Extra-large MIMO enabling slow fluid antenna massive access for millimeter-wave bands

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Fluid antenna multiple access (FAMA) is a new way of accommodating a large number of users on a single channel for massive connectivity, with slow FAMA (s-FAMA) being the practical version for achieving this. The impressive performance is understood to be achievable if the users have independent Rayleigh fading envelopes. With mobile networks vamping up the operating frequencies in 5G and beyond, nevertheless, the channel will have less multipath and become more directional. It is unclear if s-FAMA still performs well and how its performance is affected by different channel parameters. To address this, this letter first develops a multipath fading channel model capable of modelling a mixture of directional line-of-sight (LoS) and non-LoS paths over the ports of a fluid antenna system. The results indicate that a large number of paths in the channel is essential to the performance and a large Rice factor will degrade the performance rapidly. Also, contrast to the initial belief, the size of the fluid antenna plays a more important role than the number of ports or resolution of the fluid antenna. To restore the gain of s-FAMA, it is proposed to employ extra-large multiple-input multiple-output (XL-MIMO) at the base station (BS) to scramble the channel and create artificial multipath so that the users' envelopes can become independent Rayleigh again. The results confirm that XL-MIMO enabling s-FAMA is an effective technique for massive connectivity in the directional millimeter-wave (mmWave) bands.

Introduction: Spectrum scarcity means that next-generation (xG) multiple access technologies should accommodate many users on a single channel to empower massive connectivity as required by 5G and beyond mobile communications [1, 2]. One emerging technology that could fit the bill is fluid antenna [3]. Its potential impact on xG mobile communications was recently discussed in [4]. Of interest is the fluid antenna multiple access (FAMA) system where the fluid antenna at each user seeks to operate at the natural interference null on a symbol-by-symbol basis to allow spectrum sharing of many users [5]. To make the scheme more feasible, [6] proposed the slow FAMA (s-FAMA) system in which the fluid antenna only has to switch if the channel changes. The results in [6] revealed that very high multiplexing gain was achievable if the fluid antenna has high resolution.

The remarkable performance, however, was based on the assumption that the environment has rich scattering so that users have independent Rayleigh channel envelopes, which may not be the case. In particular, for millimeter-wave (mmWave) communications, it has been reported that the wireless channel has less multipath and is more directional [7, 8]. This will most certainly reduce the likelihood of the interference going into a deep fade for exploitation and affect the performance of s-FAMA. In this letter, we aim to evaluate the multiplexing gain performance for s-FAMA using a multi-ray model which is able to model the presence of both line-of-sight (LoS) and non-LoS directional paths for a fluid antenna system, suitable for the mmWave bands. Unsurprisingly, the results will show that not having rich scattering in the environment greatly limits the multiplexing gain of s-FAMA. To overcome this, we propose to use extra-large multiple-input multiple-output (XL-MIMO) at the base station (BS) to randomize the transmitted signals, which has the effect of creating artificial multipath, essential to restoring the independent Rayleigh fading envelopes observed at the fluid antenna of each user for massive multiple access.

The s*-FAMA network:* We first consider a downlink system where the BS has U antennas, each of which is sending information to one fluid antenna equipped user. Hence, there are U users communicating in the downlink on the same channel. Each user's fluid antenna has N ports evenly distributed over a linear space of $W\lambda$ where W denotes the normalised length of the fluid antenna and λ is the wavelength. The parameter N can be interpreted as the resolution of the fluid antenna. The received signal at the k-th port of user u can be written as

$$r_k^{(u)} = s_u g_k^{(u,u)} + \sum_{\substack{\tilde{u}=1\\ \tilde{u}\neq u}}^{U} s_{\tilde{u}} g_k^{(\tilde{u},u)} + \eta_k^{(u)}, \tag{1}$$

where s_u denotes the transmitted symbol for user u, $\eta_k^{(u)}$ is the zero-mean complex additive white Gaussian noise (AWGN) at the k-th port for user u, and $g_k^{(\tilde{u},u)}$ denotes the fading channel from the BS antenna dedicated for transmitting user $\tilde{u}$'s signal to the k-th port of user u.

In the s-FAMA system, each user selects the best port for maximizing the signal-to-interference plus noise ratio (SINR) so that

$$k_u^{s\text{-FAMA}} = \arg\max_k \frac{\sigma_s^2 \left|g_k^{(u,u)}\right|^2}{\sum_{\substack{\tilde{u}=1\\ \tilde{u}\neq u}}^{U} \sigma_s^2 \left|g_k^{(\tilde{u},u)}\right|^2 + \sigma_\eta^2}, \tag{2}$$

in which $\mathrm{E}[|s_u|^2] = \sigma_s^2\ \forall u$ and σ_η^2 is the noise power. In other words, the port at each user changes only if the channels change, which is contrast to the more powerful but much less practical version, f-FAMA [4, 5].

Channel model: In [6, 9], the channel, $g_k^{(\tilde{u},u)}$, is modelled based on the generalized correlation model in [10] via the correlation parameter μ, that is

$$g_k = \Omega\left(\sqrt{1-\mu^2}x_k + \mu x_0\right) + j\Omega\left(\sqrt{1-\mu^2}y_k + \mu y_0\right), \quad \text{for } k = 1, 2, \dots, N, \tag{3}$$

where $x_0, x_1, \dots, x_N, y_0, y_1, \dots, y_N$ are all independent and identically distributed (i.i.d.) Gaussian random variables with zero mean and variance of 0.5, and the parameter, μ, can be obtained using [9, Theorem 1]. Note that in (3), the superscript $(\tilde{u}, u)$ is omitted for conciseness.

While this model is highly recommended for its tractability and is also effective in modelling the correlated channel envelopes over the ports in the case of rich scattering, it is unsuitable for channels with both LoS and non-LoS paths and when the non-LoS paths are very few. Even with rich scattering, it was recently found that the model (3) seems to underestimate the correlation impact on the single-user fluid antenna system [11].

To tackle this, we propose a multi-ray channel model inspired from the mmWave model in [7, 8] which has a specular component (i.e. LoS) and N_p scattered components (i.e. non-LoS). For the specular component, it has an angle-of-arrival (AoA), θ_0,[1] while the scattered components have the AoAs, $\{\theta_\ell\}_{\ell=1}^{N_p}$. The AoAs are essential to account for the spatial correlation over the ports of the fluid antenna resulting from the phase difference of the paths. To sum up, we model the channel, $g_k^{(\tilde{u},u)}$, as

$$g_k^{(\tilde{u},u)} = \sqrt{\frac{K\Omega}{K+1}} e^{j\alpha^{(\tilde{u},u)}} e^{-j\frac{2\pi(k-1)W}{N-1}\cos\theta_0^{(\tilde{u},u)}} + \sum_{\ell=1}^{N_p} a_\ell^{(\tilde{u},u)} e^{-j\frac{2\pi(k-1)W}{N-1}\cos\theta_\ell^{(\tilde{u},u)}}, \tag{4}$$

where $\mathrm{E}[|g_k^{(\tilde{u},u)}|^2] = \Omega$, K is the Rice factor (i.e. the power ratio between the specular and scattered components), $\alpha^{(\tilde{u},u)}$ is the random phase of the specular component, and $a_\ell^{(\tilde{u},u)}$ is the random complex coefficient of the ℓ-th scattered path. By definition, we also have $\mathrm{E}[\sum_\ell |a_\ell^{(\tilde{u},u)}|^2] = \frac{\Omega}{K+1}$.

Note that if $N_p \to \infty$, then regardless of the distribution of $\{a_\ell^{(\tilde{u},u)}\}$, the sum of the scattered components will be Gaussian distributed due to central limit theorem. Consequently, the magnitude $|g_k^{(\tilde{u},u)}|$ will be Rician distributed. Evidently, if $K = 0$, the distribution of $|g_k^{(\tilde{u},u)}|$ is reverted to Rayleigh. Clearly, (4) embraces existing models but has the capability of controlling the impact of the LoS path and simulating the scenarios where the non-LoS paths are few, the characteristics of the mmWave band.

[1] The model can be easily extended to include both the azimuth and elevation AoAs.

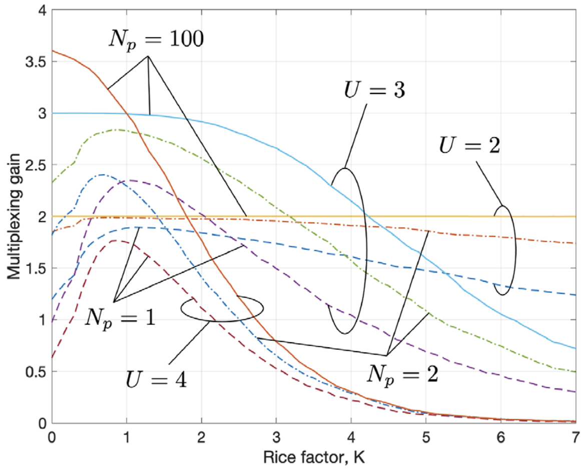

Fig. 1 *The multiplexing gain for s-FAMA without XL-MIMO against the Rice factor, K, when $\Gamma = 30$dB, $\gamma = 5$dB, $N = 1000$, and $W = 25$*

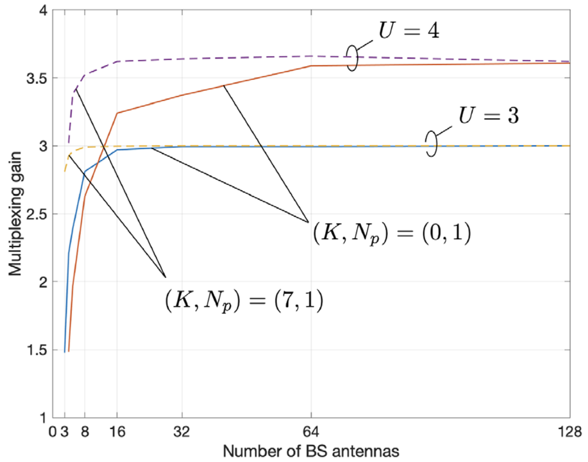

Fig. 2 *The multiplexing gain for s-FAMA with XL-MIMO against the number of BS antennas, N_t, when $\Gamma = 30$dB, $\gamma = 5$dB, $N = 1000$, and $W = 25$*

The average signal-to-noise ratio (SNR), Γ, is defined as

$$\Gamma \triangleq \frac{\sigma_s^2 \mathrm{E}[|g_k^{(\tilde{u},u)}|^2]}{\sigma_\eta^2} = \frac{\sigma_s^2 \Omega}{\sigma_\eta^2}. \tag{5}$$

For each user u, the performance is assessed by the outage probability

$$p = \mathrm{Prob}\left(\max_{k \in \{1,\dots,N\}} \frac{\sigma_s^2 \left| g_k^{(u,u)} \right|^2}{\sum_{\tilde{u}=1 \atop \tilde{u} \neq u}^{U} \sigma_s^2 \left| g_k^{(\tilde{u},u)} \right|^2 + \sigma_\eta^2} < \gamma \right), \tag{6}$$

in which γ represents the SINR threshold, below which is considered an outage. The exact value for γ depends on the actual application but for most applications, $\gamma = 5$dB for an uncoded system usually suffices. With i.i.d. users, the capacity scaling of the s-FAMA network can be obtained through the multiplexing gain

$$m = U(1 - p). \tag{7}$$

Figure 1 shows the multiplexing gain performance of an s-FAMA network with different number of users, U, and under different channel parameters, K and N_p, according to the model in (4). The fluid antenna at each user is assumed to have $N = 1000$ ports and a size of $W = 25$. The system operates against the threshold $\gamma = 5$dB with an average SNR $\Gamma = 30$dB. The results illustrate that the multiplexing gain drops when the channel has less paths, that is, smaller N_p. Also, the multiplexing gain decreases rapidly if the Rice factor, K, increases. Moreover, the degradation is more significant on the network with more users. For example, the multiplexing gain falls to close to 0 for the network with $U = 4$ users when $K = 7$. The channels $(K, N_p) = (0, 1)$ and $(K, N_p) = (7, 1)$ are the worst because they effectively have only one path, unable to provide any variation of the channel envelope for exploitation for multiple access. On the other hand, when $K = 0$ and $N_p = 100$, both $U = 2$ and $U = 3$ can get their respective maximum multiplexing gain but the network with $U = 4$ only reaches 3.5, which means that a stronger fluid antenna at each user, that is, large N and/or W, may be needed in order for s-FAMA to support more users.

XL-MIMO enabling s-*FAMA:* Given the results in Figure 1, we see that rich scattering is a must for s-FAMA to work and a strong specular component, that is, large K, will also greatly prevent fluid antenna from exploiting the ups and downs of the fading envelopes. To overcome this, we propose to employ XL-MIMO at the BS to recreate the Rayleigh envelopes needed for s-FAMA. In particular, user u's signal is mixed with a beamforming vector, $\boldsymbol{b}_u$, before transmitting and the beamforming vectors for all the users, $\{\boldsymbol{b}_u\}_{u=1}^U$, can be chosen arbitrarily from any orthonormal basis spanning the range of an $N_t \times N_t$ complex matrix, where $N_t (\geq U)$ represents the number of BS antennas. The aim is that $\{\boldsymbol{b}_u\}$ will randomize the channels and each BS antenna will act as an artificial scatterer causing more paths in the channels. In the XL-MIMO s-FAMA system, the received signal at the k-th port of the fluid antenna of user u can be expressed as

$$r_k^{(u)} = \boldsymbol{h}_{u,k}^T \boldsymbol{b}_u s_u + \sum_{\tilde{u}=1 \atop \tilde{u} \neq u}^{U} \boldsymbol{h}_{u,k}^T \boldsymbol{b}_{\tilde{u}} s_{\tilde{u}} + \eta_k^{(u)}, \tag{8}$$

where $\boldsymbol{h}_{u,k}^T = [g_k^{(1,u)} \cdots g_k^{(N_t,u)}]$ is the BS-to-user u's k-th port channel vector in which $g_k^{(n,u)}$ denotes the channel from the n-th BS antenna to the k-th port at user u and is modelled in the same way as (4). The following theorem presents a key result for the XL-MIMO s-FAMA system in the asymptotic regime where N_t goes to infinity.

Theorem 1. *As $N_t \to \infty$, the channels over different users $\{\boldsymbol{h}_{u,k}^T \boldsymbol{b}_{\tilde{u}}\}_{\forall \tilde{u}}$ become complex Gaussian distributed and are independent. As a result, user u sees independent Rayleigh fading envelopes from different users.*

Proof. The result comes directly from central limit theorem when $N_t \to \infty$ and the beamforming vectors $\{\boldsymbol{b}_u\}_{u=1}^U$ are drawn from an orthonormal basis spanning the range of an $N_t \times N_t$ complex matrix. □

In Figure 2, the results are provided to evaluate the multiplexing gain of the XL-MIMO s-FAMA network considering the two most undesirable channel scenarios $(K, N_p) = (0, 1)$ and $(K, N_p) = (7, 1)$ when the other parameters remain the same as in Figure 1. We are particularly interested in how the performance scales with the number of BS antennas. As can be observed, even the minimum number of BS antennas makes a huge difference in the performance. For example, in the case $(K, N_p) = (0, 1)$ and $U = 3$, a 3-antenna MIMO BS can raise the multiplexing gain to 1.5 compared to 1 without MIMO. A larger jump is seen for $U = 4$ with a 4-antenna MIMO BS, with the multiplexing gain reaching 1.5 compared to 0.6 without MIMO. A more remarkable performance is observed in the case $(K, N_p) = (7, 1)$ where we see the multiplexing gain increases from 0.3 to 2.8 for $U = 3$ and $N_t = 3$ and from nearly 0 to greater than 3 for $U = 4$ and $N_t = 4$. Additionally, the results illustrate that the multiplexing gain increases sharply as N_t increases further and then converges to the performance with $(K, N_p) = (0, 100)$, that is, the case with Rayleigh fading envelopes, which corroborates the results in Theorem 1. Moreover, the results indicate that with a larger U, more BS antennas are needed for the multiplexing gain to converge to the rich scattering performance.

From the above results, we note that given the parameters with $U = 4$, the multiplexing gain has not reached its maximum. Now, we investigate how the multiplexing gain of the XL-MIMO s-FAMA network varies with the size of the fluid antenna, W. The results are presented in Figure 3 when $N_t = 64$ and the channels have the parameters $(K, N_p) = (0, 1)$ while all other parameters remain unchanged. First, we see that given the range of W, the system with $U = 3$ has already reached the maximum multiplexing gain which thus appears to be unchanged as W increases. With more users in the network, the results show that a larger W will lead to an increase in the multiplexing gain. In particular, when $U = 4$, the multiplexing gain can now approach to 4 if $W = 50$. Note that at 73 GHz, $\lambda = 0.4$cm and a linear space of 10 cm will have $W = 25$

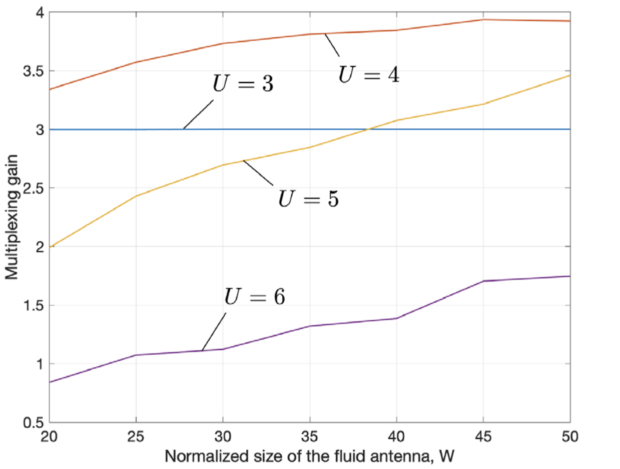

Fig. 3 *The multiplexing gain for s-FAMA with XL-MIMO against the size of fluid antenna, W, when Γ=30 dB, γ=5 dB, $N = 1000$, and $N_t = 64$, and the channel parameters are $(K, N_p) = (0, 1)$*

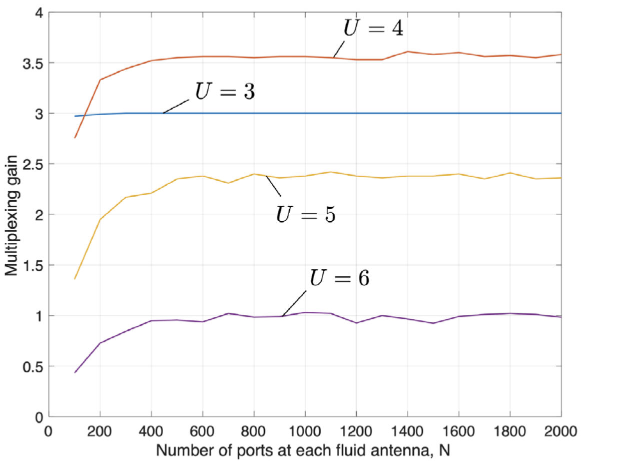

Fig. 4 *The multiplexing gain for s-FAMA with XL-MIMO against the number of ports at each fluid antenna, N, when Γ=30 dB, γ=5 dB, $W = 25$, and $N_t = 64$, and the channel parameters are $(K, N_p) = (0, 1)$*

while a space of 20 cm achieves $W = 50$. Another observation is that with a larger U, the network needs a much larger W in order to achieve a decent multiplexing gain. This observation contrasts to the initial understanding that increasing W has a diminishing return in terms of capacity scaling when the model (3) is used [6].

We conclude this section by examining the multiplexing gain of the XL-MIMO s-FAMA network in Figure 4 when the number of ports of each fluid antenna, N, is changed. All the channel and system parameters are the same as before except that N can now be changed and $W = 25$. The results demonstrate that the multiplexing gain of the network does improve if N is increased but will saturate, as opposed to the observation in [6]. Combining with the results in Figure 3, it is clear that for s-FAMA,[2] W seems to play a more important role in liberating the capacity scaling of the network than the resolution of each fluid antenna and that further increasing the number of ports of the fluid antenna will not help. The reason is that s-FAMA relies on the spatial opportunity where the interference suffers from a deep fade and the larger W, the more such opportunity occurs while N is more to do with how precise the fluid antenna can access to the opportunity. Therefore, increasing N further if N is already very large is expected to have a diminishing return which is what is observed in Figure 4. On the other hand, a possible explanation to the difference from [6] is that the model (4) appears to better model the continuous nature of the fading envelope over the ports while the channel model (3) used in [6] inevitably imposes some artificial randomness (or diversity) of the envelope over the ports, which leads to overestimation of the performance.

[2]It is worth emphasizing here that the same conclusion cannot be drawn for f-FAMA as the mechanism for identifying the interference null is different.

Conclusion: s-FAMA is a novel multiple access technology, aspired for massive connectivity but relies on rich scattering in the environment to ensure sufficient variation of the fading envelopes for the fluid antenna to exploit and escape from the inter-user interference. With mobile networks moving to higher frequency bands (including the mmWave band) for more bandwidth, there is doubt if the channels still possess the characteristics for s-FAMA to thrive. This letter first presented a channel model that can model the presence of directional LoS and non-LoS paths and utilized it to investigate the multiplexing gain performance of s-FAMA. Our results revealed that a large Rice factor could cripple s-FAMA and a large number of non-LoS paths was necessary for s-FAMA to work effectively. To make s-FAMA work under the worst channel conditions, we proposed to adopt XL-MIMO at the BS to act as artificial scatterers to restore the independent Rayleigh fading envelopes needed for s-FAMA. Our results demonstrated that XL-MIMO with s-FAMA performed very well and could support a large number of co-channel users with a high multiplexing gain if each user has a sufficiently large fluid antenna with a good resolution.

Acknowledgements: The work of K. K. Wong and K. Tong is supported by the Engineering and Physical Sciences Research Council (EPSRC) under grant EP/W026813/1 while the work of Y. Chen is supported by the National Natural Science Foundation of China under Grant 61901055.

Conflict of interest: The authors have declared no conflict of interest.

Received: *21 June 2022* Accepted: *17 October 2022*
doi: 10.1049/ell2.12662

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