Performance of Fluid Antennas in MIMO Systems

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Abstract. In recent years, there has been a notable surge in research activity pertaining to multiple-input multiple-output (MIMO) systems. Conventional antennas are a common feature of MIMO systems. Nevertheless, the deployment of conventional antennas in MIMO systems is perceived to entail considerable constraints, largely due to the fact that the distribution of conventional antennas is susceptible to near-field coupling phenomena, which ultimately results in a deterioration of the transmitted information's performance. To address this issue, the utilization of fluid antennas in MIMO systems has been put forth as a potential solution. This paper presents an initial investigation into the physical, statistical and noise models of the fluid antenna system, with a particular focus on its performance for transmitting information in MIMO systems. Finally, a comparison is made between the fluid antenna and the conventional antenna, and it is concluded that the fluid antenna system has a higher information transmission rate under high-density, multipath and challenging channel conditions.

Keywords: MIMO, fluid antennas, channel gain.

1. Introduction

In this information age, wireless communication technology is developing very rapidly and has produced many emerging technologies. Recently, MIMO technology is a hot research area, MIMO system through the deployment of multiple antennas to improve transmission performance, and through the multiplexing, spatial diversity and beamforming and other communication techniques to improve the capacity of the system, based on the excellent performance of the above MIMO technology has become an important part of the fourth and fifth generation of wireless communication technology, and people believe that it will still play an important role in the future communication standards such as the sixth generation [1, 2, 3].

The basic principle of a MIMO system is to utilize multiple antennas for the transmission and reception of signals, enabling spatial multiplexing of data streams. In a typical MIMO system, there is one antenna at the transmitting end and one at the receiving end. Ideally, MIMO technology can efficiently utilize spatial resources to transmit data over multiple parallel channels, thereby increasing system capacity. The signal transmission between these two ends can be represented by

$$\boldsymbol{y} = \boldsymbol{Hx} + \boldsymbol{n} = \boldsymbol{Hws} + \boldsymbol{n}, \tag{1}$$

Where $\boldsymbol{y} \in \mathbb{C}^{N_r \times 1}$ is the signal vector at the receiving end, $\boldsymbol{x} \in \mathbb{C}^{N_t \times 1}$ is the signal vector at the transmitting end, $\boldsymbol{H} \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix of $N_r \times N_t$ describing the wireless channel from the transmitter to the receiver, $\boldsymbol{n} \in \mathbb{C}^{\boldsymbol{N_r \times 1}}$is the received noise vector. Furthermore, the transmit signal $\boldsymbol{x}$ can be expressed as $\boldsymbol{x} = \boldsymbol{ws}$, where $\boldsymbol{x}$ represents the transmit signal vector, $\boldsymbol{w}$ is the beamforming weight vector, and $\boldsymbol{s}$ is the signal to be transmitted. In this formulation, the beamforming weights $\boldsymbol{w}$ are applied to the signal $\boldsymbol{s}$ to optimize its transmission at the transmitter. By adjusting the weight vector $\boldsymbol{w}$, power can be distributed across different antennas, allowing for control over the directionality and propagation of the signal.

It is well known that conventional antennas must adhere to the Jake's model for spatial arrangement. The model dictates that the minimum distance between antennas should satisfy the equation

$$\boldsymbol{J_0\left(\frac{2\pi d}{\lambda}\right) = 0 \Rightarrow d = \left(\frac{2.4}{2\pi}\right)\lambda \approx 0.38\lambda \approx \frac{\lambda}{2}}, \tag{2}$$

Where $J_0(\cdot)$ represents the zero-order Bessel function and λ is the propagation wavelength.

Therefore, the fixed characteristics of traditional antennas limit their adaptability and flexibility to support multiple antenna arrangements in MIMO systems. When antennas are placed too close together, coupling can occur in the near field, reducing performance. Consequently, the application of MIMO in communication devices can be constrained by the available space.

Multi-antenna technology dramatically improves the reliability and effectiveness of wireless communications by deploying antenna arrays at the transmitter and receiver ends, thereby providing additional degrees of freedom (DoFs) [4]. Kai-Kit Wong et al. proposed an innovative idea in their paper, introducing a fluid antenna system (FAS) [5, 6]. In this system, a single antenna can dynamically change its position within a small linear space. Unlike conventional solid-state antennas, fluid antennas can adjust their characteristics, such as operating frequency, radiation pattern, and gain, by altering the shape of the fluid. These unique features offer advantages in spatial frequency conversion, multi-band operation, and antenna design diversity. At this stage, there have been studies on fluid antenna port selection and interrupt performance, for example [7, 8, 9].

The combination of fluid antennas and MIMO technology enhances the flexibility and adaptability of MIMO systems. Traditional MIMO systems have fixed quantities, layouts, and directions of antennas, which can limit performance in dynamic environments. In contrast, fluid antennas allow MIMO systems to adjust antenna distribution patterns and operating frequencies based on specific needs, thus optimizing overall system performance [10]. As an emerging antenna technology, fluid antennas show significant potential to optimize MIMO configurations due to their tunability and dynamic characteristics. This paper aims to explore the application of fluid antennas in MIMO systems and analyze how they can improve signal quality and system capacity, especially in multi-user environments.

2. Modeling of Fluid Antennas

2.1. Physical Model

Fluid antennas are generally made from adjustable ionized solutions or liquid metal media. In the study of fluid antennas, they are typically modeled as a single-antenna wireless communication device, where the antenna positions are evenly distributed across N preset locations. These preset positions are linearly arranged in a one-dimensional space of length $W\lambda$, where W represents the size of the antenna and λ denotes the wavelength. In the spatial physical model of the fluid antenna, the fixed positions of the antenna are often referred to as "ports", and the antenna at each port is abstracted as an ideal point antenna [11]. If the first port is taken as the reference point, the displacement of the m-th port can be expressed as

$$\boldsymbol{d_m} = \left(\frac{\boldsymbol{m-1}}{\boldsymbol{N-1}}\right)\boldsymbol{W\lambda}, \forall \boldsymbol{m} = \boldsymbol{1}, \boldsymbol{2}, \dots, \boldsymbol{N}. \tag{3}$$

The received signal at the m-th port is

$$\boldsymbol{y_m} = \boldsymbol{g_m s} + \boldsymbol{\eta_m}, \tag{4}$$

Where g_m is the flat-fading channel coefficient for the m-th port. And s is the transmitted data symbols. The term represents the complex additive Gaussian white noise at the m-th port, with a mean of zero and a variance of σ_η^2. In the physical model of a single fluid antenna, the magnitude of the port channel coefficient $|g_m|$ follows a Rayleigh distribution. In fading communication channels with multiple independent scattering paths, the Rayleigh distribution is a well-established model for the magnitude of channel gain, and its probability density function is given by

$$\boldsymbol{p_{|g_k|}(r)} = \frac{\boldsymbol{2r}}{\boldsymbol{\sigma_g^2}} \boldsymbol{e}^{-\frac{\boldsymbol{r^2}}{\boldsymbol{\sigma_g^2}}}, \forall \boldsymbol{r} \geq \boldsymbol{0}. \tag{5}$$

2.2. Statistical Model

The statistical model of a fluid antenna is a set of correlated channel envelopes that follow a Rayleigh distribution, and its components and statistical properties are important for subsequent research analyses.

The channel envelope g_k for the k-th channel is given by the following expression [5, 11]:

$$\boldsymbol{g_k = \sigma_k\left(\sqrt{1-\mu_k^2}x_k + \mu_k x_0\right) + j\sigma_k\left(\sqrt{1-\mu_k^2}y_k + \mu_k y_0\right)}, \tag{6}$$

Where g_k represents the complex channel envelope, which consists of a real part and an imaginary part, both contributing to the overall channel gain. The parameter σ_k is a scaling factor associated with the k-th channel, typically reflecting path loss or average channel power. The term μ_k is the correlation coefficient between channels, constrained to the interval $(-1,1)$ but excluding zero. This parameter quantifies the degree of correlation between different channels.

The random variables x_k and y_k are independent standard Gaussian variables with zero mean and unit variance, i.e., they are normal random variables with variance $1/2$. On the other hand, x_0 and y_0 are also Gaussian variables, but they are shared across all channels, representing a common random source affecting all the channel envelopes.

Since g_k is a linear combination of two independent Gaussian random variables (representing the real and imaginary parts), it follows a complex Gaussian distribution. Specifically, this means that the expected value of g_k is zero, i.e., $\mathbb{E}[g_k] = 0$, and its second moment, which represents the power of g_k, is given by $\mathbb{E}[g_k|^2] = \sigma_k^2$.

This shows that g_k is a zero-mean, complex Gaussian random variable with variance σ_k^2.

Because g_k is a complex Gaussian random variable, its magnitude g_k follows a Rayleigh distribution. The probability density function (PDF) of the Rayleigh distribution is given by

$$\boldsymbol{f_{|g_k|}(r) = \frac{r}{\sigma_k^2}e^{-\frac{r^2}{2\sigma_k^2}}, r \geq 0}. \tag{7}$$

The Rayleigh distribution is commonly used in wireless communications to model the fading magnitude of a complex channel gain. The magnitude $|g_k|$ of the channel gain has two key properties: its expected value is $\mathbb{E}[|g_k|] = \sigma_k\sqrt{\pi/2}$, and its variance is $\mathrm{Var}(|g_k|) = \sigma_k^2\left(2-\frac{\pi}{2}\right)$.

These properties are typical for Rayleigh-distributed variables, which arise naturally when considering fading in wireless channels with multiple propagation paths.

The correlation between two distinct channel envelopes, g_k and g_l, is given by

$$\boldsymbol{\mu_{k,l} = \frac{\mathbb{E}[g_k g_l^*] - \mathbb{E}[g_k]\mathbb{E}[g_l^*]}{\mathbb{E}[g_k|^2]\mathbb{E}[g_l|^2]} = \mu_k\mu_l}, \tag{8}$$

Where g_l^* denotes the complex conjugate of g_l. This expression shows that the correlation between g_k and g_l depends on the correlation coefficients μ_k and μ_l of the individual channels.

Therefore, when $\mu_k = \mu_l$, the correlation between the two channels is maximized, whereas if μ_k and μ_l approach zero, the two channels become nearly uncorrelated.

The correlation between the different channel envelopes can be described using a correlation matrix $\boldsymbol{R}$, where the (k,l)-th element is $\mu_k\mu_l$. This matrix fully captures the correlation structure between all pairs of channels. The correlation matrix is symmetric and takes the form:

$$\boldsymbol{R} = \begin{bmatrix} \mu_0^2 & \mu_0\mu_1 & \cdots & \mu_0\mu_{N-1} \\ \mu_1\mu_0 & \mu_1^2 & \cdots & \mu_1\mu_{N-1} \\ \vdots & \vdots & \ddots & \vdots \\ \mu_{N-1}\mu_0 & \mu_{N-1}\mu_1 & \cdots & \mu_{N-1}^2 \end{bmatrix}. \tag{9}$$

This matrix provides a complete description of the pairwise correlation between N channels, where each element $\mu_k\mu_l$ represents the correlation between channels g_k and g_l.

In the fluid antenna model, the channel gain for the k-th port is parameterized as follows

$$\boldsymbol{g_k = \sigma\left(\sqrt{1-\mu_k^2}x_k + \mu_k x_0\right) + j\sigma\left(\sqrt{1-\mu_k^2}y_k + \mu_k y_0\right)}, \tag{10}$$

$$\boldsymbol{\mu_k = J_0\left(\frac{2\pi(k-1)W}{N-1}\right)}. \tag{11}$$

In this extended model, all channels share the same scaling factor σ, and the correlation between each channel is governed by the parameter μ_k, which is specific to each channel. This model is particularly useful in MIMO systems where multiple antennas experience correlated fading. The correlation structure between channels plays a significant role in the overall system performance, especially when the channels are not independent. Fig.1 illustrates the distribution of the channel gain magnitude $|g_k|$ in the MIMO system. Fig. 1 compares the PDF normalised by our established amplitude gain formula with the PDF of the Rayleigh distribution.

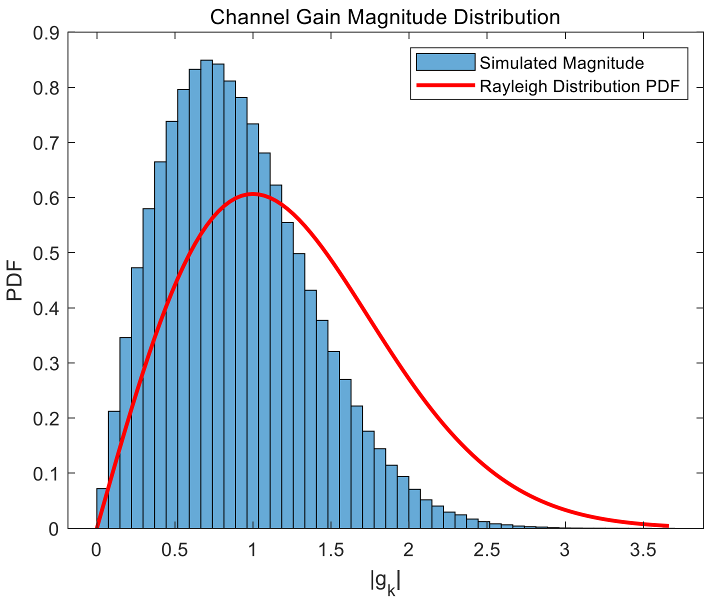

Figure 1. Channel Gain Magnitude Distribution

Furthermore, the histogram is overlaid with the theoretical Rayleigh distribution PDF in red lines for illustrative purposes.

It is defined by a specific fading scale factor. Fig. 1 presents a comparison between the simulated and theoretical channel gain magnitude distributions. From this figure, it can be observed that the channel gain magnitude in MIMO is in close alignment with the Rayleigh fading model, exhibiting statistical properties that align with those of Rayleigh fading. This provides compelling evidence to support the rationale behind the channel model employed in this study.

2.3. Noisy Model

The noise in the system is complex Gaussian white noise with zero mean and variance σ_η^2. For each antenna, the noise is given by

$$\boldsymbol{n = \sqrt{\frac{\sigma_\eta^2}{2}}\left(\mathcal{N}_r(N,M) + i\cdot\mathcal{N}_i(N,M)\right)}, \tag{12}$$

Where $\mathcal{N}_r(N,M)$ and $\mathcal{N}_i(N,M)$ are independent random matrices of $N\times M$,and each element in them are drawn from standard normal distribution $\mathcal{N}(0,1)$. $\mathcal{N}_r(N,M)$ is the real and $\mathcal{N}_\mathrm{i}(N,M)$

is the imaginary parts of the complex Gaussian noise. The factor $\sqrt{\frac{\sigma_\eta^2}{2}}$ ensures the proper scaling of the noise for both the real and imaginary components. This formulation represents complex additive white Gaussian noise (AWGN), which is added to the received signal, with the noise being independent and identically distributed (i.i.d.) across both the real and imaginary parts.

3. FAS in MIMO Systems

3.1. Analysis of Received Signal Magnitude

The signal generation model assumes a MIMO system, where the transmitted symbol matrix s consists of complex symbols, each representing data transmitted by one of the antennas. The noise is modeled as Gaussian white noise with zero mean and variance σ_η^2. The received signal $\boldsymbol{y}$ is given by equation (1).

Once the received signal $\boldsymbol{y}$ is computed, its magnitude is calculated since the received signal is a complex number. The magnitude $\boldsymbol{y}$ of each sample of the received signal is computed as the modulus of the complex number

$$|\boldsymbol{y}| = \sqrt{\Re(\boldsymbol{y})^2 + \Im(\boldsymbol{y})^2}, \tag{13}$$

Where $\Re(\boldsymbol{y})$ and $\Im(\boldsymbol{y})$ represent the real and imaginary parts of the received signal, respectively. The magnitude reflects the instantaneous strength of the signal. This magnitude is stored and visualized by plotting it against the sample index, which provides insight into how the signal amplitude fluctuates over time due to fading and noise.

Fig.2 is used to show the variation of the received signal's magnitude (i.e., $|\boldsymbol{y}|$) at different symbol times. Since the signal is affected by noise and channel gains, the magnitude of the received signal will fluctuate. By observing the fluctuations in the received signal's magnitude, we can analyze the signal quality and system performance, and further study metrics such as the Signal-to-Noise Ratio (SNR).

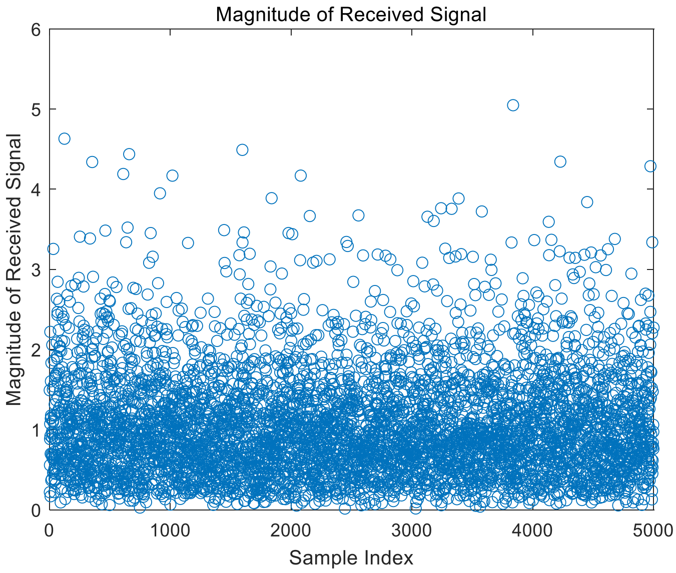

Figure 2. Magnitude of Received Signal

In order to quantitatively assess the characteristics of the received signal, it is necessary to calculate the mean and variance of the received signal amplitude. These statistics provide more insight into how the signal behaves in the presence of noise. The mean of the received signal amplitude reflects the average signal strength and can be used as an estimate of the overall received power. On the other hand, the variance quantifies the spread of the received signal amplitude around the mean value and can indicate the stability and degree of fluctuation of the signal.

A larger variance indicates more pronounced fluctuations in signal strength, which may be due to fading or other channel impairments, while a smaller variance indicates more stable signal reception. These statistical properties are essential for assessing the reliability and stability of a communication system.

SNR calculated based on the mean and variance of the received signal amplitude, and it is a key metric for assessing the quality of the received signal relative to the noise. A higher SNR implies a cleaner signal with less interference, which typically results in lower bit error rates and improved reliability. The SNR formula is as follows

$$SNR=10^{log_{10}}\left(\frac{E[|y|^2]}{E[|n|^2]}\right), \tag{14}$$

Where $E[|\boldsymbol{y}|^2]$ is the expected value of the squared magnitude of the received signal, and $E[|\boldsymbol{n}|^2]$ is the expected value of the squared noise magnitude.

3.2. Performance Comparison of FAS and Traditional Antenna Systems

This section will present a comparative analysis of the average rate performance of conventional antenna systems and fluid antenna systems under varying SNR ratio conditions. Channel capacity represents a pivotal performance metric in wireless communications, expressed in bits per second per hertz. This is closely correlated with the information transfer rate of antenna systems. This paper presents a comparative study of the channel capacity performance of two types of antenna systems, with the relevant formulas constructed to facilitate analysis.

It is well established that the channel matrix is a random matrix employed for the simulation of the communication channel between the transmitting and receiving antennas. Conventional antennas are correlated with each other, and this correlation is described by the covariance matrix of the receiving antenna and the covariance matrix of the transmitting antenna. As a result of this correlation, the antennas interfere with each other, affecting the overall SNR Therefore, both internal interference and external noise must be included in the formula.

In this paper, the $C_{\text{Traditional}}$ is calculated using Shannon's capacity formula for a conventional antenna system, which is given as

$$\boldsymbol{C}_{\textit{Traditional}} = \boldsymbol{log_2}\left(\boldsymbol{det}\left(\boldsymbol{I} + \frac{\boldsymbol{SNR}}{\boldsymbol{N_t}}\boldsymbol{H}_{\textit{Traditional}}\boldsymbol{H}^{\boldsymbol{H}}_{\textit{Traditional}} - \boldsymbol{I}_{\textit{Interference}}\boldsymbol{H}^{\boldsymbol{H}}_{\textit{Traditional}}\right)\right), \tag{15}$$

Where I is the identity matrix, N_t is the quantities of transmit antennas, and $I_{\text{Interference}}$ is the interference matrix, which models external noise or interference sources affecting the signal. The capacity is calculated by taking the logarithm of the determinant of the matrix, which represents the total available capacity for communication.

Because fluid antennas introduce fluid dynamics and fluid motion as part of the system, they are more complex to model than conventional antennas. Moreover, the channel gain of each transmitting antenna port in a fluid antenna system is affected not only by the spatial correlation between the antennas, but also by the fluid velocity and system dynamics.

The gain g_k for each port is computed using the following equation

$$\boldsymbol{g_k} = \boldsymbol{\sigma} \cdot \boldsymbol{exp}\left(-\frac{\boldsymbol{v}}{\boldsymbol{10}}\right)\left(\sqrt{\boldsymbol{1}-\boldsymbol{\mu_k^2}}\boldsymbol{x_k} + \boldsymbol{\mu_k x_0}\right) + \boldsymbol{j\sigma} \cdot \boldsymbol{exp}\left(-\frac{\boldsymbol{v}}{\boldsymbol{10}}\right)\left(\sqrt{\boldsymbol{1}-\boldsymbol{\mu_k^2}}\boldsymbol{y_k} + \boldsymbol{\mu_k y_0}\right), \tag{16}$$

Where $\mu_k = J_0\left(\frac{2\pi(k-1)W}{N_t-1}\right)$ is the spatial correlation factor described by the Bessel function J_0, which models the correlation between antennas based on their relative positions. W is a parameter controlling the spatial frequency between antennas. v is the velocity of the fluid, which affects the attenuation of the channel gain. σ is the standard deviation of the channel gain, and x_{k}, y_{k} and x_0, y_0 are random variables that model the randomness in the channel gain.

The channel matrix H_{Fluid} is constructed by the gains g_k for each transmit antenna, and it varies dynamically with the fluid velocity and the spatial positioning of antennas. The channel gain also incorporates fluid motion, which is not present in the traditional antenna model.

The channel capacity for the fluid antenna system is similarly calculated using the Shannon capacity equation

$$\boldsymbol{C}_{\boldsymbol{Fluid}} = \boldsymbol{log_2}\left(\boldsymbol{det}\left(\boldsymbol{I} + \frac{\boldsymbol{SNR}}{\boldsymbol{N_t}}\boldsymbol{H}_{\boldsymbol{Fluid}}\boldsymbol{H}^{\boldsymbol{H}}_{\boldsymbol{Fluid}} - \boldsymbol{I}_{\boldsymbol{Interference}}\boldsymbol{H}^{\boldsymbol{H}}_{\boldsymbol{Fluid}}\right)\right), \tag{17}$$

This Equation is structurally the same as for the traditional antenna system, but the key difference is that the channel matrix H_{Fluid} takes into account the fluid dynamics and the spatial correlation modeled by the Bessel function.

By comparing the performance of fluid antennas and traditional antennas in a MIMO system, Fig.3 demonstrates that fluid antennas exhibit a significant advantage in high SNR environments, particularly when considering dynamic gain, spatial correlation, and fluid motion.

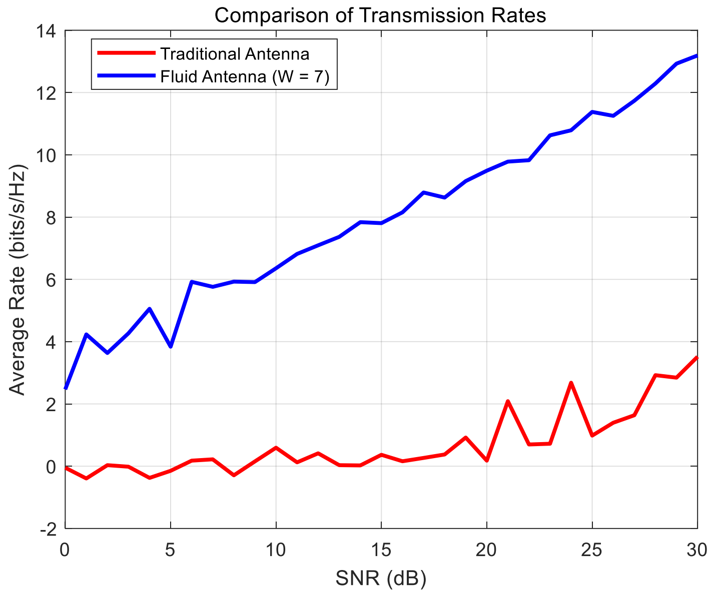

Figure 3. Comparison of Average Transmission Rates between Fluid Antenna and Traditional Antenna

In previous studies, the fluid antenna system performs better at higher SNR locations due to the fact that the fluid antenna can adapt to very high SNR conditions, which results in higher channel capacity, and thus an increase in the information transmission rate. In contrast, conventional antennas do not adapt to high signal-to-noise ratio conditions. By increasing the quantities of FAS ports, increasing the spatial distribution, and reducing the distance between the transmitting and receiving antennas it is possible to increase the effective capacity and transmission performance of the system, and therefore, the fluid antenna is able to provide a better performance than the conventional antenna under high-density and high-SNR conditions.

4. Conclusion

This paper explores the physical, statistical and noise models of FAS and demonstrates its potential to outperform conventional antenna systems under specific conditions. An analysis of the performance of FAS in MIMO systems shows that even with a small allocated space, single-antenna FAS systems can achieve good performance with a sufficiently large quantities of positions (N). It also shows that by adjusting the antenna positions along a fixed linear space, FAS has a significant advantage in adapting to changing channel conditions. Furthermore, a comparison between FAS and conventional antenna systems reveals that FAS not only offers greater flexibility in signal reception, but also has the potential to significantly improve system performance, especially in environments with high channel correlation or fading. The results of this paper suggest that fluid antennas may become a key component of next-generation wireless communication systems, especially in the development of MIMO technologies for 6G and beyond. Future work will focus on further combining FAS with advanced signal processing techniques and analysing its performance in more complex channel environments.

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