication.

The average outage capacity of the SIR is the expected value of the logarithmic function of the SIR. This value is calculated as follows:

$$C_{\text{out}} = \mathbb{E}\left[\log_2(1+\text{SIR})\right] = \int_0^\infty \log_2(1+x) f_{\text{SIR}}(x)\mathrm{d}x \quad (7)$$

where, $f_{SIR}(x)$ is the probability density function of SIR. This function is found like this:

$$f_{\text{SIR}}(x) = \frac{K}{\sigma_d^2}\exp\left(-\frac{x}{\sigma_d^2}\right)\left(1-\exp\left(-\frac{x}{\sigma_d^2}\right)\right)^{K-1} \quad (8)$$

SIR's average outage capacity formula is in the form of a single integral. It is difficult to solve this integral analytically. Therefore, to simplify this formula, it is possible to obtain a lower bound. This lower bound is given by:

$$C_{\text{out}} \geq \log_2\left(1+\frac{\sigma_d^2}{K}\right) - \frac{1}{\ln 2}\frac{K}{K+1}\exp\left(-\frac{K+1}{\sigma_d^2}\right) \quad (9)$$

This lower limit expresses the average outage capacity of the SIR in closed form. In this way, it is possible to analyze the performance of the FAMA system more easily.

E. MULTIPLEXING GAIN

Multiplexing gain is a measure of the number of concurrent users supported on a system. In the FAMA system, each user has a single fluid antenna and antenna positions are changed on a symbol-by-symbol basis using deep fading moments of interference to obtain a favorable channel state for the desired signal. Multiplexing gain is one of the advantages provided by FAMA. This is a concept used to enable multiple users or services to communicate at the same time. Multiplexing gain represents more effective use of the communication channel, meaning more data transfer and better spectral efficiency [34].

Multiplexing gain measures the increase in capacity achieved by increasing the number of positions of fluid antennas. The multiplexing gain can be written as:

$$r = \lim_{\sigma_d^2 \to \infty} \frac{C_{\text{out}}}{\log_2 \sigma_d^2} \quad (10)$$

TABLE 3. Comparisons of some technologies.

Technology	Description	Relationship to FAMA
THz	The THz band covers the frequency range 0.1-10 THz and provides very high data rates.	FAMA can operate in the THz band and reduce the challenges of THz communication (high path loss, reflection, diffraction, etc.).
MIMO	Massive MIMO increases spectral efficiency and link quality by using multiple antennas.	FAMA can reduce the number of antennas in the massive MIMO system and increase the channel diversity and capacity by changing the positions of the antennas.
AI	AI uses intelligent algorithms for data analysis, learning, optimization, etc.	FAMA can be used in conjunction with AI, and AI algorithms can be used to optimize the positions of antennas and channel selection problems.
Quantum communication	Quantum communication provides data transmission and security using the principles of quantum mechanics.	FAMA can be used in conjunction with quantum communications and can improve the quantum channel by changing the positions of antennas to facilitate the transmission and detection of quantum signals.
Blockchain	Blockchain ensures data integrity and security using a distributed database.	FAMA can be used in conjunction with blockchain, and blockchain can be used to verify and record antennas' positions and signal processing parameters.
IRS	IRS improves the channel condition by intelligently reflecting incoming waves.	FAMA can be used in conjunction with IRS, and IRS can be used to increase channel diversity and capacity by changing the positions of antennas.
mmWave	mmWave is a range of electromagnetic frequencies between microwaves and infrared.	FAMA compensates for the high path loss and molecular absorption of mmWave signals by changing the position and shape of the antenna. FAMA exploits the high bandwidth and resolution of mmWave signals by varying the gain, radiation pattern and frequency of the antenna.

According to this definition, the multiplexing gain for the FAMA system is found as:

$$r = \frac{1}{1 + \frac{1}{K}}. \tag{11}$$

This result shows that the multiplexing gain of the FAMA system depends on the number of interferences. As the number of interferences increases, the multiplexing gain decreases. When the interference count is zero, the multiplexing gain becomes one. This means that with increasing the number of positions of fluid antennas, the capacity increases linearly. When the number of interferences is infinite, the multiplexing gain becomes zero. This means that increasing the number of positions of fluid antennas does not increase the capacity.

IV. FAMA WITH OTHER EMERGING TECHNOLOGIES FOR 6G

We study FAMA in conjunction with other 6G upcoming technologies including IRS, MIMO, and THz communication in this section. FAMA can provide very high data speed and low latency, which is one of the key requirements of 6G. FAMA can also support other goals of 6G, such as very high link density, very high energy efficiency, very high spectral efficiency, very high reliability, very high mobility, very high coverage. FAMA can interoperate and leverage other emerging technologies for 6G. In this section, some ideas will be presented about the integration and synergy of FAMA with new technologies such as deep learning, artificial intelligence, cognitive radio, smart grid, internet of things, industrial internet, smart city, smart transportation, smart health. Table 3 presents comparisons of some technologies.

➢ Deep Learning and AI: Deep learning and AI can be used to perform tasks such as data analysis, signal processing, resource management, security, optimization, decision-making, etc. in the complex and dynamic environments of 6G. When combined with deep learning and artificial intelligence, FAMA can intelligently learn to optimize the antenna's position, shape, radiation pattern, gain, operating frequency and other characteristics. Deep learning and artificial intelligence can help FAMA predict channel status, reduce interference, increase diversity, improve multiplexer power, increase data rate, reduce latency, reduce energy consumption, increase reliability, support mobility, and expand coverage. Deep learning and artificial intelligence can enable FAMA to work adaptively and flexibly in different scenarios, e.g., MIMO, multi-user detection, multi-antenna selection, multi-antenna diversity, multi-antenna collaboration, multi-antenna relay, multi-antenna coding. Deep learning and artificial intelligence can also play an important role in FAMA's integration and synergy with new technologies.

- Cognitive Radio: Cognitive radio is a smart technology for efficient use of spectrum. Cognitive radio can sense the spectrum environment, detect spectrum gaps, coordinate spectrum access, optimize spectrum sharing, manage spectrum interaction, and support spectrum mobility. FAMA can work with and leverage cognitive radio. FAMA can assist cognitive radio to sense the spectrum environment by changing the position and shape of the antenna. By varying the gain, radiation pattern, and operating frequency of the antenna, FAMA can assist cognitive radio to exploit spectrum gaps, coordinate spectrum access, optimize spectrum sharing, manage spectrum interaction, and support spectrum mobility. FAMA, together with cognitive radio, can improve spectrum efficiency, make spectrum assignments flexible, reduce spectrum conflicts, ensure spectrum compatibility, and facilitate spectrum mobility.
- Smart Grid: Smart grid is an intelligent system for the production, transmission, distribution and consumption of electrical energy. Smart grid uses technologies such as communication, information, control, measurement and automation to increase the quality, security, efficiency, reliability and sustainability of electrical energy. FAMA can interoperate and benefit from the smart grid. By changing the position, shape, radiation pattern, gain, operating frequency and other characteristics of the antenna, FAMA can help the smart grid to perform tasks such as communication, information, control, measurement, automation for the smart grid. FAMA, together with the smart grid, can improve the quality, safety, efficiency, reliability and sustainability of electrical energy, optimizing the demand, supply, storage, distribution, consumption, pricing, management and protection of electrical energy.
- Internet of Things: The Internet of Things enables objects to collect data, share data, analyze data, process data, make data decisions, and take data action. FAMA can interoperate and leverage the Internet of Things.

A. FAMA WITH IRS

The IRS is a novel technology that can smartly adjust the phase and amplitude of the incident signals and reflect them to the desired directions. IRS can enhance the wireless communication performance by creating favorable propagation conditions, improving signal quality, extending coverage area, reducing interference, and saving energy [35], [36], [37], [38], [39], [40], [41], [42], [43], [44]. Figure 3 depicts a concept of employing the IRS to offer a huge surface with numerous scatterers for multiuser signals originating from the BS off to neighboring user equipment.

FAMA can benefit from IRS and vice versa. FAMA can use IRS to create more deep fading moments for the interference signals, and thus improve the channel condition for the desired signal [45], [46]. FAMA can also use IRS to adjust the antenna radiation pattern, gain, frequency, and other features to optimize the communication performance. IRS can use FAMA to achieve multiple access with a single fluid antenna, and thus reduce the hardware complexity, cost, and energy consumption. IRS can also use FAMA to adapt to different scenarios, such as MIMO, NOMA, UAV, and mmWave, and enhance the compatibility and flexibility. FAMA with IRS can achieve the following advantages:

- FAMA with IRS can improve the data rate and latency by creating favorable channel conditions for the desired signal and unfavorable channel conditions for the interference signals.
- FAMA with IRS can improve the connection density and reliability by extending the coverage area and enhancing the signal quality.
- FAMA with IRS can improve the energy efficiency and spectral efficiency by reducing the transmission power and increasing the spatial multiplexing.
- FAMA with IRS can improve the mobility and coverage by adjusting the antenna position, shape, gain, radiation pattern, frequency, and other features to adapt to the dynamic environment.
- FAMA with IRS can work with other emerging technologies such as NOMA, MIMO, UAV, and mmWave to achieve further gains and synergies.

FAMA with IRS also faces some challenges that need to be addressed:

- FAMA with IRS requires accurate CSI of the direct, reflecting, and interfering links, which is difficult to obtain and update in real time.
- FAMA with IRS requires efficient and robust algorithms for joint optimization of the fluid antenna and IRS parameters, such as position, shape, gain, radiation pattern, frequency, phase, and amplitude, which is a high-dimensional and non-convex problem.
- FAMA with IRS requires effective and secure protocols for coordination and communication between the fluid antenna and IRS, which may incur additional overhead and vulnerability.
- FAMA with IRS requires careful design and implementation of the fluid antenna and IRS hardware, such as the mechanism, material, structure, and circuit, which may affect the performance and reliability.

FAMA with IRS can be applied to several developments, such as:

- FAMA with IRS can be used for indoor communication, where the fluid antenna can be mounted on the ceiling or wall, and the IRS can be deployed on the furniture or appliances, to provide high-quality and ubiquitous service for the users.
- FAMA with IRS can be used for outdoor communication, where the fluid antenna can be mounted on the UAV or balloon, and the IRS can be deployed on the building

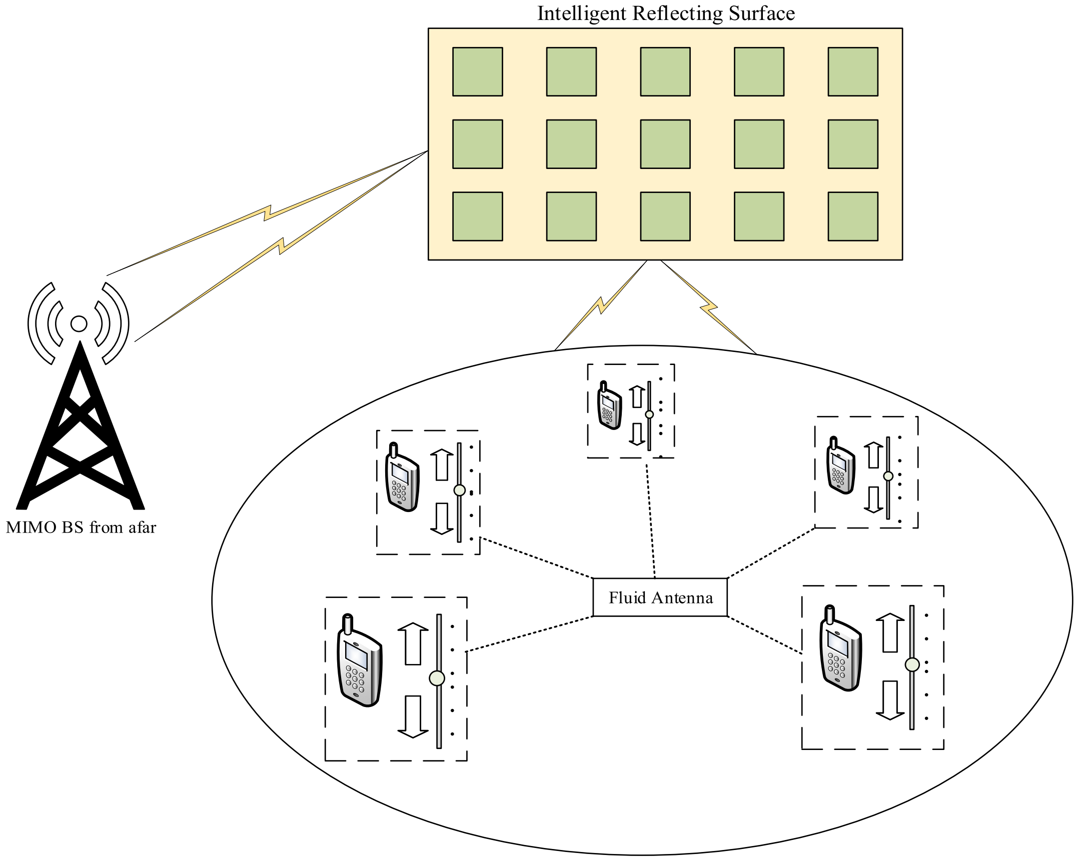

FIGURE 3. A general system of FAMA with IRS.

or tower, to provide flexible and reliable service for the users.

- ➢ FAMA with IRS can be used for vehicular communication, where the fluid antenna can be mounted on the vehicle or roadside unit, and the IRS can be deployed on the traffic sign or lamp post, to provide fast and seamless service for the users.
- ➢ FAMA with IRS can be used for mmWave communication, where the fluid antenna can be mounted on the BS or MS, and the IRS can be deployed on the reflector or scatterer, to provide high-capacity and low-latency service for the users.

B. FAMA WITH MIMO

Massive MIMO is a key technology for 6G that can achieve low latency, high data rate, high energy efficiency, and high spectral efficiency by using a large number of antennas at the BS to serve multiple users simultaneously. Massive MIMO can exploit the channel hardening and favorable propagation effects to simplify the signal processing and improve the performance [14], [47], [48], [49], [50]. Massive MIMO can also work with other emerging technologies such as NOMA, IRS, UAV, and mmWave to achieve further gains. MIMO uses four uplink and up to eight downlink antennas for 4G LTE, while a 5G BS may use up to 64 antennas total. However, compared to the number of UE sharing the same time-frequency resource block, the number of BS antennas must be significantly higher—for example, ten times higher. To achieve genuinely large connection, there is still considerable work to be done. In 5G, the number of antennas at a BS has risen significantly, while the number of antennas at a UE is still minimal (≤ 4). This is because the UE has a limited amount of space. For years, researchers have been studying metamaterials to make small-sized antennas possible by overcoming the physical limitations. But adequate space between the antennas is also necessary, so it's not simply about antenna size. It is customary to only deploy several antennas if they are far enough apart ($\geq$ half of the wavelength λ) to prevent mutual coupling and provide adequate signal diversity at each antenna. Even if this general guideline makes sense, it would be nice to find out if the "half-λ" rule may be loosened or even broken while making use of the spatial variety in a UE's condensed area. However, FAMA can offer the extra dimensions needed to free up MIMO at the base stations to support a greater number of users, potentially also streamlining the MIMO antenna optimization process. To make things easier to understand, Figure 4 illustrates how the fluid antenna surface is placed into a Cartesian coordinate system with a grid distance $\Delta\lambda$ for a given Δ. We examine a 2D rectangular surface with dimensions $W\lambda \times D\lambda$, where λ represents the wavelength.

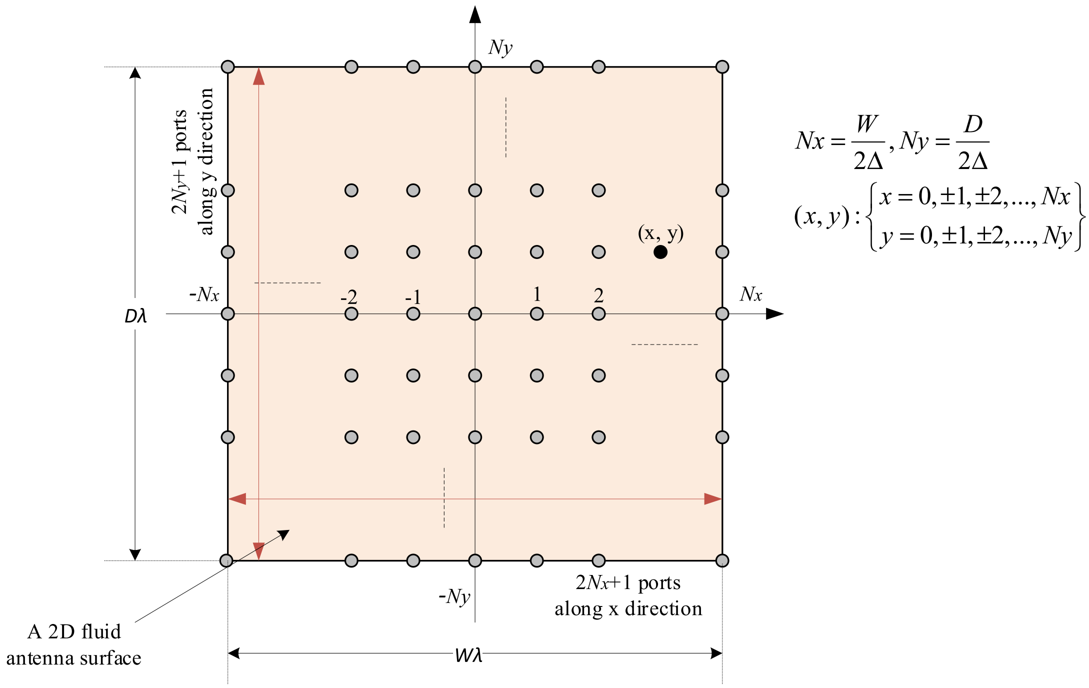

FIGURE 4. The 2D FA surface with dimensions Wλ × Dλ is characterized by a coordinate system.

It is presumed that W ≤ D without sacrificing generality. There are several antenna ports uniformly spaced throughout the surface; each port designates a place where the fluid radiator or antenna can be selected for activation. It is believed that one port may only be in use at any one time. This is referred to as the fluid MIMO scenario, where many ports can be active simultaneously.

FAMA can benefit from massive MIMO and vice versa. FAMA can use massive MIMO to increase the diversity and multiplexing gains by switching the antenna position in a predefined space. FAMA can also use massive MIMO to reduce the interference and enhance the signal quality by adjusting the antenna shape, gain, radiation pattern, and frequency. Massive MIMO can use FAMA to achieve multiple access with a single fluid antenna at each user terminal (UT), and thus reduce the hardware complexity, cost, and energy consumption. Massive MIMO can also use FAMA to adapt to different scenarios, such as NOMA, IRS, UAV, and mmWave, and enhance the compatibility and flexibility. FAMA with MIMO can achieve the following advantages:

- ➢ FAMA with massive MIMO can improve the data rate and latency by exploiting the large array gain, spatial multiplexing, and channel hardening effects of massive MIMO.
- ➢ FAMA with massive MIMO can improve the energy efficiency and spectral efficiency by reducing the transmission power, increasing the spatial reuse, and exploiting the favorable propagation effects of massive MIMO.
- ➢ FAMA with massive MIMO can improve the connection density and reliability by serving more users, improving the signal-to-noise ratio (SNR), and exploiting the channel diversity effects of massive MIMO.
- ➢ FAMA with massive MIMO can improve the mobility and coverage by adjusting the antenna position, shape, gain, radiation pattern, and frequency to adapt to the dynamic environment and user movement.
- ➢ FAMA with massive MIMO can work with other emerging technologies such as NOMA, IRS, UAV, and mmWave to achieve further gains and synergies.

FAMA with massive MIMO also faces some challenges that need to be addressed:

- ➢ FAMA with massive MIMO requires accurate CSI of the direct and reflecting links, which is difficult to obtain and update in real time due to the large number of antennas and the dynamic environment.
- ➢ FAMA with massive MIMO requires efficient and robust algorithms for joint optimization of the fluid antenna and massive MIMO parameters, such as position, shape, gain, radiation pattern, frequency, power, and precoding, which is a high-dimensional and non-convex problem.
- ➢ FAMA with massive MIMO requires effective and secure protocols for coordination and communication between the fluid antenna and massive MIMO, which may incur additional overhead and vulnerability.
- ➢ FAMA with massive MIMO requires careful design and implementation of the fluid antenna and massive MIMO hardware, such as the mechanism, material, structure, and circuit, which may affect the performance and reliability.

FAMA with massive MIMO can be applied to various aspects, such as:

- ➢ FAMA with massive MIMO can be used for indoor communication, where the fluid antenna can be mounted on the mobile device or wearable device, and the massive MIMO can be deployed on the access point or router, to provide high-quality and ubiquitous service for the users.
- ➢ FAMA with massive MIMO can be used for outdoor communication, where the fluid antenna can be mounted on the vehicle or drone, and the massive MIMO can be deployed on the BS or satellite, to provide flexible and reliable service for the users.
- ➢ FAMA with massive MIMO can be used for mmWave communication, where the fluid antenna can be mounted on the BS or UT, and the massive MIMO can be deployed on the reflector or scatterer, to provide high-capacity and low-latency service for the users.

C. FAMA WITH THz COMMUNICATION

THz communication is a promising technology for 6G that can achieve ultra-high data rate, ultra-low latency, ultra-high bandwidth, and ultra-high resolution by using the electromagnetic spectrum in the range of 0.1-10 THz. THz communication can enable new applications such as wireless brain-computer interface, holographic communication, terabit wireless local area network, and high-precision sensing [51], [52], [53], [54], [55].

FAMA can benefit from THz communication and vice versa. FAMA can use THz communication to exploit the large bandwidth and high resolution of the THz spectrum by switching the antenna position in a predefined space. FAMA can also use THz communication to overcome the high path loss and molecular absorption of the THz signals by adjusting the antenna shape, gain, radiation pattern, and frequency. THz communication can use FAMA to achieve multiple access with a single fluid antenna at each user terminal (UT), and thus reduce the hardware complexity, cost, and energy consumption. THz communication can also use FAMA to adapt to different scenarios, such as MIMO, NOMA, IRS, and UAV, and enhance the compatibility and flexibility. FAMA with THz communication can achieve the following advantages:

- ➢ FAMA with THz communication can improve the data rate and latency by exploiting the ultra-high bandwidth and ultra-low latency of the THz spectrum.
- ➢ FAMA with THz communication can improve the energy efficiency and spectral efficiency by reducing the transmission power and increasing the spatial reuse of the THz spectrum.
- ➢ FAMA with THz communication can improve the connection density and reliability by serving more users, improving the SNR, and exploiting the channel diversity of the THz spectrum.
- ➢ FAMA with THz communication can improve the mobility and coverage by adjusting the antenna position, shape, gain, radiation pattern, and frequency to adapt to the dynamic environment and user movement.

TABLE 4. **AI techniques that are used in FAMA.**

AI Techniques	Use in FAMA System
Deep Learning	Deep neural networks are used to optimize the positions of fluid antennas.
Data Science	Data science methods are used to analyze the statistical properties of the positions of fluid antennas.
Signal Processing	Signal processing techniques are used to increase the signal-to-interference ratio of the positions of fluid antennas.
Missing Data Estimation	In cases where the positions of fluid antennas are missing, missing data estimation methods are used.

- ➢ FAMA with THz communication can work with other emerging technologies such as MIMO, NOMA, IRS, and UAV to achieve further gains and synergies.

FAMA with THz communication also faces some challenges that need to be addressed:

- ➢ FAMA with THz communication requires accurate CSI of the direct and reflecting links, which is difficult to obtain and update in real time due to the high frequency and high resolution of the THz signals.
- ➢ FAMA with THz communication requires efficient and robust algorithms for joint optimization of the fluid antenna and THz communication parameters, such as position, shape, gain, radiation pattern, frequency, power, and modulation, which is a high-dimensional and non-convex problem.
- ➢ FAMA with THz communication requires effective and secure protocols for coordination and communication between the fluid antenna and THz communication, which may incur additional overhead and vulnerability.
- ➢ FAMA with THz communication requires careful design and implementation of the fluid antenna and THz communication hardware, such as the mechanism, material, structure, and circuit, which may affect the performance and reliability.

FAMA with THz communication can be applied to various scenarios, such as:

- ➢ FAMA with THz communication can be used for wireless brain-computer interface, where the fluid antenna can be mounted on the brain implant or wearable device, and the THz communication can be deployed on the external device or server, to provide high-speed and high-precision service for the users.
- ➢ FAMA with THz communication can be used for holographic communication, where the fluid antenna can be mounted on the hologram projector or display, and the THz communication can be deployed on the holo-

TABLE 5. Future research direction of FAMA.

Future research direction	Explanation	Importance for FAMA
FAMA's theoretical analysis	To mathematically analyze the performance and limits of FAMA.	Theoretical analysis of FAMA can reveal the advantages and disadvantages of FAMA and guide the design and optimization of FAMA.
Experimental validation of FAMA	Conducting experimental tests to show that FAMA works in real environments.	Experimental validation of FAMA can prove the feasibility and reliability of FAMA and identify practical problems and challenges of FAMA.
Standardization of FAMA	FAMA develops standard protocols and guidelines for industrial and commercial applications.	Standardizing FAMA can facilitate FAMA dissemination and compliance and ensure the quality and safety of FAMA.
Expanding FAMA's application areas	Exploring the use of FAMA in different scenarios and objectives.	Expanding FAMA's areas of application can increase FAMA's flexibility and diversity and create new opportunities and challenges for FAMA.
Integration of FAMA with other technologies	Enabling FAMA to work with other advanced technologies.	Integration of FAMA with other technologies can improve the functionality and efficiency of FAMA and provide FAMA with new capabilities and synchronization.

gram source or receiver, to provide high-resolution and high-fidelity service for the users.

➢ FAMA with THz communication can be used for terabit wireless local area network, where the fluid antenna can be mounted on the access point or router, and the THz communication can be deployed on the user device or terminal, to provide high-capacity and low-latency service for the users.

➢ FAMA with THz communication can be used for high-precision sensing, where the fluid antenna can be mounted on the sensor or detector, and the THz communication can be deployed on the target or monitor, to provide high-sensitivity and high-accuracy service for the users.

V. ARTIFICIAL INTELLIGENCE FOR FAMA

This section presents several AI-based techniques that are proposed to improve FAMA. Studies on this subject are quite limited in the literature. The integration of FAMA and Deep Learning in recent literature presents innovative approaches in the field of wireless communication. The research in this niche area is limited to past couple years however it is projected to grow significantly in the upcoming years. The related research seems to focus mostly on channel estimation and port selection problems for FASs. Table 4 shows some AI techniques that are used in FAMA.

Waqar et al. [56] propose a low-complexity port selection scheme for FAMA using deep learning. The authors present several key findings related to the performance of a s-FAMA system enhanced by deep learning. This scheme significantly reduces outage probability and improves multiplexing gain with a limited number of ports observations. Long-Short-Term-Memory (LSTM) networks, an advanced form of recurrent neural networks, are employed. In this study, LSTM is used to estimate the received Signal-to-Interference-plus-Noise Ratio (SINR) at unobserved ports by considering SINR information over the ports as a time (space) series. The simulation results demonstrate that the proposed deep learning-based method can accurately estimate SINR with only 25% of the ports observed. This significantly reduces the need for exhaustive channel measurements while maintaining high performance in SINR prediction. The proposed method is compared with two benchmarks - an 'Ideal' system that assumes availability of the SINR at all the ports and a 'Reference' system that selects the best port only among observed ports.

In another study Ye et al. [57] propose an innovative approach using deep learning for efficient port selection in FASs, addressing the challenges posed by the large number of ports and the need for efficient CSI estimation and prediction. The deep learning approach in the paper addresses the practical challenge of selecting the port with the largest SNR in a FAS that has many ports. In the study, LSTM models are leveraged to exploit the temporal correlation of channels at any given port over different time slots by treating them as a time series. To estimate the channel gains of the ports in space, the spatial correlation between different ports is also treated as a time series, and LSTM is used to model this relationship.

Chai et al. [58] also investigate the performance of deep learning aided FAS. The authors address the challenge of port selection in FASs, especially when dealing with many ports and limited observations. Port selection algorithms enhanced with deep learning methods are employed to select the best port out of a large number, based on the strong channel correlation due to the high density of the ports. The paper further combines a deep learning-based LSTM model with an additional method called Smart, 'Predict and Optimize' (SPO) Method. This combined approach is referred to as SPO+LSTM.

VI. FUTURE RESEARCH DIRECTIONS

FAMA is still a new technology and requires further research. Improving the performance of FAMA, obtaining analytical and numerical results for different channel models, fading distributions and antenna lengths, investigating the applicability and compatibility of FAMA in different scenarios, learning more about the integration and synergy of FAMA with new technologies, are future research directions. FAMA could create a new paradigm in mobile communications and unlock the potential of liquid antenna technology. Table 5 shows future research direction of FAMA. FAMA's future research directions include:

- ➢ To improve the performance of FAMA, the speed, precision and reliability of the mechanism used to change the position of the antenna can be improved.
- ➢ Analytical and numerical results of FAMA can be obtained for different channel models, fading distributions and antenna lengths.
- ➢ The applicability and compatibility of FAMA in different scenarios, such as MIMO, multi-user detection, multi-antenna selection, multi-antenna diversity, multi-antenna cooperation, multi-antenna relay, multi-antenna coding, can be investigated.
- ➢ The integration and synergy of FAMA with new technologies such as deep learning, artificial intelligence, cognitive radio, smart grid, internet of things, industrial internet, smart city, smart transportation, smart health can be examined.

The research on FAMA is practically feasible with experimentation research studies that conducted experiments with simulation were mentioned. In order to prove the practical applicability of this technology, in our future studies, we will apply FAMA technology on a small-scale prototype antenna system and conduct experiments in a laboratory environment.

VII. CONCLUSION

This paper presents a thorough overview of FAMA for 6G which is a new multiple access technology that provides great diversity in a small space. The FAS system is covered first. After that, the FAMA mechanism is introduced together with its diversity gain and channel modelling. Subsequently, FAMA is examined in conjunction with other cutting-edge technologies like IRS, THz communication, MIMO, etc. AI methods to improve FAMA are presented. We conclude by discussing possible avenues for further research in all of these areas. FAMA uses fading envelope scanning to choose the best option among many ports that are tightly spaced within a limited linear region, effectively handling inter-user interference. The concept of FAMA stems from the understanding that all signals, including interference, experience deep fades. By strategically using these deep fade times in space, multiple access may be achieved for interference. The idea is also inspired by the FA technology that is being developed for position-flexible, software-controlled antennas. It has been found that, theoretically, a FA may achieve any arbitrarily minimal SIR outage probability if the number of ports is high enough, proving its viability for interference reduction. The use of FAMA, together with other promising approaches like as AI, IRS, MIMO, THz communication, etc., will stimulate more study in this flourishing field.

REFERENCES

[1] K.-K. Wong, W. K. New, X. Hao, K.-F. Tong, and C.-B. Chae, "Fluid antenna system—Part I: Preliminaries," *IEEE Commun. Lett.*, vol. 27, no. 8, pp. 1919–1923, Aug. 2023.

[2] K.-K. Wong, K.-F. Tong, and C.-B. Chae, "Fluid antenna system—Part II: Research opportunities," *IEEE Commun. Lett.*, vol. 27, no. 8, pp. 1924–1928, Aug. 2023.

[3] L. Tlebaldiyeva, S. Arzykulov, K. M. Rabie, X. Li, and G. Nauryzbayev, "Outage performance of fluid antenna system (FAS)-aided terahertz communication networks," in *Proc. IEEE Int. Conf. Commun.*, Rome, Italy, May 2023, pp. 1922–1927.

[4] K. S. Babu and K. R. Devi, "A reconfigurable antenna design using dielectric fluids," in *Proc. 2nd Int. Conf. Commun. Electron. Syst. (ICCES)*, Coimbatore, India, Oct. 2017, pp. 471–475.

[5] Y. Shen, K.-F. Tong, and K.-K. Wong, "Radiation pattern diversified double-fluid-channel surface-wave antenna for mobile communications," in *Proc. IEEE-APS Topical Conf. Antennas Propag. Wireless Commun. (APWC)*, Sep. 2022, pp. 085–088.

[6] J. Ren, Z. Zhou, Z. H. Wei, H. M. Ren, Z. Chen, Y. Liu, and Y. Z. Yin, "Radiation pattern and polarization reconfigurable antenna using dielectric liquid," *IEEE Trans. Antennas Propag.*, vol. 68, no. 12, pp. 8174–8179, Dec. 2020.

[7] L. Cai and K.-F. Tong, "Fluid switch for radiation pattern reconfigurable antenna," in *Proc. IEEE Int. Workshop Electromagnetics: Applications Student Innov. Competition (iWEM)*, Nagoya, Japan, Aug. 2018, pp. 1–2.

[8] Y. Shen, K.-F. Tong, and K.-K. Wong, "Radiation pattern diversified single-fluid-channel surface-wave antenna for mobile communications," in *Proc. IEEE-APS Topical Conf. Antennas Propag. Wireless Commun. (APWC)*, Sep. 2022, pp. 049–051.

[9] Y. Shen, K.-F. Tong, and K.-K. Wong, "Reconfigurable surface wave fluid antenna for spatial MIMO applications," in *Proc. IEEE-APS Topical Conf. Antennas Propag. Wireless Commun. (APWC)*, Honolulu, HI, USA, Aug. 2021, pp. 150–152.

[10] H. Wang, Y. Shen, K.-F. Tong, and K.-K. Wong, "Continuous electrowetting surface-wave fluid antenna for mobile communications," in *Proc. IEEE Region 10 Conf. (TENCON)*, Hong Kong, Nov. 2022, pp. 1–3.

[11] P. Bieńkowski, B. Zubrzak, P. Sobkiewicz, K. Bechta, and M. Rybakowski, "Simplified methodology of electromagnetic field measurements in the vicinity of 5G massive MIMO base station for environmental exposure assessment," *IEEE Access*, vol. 12, pp. 8071–8080, 2024.

[12] N. A. Alhaj, M. F. Jamlos, S. A. Manap, S. Abdelsalam, A. A. Bakhit, R. Mamat, M. A. Jamlos, M. S. M. Gismalla, and M. Hamdan, "Integration of hybrid networks, AI, ultra massive-MIMO, THz frequency, and FBMC modulation toward 6G requirements: A review," *IEEE Access*, vol. 12, pp. 483–513, 2024.

[13] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.

[14] F. A. P. de Figueiredo, "An overview of massive MIMO for 5G and 6G," *IEEE Latin Amer. Trans.*, vol. 20, no. 6, pp. 931–940, Jun. 2022.

[15] S. J. Kar, A. Chakrabarty, and B. K. Sarkar, "Fluid antennas," in *Proc. IEEE Middle East Conf. Antennas Propag. (MECAP)*, Cairo, Egypt, Oct. 2010, pp. 1–6.

[16] 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.

[17] Z. Chai, K.-K. Wong, K.-F. Tong, Y. Chen, and Y. Zhang, "Port selection for fluid antenna systems," *IEEE Commun. Lett.*, vol. 26, no. 5, pp. 1180–1184, May 2022.

[18] K.-K. Wong and K.-F. Tong, "Fluid antenna multiple access," *IEEE Trans. Wireless Commun.*, vol. 21, no. 7, pp. 4801–4815, Jul. 2022.
[19] 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," *Frontiers Commun. Netw.*, vol. 3, Mar. 2022, Art. no. 853416.
[20] 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.
[21] Y. Chen, S. Li, Y. Hou, and X. Tao, "Energy-efficiency optimization for slow fluid antenna multiple access using mean-field game," *IEEE Wireless Commun. Lett.*, vol. 13, no. 4, pp. 915–918, Apr. 2024, doi: 10.1109/LWC.2023.3341460.
[22] K. Wong, K. Tong, Y. Chen, and Y. Zhang, "Maximizing the network outage rate for fast fluid antenna multiple access systems," *IET Commun.*, vol. 17, no. 8, pp. 928–939, May 2023.
[23] S. Zhang, J. Mao, Y. Hou, Y. Chen, K.-K. Wong, Q. Cui, and X. Tao, "Fast port selection using temporal and spatial correlation for fluid antenna systems," in *Proc. IEEE Stat. Signal Process. Workshop (SSP)*, Hanoi, Vietnam, Jul. 2023, pp. 95–99.
[24] Y. Liu, W. Yi, Z. Ding, X. Liu, O. A. Dobre, and N. Al-Dhahir, "Developing NOMA to next generation multiple access: Future vision and research opportunities," *IEEE Wireless Commun.*, vol. 29, no. 6, pp. 120–127, Dec. 2022.
[25] H. Kong, M. Lin, L. Han, W.-P. Zhu, Z. Ding, and M.-S. Alouini, "Uplink multiple access with semi-grant-free transmission in integrated satellite-aerial-terrestrial networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1723–1736, Jun. 2023.
[26] X. Mu, Z. Wang, and Y. Liu, "NOMA for integrating sensing and communications towards 6G: A multiple access perspective," *IEEE Wireless Commun.*, vol. 31, no. 3, pp. 316–323, Jun. 2023.
[27] W. K. New, C. Y. Leow, K. Navaie, and Z. Ding, "Robust non-orthogonal multiple access for aerial and ground users," *IEEE Trans. Wireless Commun.*, vol. 19, no. 7, pp. 4793–4805, Jul. 2020.
[28] C. Skouroumounis and I. Krikidis, "Fluid antenna with linear MMSE channel estimation for large-scale cellular networks," *IEEE Trans. Commun.*, vol. 71, no. 2, pp. 1112–1125, Feb. 2023.
[29] L. Zhu, W. Ma, B. Ning, and R. Zhang, "Movable-antenna enhanced multiuser communication via antenna position optimization," 2023, *arXiv:2302.06978*.
[30] L. Tlebaldiyeva, S. Arzykulov, T. A. Tsiftsis, and G. Nauryzbayev, "Full-duplex cooperative NOMA-based mmWave networks with fluid antenna system (FAS) receivers," in *Proc. Int. Balkan Conf. Commun. Netw. (BalkanCom)*, Istanbul, Turkey, Jun. 2023, pp. 1–6.
[31] W. K. New, K.-K. Wong, H. Xu, K.-F. Tong, C.-B. Chae, and Y. Zhang, "Fluid antenna system enhancing orthogonal and non-orthogonal multiple access," *IEEE Commun. Lett.*, vol. 28, no. 1, pp. 218–222, Jan. 2024.
[32] W. K. New, K.-K. Wong, H. Xu, K.-F. Tong, and C.-B. Chae, "Fluid antenna system: New insights on outage probability and diversity gain," *IEEE Trans. Wireless Commun.*, vol. 23, no. 1, pp. 128–140, Jan. 2024.
[33] H. Xu, K.-K. Wong, W. K. New, and K.-F. Tong, "On outage probability for two-user fluid antenna multiple access," in *Proc. IEEE Int. Conf. Commun.*, Rome, Italy, May 2023, pp. 2246–2251.
[34] K. Wong, K. Tong, Y. Chen, and Y. Zhang, "Extra-large MIMO enabling slow fluid antenna massive access for millimeter-wave bands," *Electron. Lett.*, vol. 58, no. 25, pp. 1016–1018, Dec. 2022.
[35] X. Qiao, Y. Zhang, J. Zhang, H. Fang, L. Yang, and H. Zhu, "Novel beamforming design for IRS-assisted cell-free massive MIMO systems," *IEEE Wireless Commun. Lett.*, vol. 13, no. 4, pp. 1068–1072, Apr. 2024, doi: 10.1109/LWC.2024.3360114.
[36] Z. Wang, D. Shi, and H. Wu, "The role of massive MIMO and intelligent reflecting surface in 5G/6G networks," in *Proc. Int. Conf. Wireless Commun. Smart Grid (ICWCSG)*, Hangzhou, China, Aug. 2021, pp. 309–312.
[37] T. Zhou, K. Xu, X. Xia, W. Xie, and X. Yang, "Achievable rate maximization for aerial intelligent reflecting surface-aided cell-free massive MIMO system," in *Proc. IEEE 6th Int. Conf. Comput. Commun. (ICCC)*, Chengdu, China, Dec. 2020, pp. 623–628.
[38] R. Kaur and B. Bansal, "Secure beamforming for intelligent reflecting surface assisted MISO wireless communications," in *Proc. 3rd Int. Conf. Intell. Commun. Comput. Techn. (ICCT)*, Jaipur, India, Jan. 2023, pp. 1–5.
[39] Y. Liu, L. Zhang, P. V. Klaine, and M. A. Imran, "Optimal multi-user transmission based on a single intelligent reflecting surface," in *Proc. IEEE 4th Int. Conf. Electron. Inf. Commun. Technol. (ICEICT)*, Aug. 2021, pp. 1–4.
[40] A. Taha, Y. Zhang, F. B. Mismar, and A. Alkhateeb, "Deep reinforcement learning for intelligent reflecting surfaces: Towards standalone operation," in *Proc. IEEE 21st Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Atlanta, GA, USA, May 2020, pp. 1–5.
[41] K. S. Tejas, M. Udaykumar, and R. Varun, "Intelligent reflecting surface assisted wireless communication for coverage enhancement," in *Proc. Int. Conf. Smart Syst. Appl. Electr. Sci. (ICSSES)*, Tumakuru, India, Jul. 2023, pp. 1–6.
[42] J. Lončar, "Bandwidth and stability of reflection amplifiers for intelligent reflecting surfaces," in *Proc. 24th Int. Conf. Appl. Electromagn. Commun. (ICECOM)*, Dubrovnik, Croatia, Sep. 2023, pp. 1–5.
[43] I. Chatzigeorgiou, "The impact of 5G channel models on the performance of intelligent reflecting surfaces and decode-and-forward relaying," in *Proc. IEEE 31st Annu. Int. Symp. Pers., Indoor Mobile Radio Commun.*, Aug. 2020, pp. 1–4.
[44] A. Shojaeifard, K.-K. Wong, K.-F. Tong, Z. Chu, A. Mourad, A. Haghighat, I. Hemadeh, N. T. Nguyen, V. Tapio, and M. Juntti, "MIMO evolution beyond 5G through reconfigurable intelligent surfaces and fluid antenna systems," *Proc. IEEE*, vol. 110, no. 9, pp. 1244–1265, Sep. 2022.
[45] A. Dey, R. Guldiken, and G. Mumcu, "Microfluidically reconfigured wideband frequency-tunable liquid-metal monopole antenna," *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2572–2576, Jun. 2016.
[46] K.-K. Wong, K.-F. Tong, and C.-B. Chae, "Fluid antenna system—Part III: A new paradigm of distributed artificial scattering surfaces for massive connectivity," *IEEE Commun. Lett.*, vol. 27, no. 8, pp. 1929–1933, Aug. 2023.
[47] K.-K. Wong, K.-F. Tong, Y. Chen, and Y. Zhang, "Fast fluid antenna multiple access enabling massive connectivity," *IEEE Commun. Lett.*, vol. 27, no. 2, pp. 711–715, Feb. 2023.
[48] D. Serghiou, M. Khalily, T. W. C. Brown, and R. Tafazolli, "Terahertz channel propagation phenomena, measurement techniques and modeling for 6G wireless communication applications: A survey, open challenges and future research directions," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 4, pp. 1957–1996, 4th Quart., 2022.
[49] S. Suyama, T. Okuyama, N. Nonaka, and T. Asai, "Recent studies on massive MIMO technologies for 5G evolution and 6G," in *Proc. IEEE Radio Wireless Symp. (RWS)*, Las Vegas, NV, USA, Jan. 2022, pp. 90–93.
[50] A. F. M. S. Shah, "A survey from 1G to 5G including the advent of 6G: Architectures, multiple access techniques, and emerging technologies," in *Proc. IEEE 12th Annu. Comput. Commun. Workshop Conf. (CCWC)*, Las Vegas, NV, USA, Jan. 2022, pp. 1117–1123.
[51] K. M. S. Huq, I. E. Otung, and J. Rodriguez, "A study of coverage probability-based energy-efficiency analysis for UAV-aided THz-enabled 6G networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 7, pp. 7404–7411, Jul. 2023.
[52] K. Guan, H. Yi, D. He, B. Ai, and Z. Zhong, "Towards 6G: Paradigm of realistic terahertz channel modeling," *China Commun.*, vol. 18, no. 5, pp. 1–18, May 2021.
[53] J. Tan and L. Dai, "THz precoding for 6G: Challenges, solutions, and opportunities," *IEEE Wireless Commun.*, vol. 30, no. 4, pp. 132–138, Aug. 2023.
[54] S. Liu, X. Yu, R. Guo, Y. Tang, and Z. Zhao, "THz channel modeling: Consolidating the road to THz communications," *China Commun.*, vol. 18, no. 5, pp. 33–49, May 2021.
[55] A. Shafie, N. Yang, C. Han, J. M. Jornet, M. Juntti, and T. Kurner, "Terahertz communications for 6G and beyond wireless networks: Challenges, key advancements, and opportunities," *IEEE Netw.*, vol. 37, no. 3, pp. 162–169, May/Jun. 2023.
[56] N. Waqar, K.-K. Wong, K.-F. Tong, A. Sharples, and Y. Zhang, "Deep learning enabled slow fluid antenna multiple access," *IEEE Commun. Lett.*, vol. 27, no. 3, pp. 861–865, Mar. 2023.
[57] N. Ye, J. An, and J. Yu, "Deep-learning-enhanced NOMA transceiver design for massive MTC: Challenges, state of the art, and future directions," *IEEE Wireless Commun.*, vol. 28, no. 4, pp. 66–73, Aug. 2021.
[58] Z. Chai, K.-K. Wong, K.-F. Tong, Y. Chen, and Y. Zhang, "Performance of machine learning aided fluid antenna system with improved spatial correlation model," in *Proc. 1st Int. Conf. 6G Netw. (6GNet)*, Paris, France, Jul. 2022, pp. 1–6.

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