Fluid Antenna System—Part II: Research Opportunities

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***Abstract*—The promising performance of fluid antenna systems (FAS) relies on activating the optimal port to access the spatial opportunity for favourable channel conditions for wireless communications. This nevertheless can imply enormous overheads in channel estimation and signal reception as the resolution of fluid antenna could be arbitrarily high. There is also the challenge of optimizing jointly the selected ports and beamforming when FAS combines with multiple-input multiple-output (MIMO) systems. This letter discusses some of these obstacles in FAS. Moreover, we present several research opportunities that, if addressed properly, FAS could synergize with other enabling mobile technologies for meeting the requirements of the sixth generation (6G).**

***Index Terms*—6G, enabling technology, fluid antenna system, multiuser communications, wireless communications.**

I. INTRODUCTION

A. 6G and Limitations of Current Technologies

SIXTH-generation (6G) mobile communications thrives to elevate the requirements to extreme levels. NTT Docomo envisaged that use cases in future 6G will be combinations of the following six extreme requirements [1]:

- Extreme high data rate/capacity;
- Extreme coverage;
- Extreme low energy and cost;
- Extreme high reliability;
- Extreme massive connectivity, and
- Extreme low latency.

Achieving the above, even not simultaneously, will require more than just physical-layer technologies. Indeed, cross-layer approaches are very much expected [2]. With that being said, the scope of this letter is on physical layer since the physical layer dictates the fundamental performance limits. Below we analyze why existing technologies may find them difficult to boost their performance to meet the 6G requirements.

Over the past decades, the most celebrated mobile technology is arguably multiple-input multiple-output (MIMO). It has also transformed from point-to-point MIMO in 3G to multiuser MIMO in 4G, and massive MIMO in 5G. Recent developments suggest that 6G will see extra-large MIMO to prosper [3] and some even champion to have continuous-aperture MIMO (CP-MIMO), using subwavelength metamaterials to realize infinite discrete antenna elements at a terminal [4]–[6]. It is very much well known why MIMO performs so greatly but MIMO does have its limitations. Upsizing MIMO comes with complexity in channel estimation and beamforming optimization. In 5G, the Type II New Radio (NR) multiuser MIMO precoder is not a simple solution [7] and pushing it to serve many more users implies serious overheads. It is also fair to evaluate that it will take time to realize CP-MIMO in the future as this will require a technology that can produce any arbitrary, steerable current distribution over a two-dimensional (2D) antenna surface.

Additionally, there is recently a lot of optimism around the reconfigurable intelligent surface (RIS) technology [8] which can combine with MIMO to greatly extend the coverage of a base station (BS) needed for 6G. RIS serves like a passive but intelligent beamformer that redirects signals from the BS to targeted user equipments (UEs). The working principle largely follows MIMO precoding and thus extraordinary performance is anticipated under ideal conditions. Nonetheless, in practical terms, the acquisition of channel state information (CSI) over two hops of RIS is difficult and the precoding optimization is subjected to additional constraints on the unit cells.

Non-orthogonal multiple access (NOMA) [9] and generally rate-splitting multiple access (RSMA) [10] are widely regarded as capacity-maximizing schemes to handle massive connectivity. Yet, both NOMA and RSMA demand UE to be equipped with a highly complex multiuser detector, often in the form of an interference canceller. Moreover, there is the requirement of complex optimization of power allocation and user clustering as well as the CSI requirement at the BS side. Given the high complexity, NOMA is not in 5G. It remains to be seen if any form of NOMA or RSMA will appear in 6G. Even if it does, it is likely to be limited to serving only very few UEs.

Evidently, 6G will turn to higher frequency bands for larger quantities of spectrum and capacity [11]. As a matter of fact, 5G NR supports up to 60 GHz, known as the millimeter-wave (mmWave) band. For 6G, FCC recommends that frequencies such as 95 GHz to 3 THz (i.e., terahertz bands) be utilized [12]. Higher bands, however, mean shorter coverage distances. More power and power-hungry signal processing will be needed. It certainly poses obstacles when MIMO, RIS and NOMA, etc. are employed in the mmWave and terahertz bands. To alleviate this, an uninterrupted power supply would be necessary.

Generally speaking, complex approaches should be avoided if possible. Complexity in the physical layer also implies that the protocol stack can be highly complex, causing communication delay due to scheduling and management overheads.

B. Fluid Antenna-aided Communications

Despite the promises of the state-of-the-art technologies, it is apparent that something different is needed. We believe fluid antenna system (FAS) can be a game-changing technology that transforms mobile communications [13], [14]. As discussed in the first part [15], FAS uses novel dynamic radiating structures to obtain tremendous diversity and multiplexing benefits. For example, a $0.5\lambda \times 0.5\lambda$-space at both ends ensures a MIMO system to have the maximum diversity order of 16[1] while the

The work of Wong and Tong is supported by the Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/W026813/1. For the purpose of open access, the authors will apply a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising.

The work of C. B. Chae is supported by the Institute of Information and Communication Technology Promotion (IITP) grant funded by the Ministry of Science and ICT (MSIT), Korea (No. 2021-0-02208, No. 2021-0-00486).

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[1] This can be interpreted as having 4 independent fixed antennas at one end, so a 4×4 MIMO gives a diversity order of 16.

This article has been accepted for publication in IEEE Communications Letters. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/LCOMM.2023.3284318

same space delivers a diversity order of 81 if MIMO combines with FAS, in which λ denotes the wavelength. Increasing the size to a $1\lambda \times 1\lambda$ space brings the comparison to 64 versus 225 [16].[2] As a consequence, FAS can elevate MIMO to an unprecedented level for extreme high data rate and reliability. The extreme high diversity gain of MIMO-FAS should also contribute to realizing extreme low energy transmission.

Another great potential of FAS is its unique capability of tackling interference in a very simple way. The fluid antenna multiple access (FAMA) concept empowers UE the ability to exploit the spatial opportunity of the interference null created naturally by the propagation environment by changing the port of fluid antenna at the UE [17]–[19]. In other words, the BS does not need to optimize the precoding matrix for interference avoidance at the UEs and can work with random precoding or simply chooses each antenna to transmit one particular UE's signal. Further, the UEs also do not need multiuser detectors like NOMA. In [19], it was demonstrated that at 60 GHz with a 20 cm long fluid antenna (i.e., 40λ in size) at each UE, fast FAMA could achieve 24 times capacity scaling, serving 30 UEs on the same time-frequency channel. Additionally, we have shown in [15] that in the two-user case, FAMA obtains a much higher generalized degree-of-freedom (gDoF) than the Han-Kobayashi (HK) scheme. This suggests that FAS be the solution for realizing extreme massive connectivity.

A by-product of FAMA is that it can reduce communication latency for two reasons. First, the overheads for CSI acquisition at the BS are eliminated since the CSI is no longer needed in the downlink, which will also greatly simplify the protocol stack. Secondly, if more UEs can be supported on one channel use using FAMA, the need for UEs to take turn to access the channel is less, thereby reducing the scheduling delay.

In terms of coverage, RIS will almost certainly be deployed to extend the coverage of BS, especially in the mmWave and terahertz bands. However, the optimization needed for RIS is a very complex and expensive process, let alone the bandwidth limitation of the state-of-the-art unit cell technology that casts doubt on the use of RIS for wideband communications. In this regard, FAS can be the technology that reduces RIS to be an effective, massive scattering surface, creating a rich scattering environment for FAMA to flourish. The complex optimization of RIS can therefore be avoided. Furthermore, this also means that the bandwidth of RIS can be unleashed.[3] The potential of combining RIS and FAS was first discussed in [13], [14] and will be covered in the finale of this three-part letter.

C. *Aim of this Letter*

Following the first-part letter providing an overview of FAS, this letter's aim is to first discuss some classical problems before we introduce a few open problems of great opportunities to utilize FAS for meeting the 6G goals.

II. CLASSICAL PROBLEMS OF FAS

The working principle of FAS depends upon the technology that makes the fluid antenna. For the range of implementation techniques, see [13]. In the physical layer, nevertheless, one can adopt a simplified model, independent of the techniques, that treats the fluid antenna as a moving 'point' antenna with an omnidirectional radiation pattern.[4] Moreover, the delay for the antenna to move from one port to another is often assumed negligible, which is reasonable for pixel-based fluid antennas but needs further justification for liquid-based antennas.

Considering a one-dimensional (1D) N-port, $W\lambda$-long fluid antenna at UE u with the above-mentioned assumptions, the received signal at the k-th port is given by

$$r_k^{(u)} = g_k^{(u,u)} s_u + \underbrace{\sum_{\substack{\tilde{u}\neq u\\ \tilde{u}=1}}^{U} g_k^{(\tilde{u},u)} s_{\tilde{u}} + \eta_k^{(u)}}_{\tilde{g}_k^{(u)}}, \quad (1)$$

where all the parameters are defined in [15, Sec. II].[5]

To perform well, FAS finds and activates the best port k^* according to some criterion, often maximizing some objective function $f(\{r_k^{(u)}\})$, e.g., the signal-to-interference plus noise ratio (SINR) or similar, i.e.,

$$k^* = \arg\max_k f(\{r_k^{(u)}\}). \quad (2)$$

The function f for the single-user and multiuser cases is given, respectively, in [15, (2)] and [15, (4) & (5)]. In [21] and [22], (2) was efficiently addressed using deep learning in single-user FAS and slow FAMA systems, respectively.

A. *Spatial Sampling*

Before the optimization (2) can be conducted, we first need to obtain the values $\{r_k^{(u)}\}$ for $k = 1, 2, \dots, N$ and N can be extremely large. In the existing work, full knowledge of $\{r_k^{(u)}\}$ is assumed but for FAS to be practically viable, only a subset of $\{r_k^{(u)}\}$ should be observed. In fact, if we treat r_k (omitting the user index) in space as a time series, then according to the Nyquist sampling theorem, a finite number of samples are sufficient to completely determine r_k even if $N \to \infty$. Hence, it would be important to know the maximum distance between the samples that guarantees perfect recovery.

Unfortunately, without knowing the continuous-space function r_k beforehand, the required sampling interval, Δ_d, cannot be obtained. To shed light on this, we look into the autocorrelation function by ignoring the noise, given by

$$\mathrm{E}[r_k r_{k+m}^*] = U\sigma_s^2 J_0(2\pi\tau), \quad (3)$$

in which τ denotes the distance between the two signals. Then the power spectral density (PSD) can be obtained by

$$\mathcal{F}\left\{\mathrm{E}[r_k r_{k+m}^*]\right\} = \frac{U\sigma_s^2 \mathrm{rect}\left(\frac{\omega}{4\pi}\right)}{\pi\sqrt{1-\left(\frac{\omega}{2\pi}\right)^2}}, \quad (4)$$

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[2] The comparison has accounted for the correlation in the given space.

[3] The bandwidth of RIS is normally limited by the bandwidth of each unit cell in which it has the ability to have a full (or close to) 360° phase control of the reflection coefficient. It was shown in [20] that the patch-based unit cell achieves only a maximum of 225° phase shift range, and this range also diminishes quickly as the operating frequency expands.

[4] The assumption of an omnidirectional pattern for the fluid antenna does not imply an ideal performance. To the contrary, preliminary results suggest that a non-omnidirectional pattern obtain better performance due to gains. Thus, the assumption is mainly to simplify the model for performance analysis.

[5] Throughout this letter, we will use the notations already defined in [15] without explanation to allow space for discussion of the main ideas.

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where $\mathrm{rect}(\cdot)$ is the rectangular function. Based on the PSD, we might infer that $\Delta_d = \lambda/2$. However, this is only based on the second-order statistics and the actual Δ_d varies according to the channel realization. A better method needs to be sought to obtain a more effective Δ_d and accurate recovery of $\{r_k\}$. In this regard, sub-Nyquist sampling should be useful [23].

B. Channel Estimation

Another important problem in FAS is to estimate the channel coefficients $\{g_k\}_{k=1}^{N}$ in (1) where the user index is omitted for conciseness. In [21], deep learning was applied to estimate the missing channels if only a subset of $\{g_k\}_{k=1}^{N}$ were known. The work was then extended to a slow FAMA system in [22] to estimate the port SINRs. Indeed, channel estimation in FAS is an expensive process as N is usually very large. Most recently, [24] presented a channel estimation framework for a multiuser network with FAS UEs that skipped estimating the channels for a number of adjacent ports for complexity reduction.

To make the channel estimation process more practical, one can use the finite-scatterer channel model given by[6]

$$g_k = \sqrt{\frac{K\Omega}{K+1}} e^{j\alpha} e^{-j\frac{2\pi(k-1)W}{N-1}\sin\theta_0\cos\phi_0} + \sum_{\ell=1}^{N_p} a_\ell e^{-j\frac{2\pi(k-1)W}{N-1}\sin\theta_\ell\cos\phi_\ell}, \quad (5)$$

where K is the Rice factor, α denotes the random phase of the specular component, and a_ℓ is the random complex coefficient of the ℓ-th scattered path. Moreover, $\mathrm{E}[\sum_\ell |a_\ell|^2] = \frac{\Omega}{K+1}$. The parameters, $\{\theta_m\}$ and $\{\phi_m\}$, are, respectively, the azimuth and elevation angle of arrivals (AoAs) of the corresponding paths.

If N_p and the AoAs are given (or estimated by single-pixel based methods [25]), the only unknown parameters in (5) are K, α and $\{a_\ell\}$, i.e., N_p+2 unknowns. Thus, if we have N_p+2 spatial samples, these remaining parameters can be found. In what follows, the channels $\{g_k\}$ can then be computed using (5) for any N. Note that for mmWave channels, $N_p < 4$ and as a result, a few spatial samples would suffice to obtain $\{g_k\}$ regardless of the value of N [26]. Future work should explore this idea and evaluate the complexity and overhead.

III. RESEARCH OPPORTUNITIES

A. FAS as Approximation to CP-MIMO

The research in CP-MIMO so far is highly theoretical. From the implementation side, while the holographic concept seems to be a refreshing route to precoding optimization, the need for full manipulation of the current distribution of a continuous aperture antenna is the technology bottleneck. Additionally, it is worth pointing out that existing results are limited to using CP-MIMO for deterministic channels, e.g., [6].

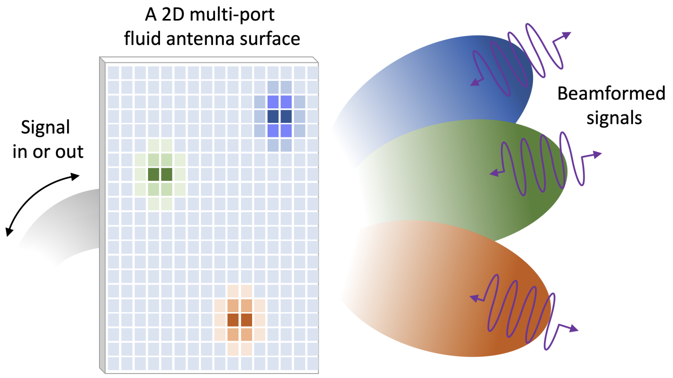

Fig. 1. A MIMO-FAS transceiver to approximate a CP-MIMO transceiver using a reconfigurable pixel-based architecture over a 2D surface.

In this regard, FAS can be interpreted as a simplified CP-MIMO architecture. Specifically, instead of requiring control of current distribution over an entire 2D radiating surface, FAS only activates a few selected (small) regions (i.e., an extended port selection), as depicted in Fig. 1. The number of selected regions depends on the number of radio frequency (RF) chains of the transceiver.[7] The handling of the current distribution is therefore reduced to controlling only the current feeds to the selected regions, similar to a standard MIMO transceiver, and existing MIMO techniques can also be employed.

In so doing, we can approximate a system with CP-MIMO at both ends as MIMO-FAS and the resulting received signals in vector form are expressed as

$$\tilde{\mathbf{r}} = \mathbf{W}_{\mathrm{R}}\mathbf{A}_{\mathrm{R}}\mathbf{H}\mathbf{A}_{\mathrm{T}}\mathbf{W}_{\mathrm{T}}\mathbf{s} + \mathbf{W}_{\mathrm{R}}\mathbf{A}_{\mathrm{R}}\boldsymbol{\eta}, \quad (6)$$

where $\mathbf{W}_{\mathrm{T}}$ and $\mathbf{W}_{\mathrm{R}}$ are the combining matrix, $\mathbf{A}_{\mathrm{T}}$ and $\mathbf{A}_{\mathrm{R}}$ are the port activation matrix,[8] respectively, at the transmitter and receiver side, $\mathbf{H}$ is the channel matrix that has been defined in [15, (14)], $\boldsymbol{\eta}$ is the noise vector, and $\mathbf{s}$ is the information-bearing symbol vector. Note that this channel model $\mathbf{H}$ is in contrast to the Green function-based approach[9] in [6] that fails to account for the scattering phenomenon of wireless channels, and can encompass the fading effects, with spatial correlation. As such, MIMO-FAS does not only provide a simpler practical solution to CP-MIMO but allows a wealth of statistical tools to be utilized to characterize the system performance. In fact, the diversity-multiplexing tradeoff (DMT) of MIMO-FAS has recently been analyzed in [16] and reviewed in [15].

B. MIMO-FAS for FAMA Massive Connectivity

FAMA is a whole new approach to massive multiple access. Like FAS in a single-user channel, if more than one ports can be activated at a time, the resulting MIMO-FAS can greatly improve the performance. Indeed, it is expected that more than one RF chains are available at a UE. It is therefore important to study how FAMA can be extended to benefit from having MIMO-FAS at both the BS and the UEs. Evidently, this will imply higher complexity at the BS and UEs and the need for CSI at the BS. It is crucial to understand if the performance gain can justify the added complexity and overheads.

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[6] Here, the model assumes a far-field analysis which is valid as the physical size of FAS is small compared to the propagation distance. That said, near-field consideration may be necessary if FAS operates in a scenario with RIS which takes up a much larger space comparable to the propagation distance.

[7] In theory, for a CP-MIMO transceiver, it will require an infinite number of RF chains each attached to a particular point of the antenna aperture.

[8] The port activation matrix contains only ones and zeros, and the number of ones represents the number of activated ports at the FAS. Also, the locations of the ones (i.e., the activated ports) are set by the port indices.

[9] This is a free-space channel model, tracing the direct links between any two points from the antenna's continuous aperture of the two ends.

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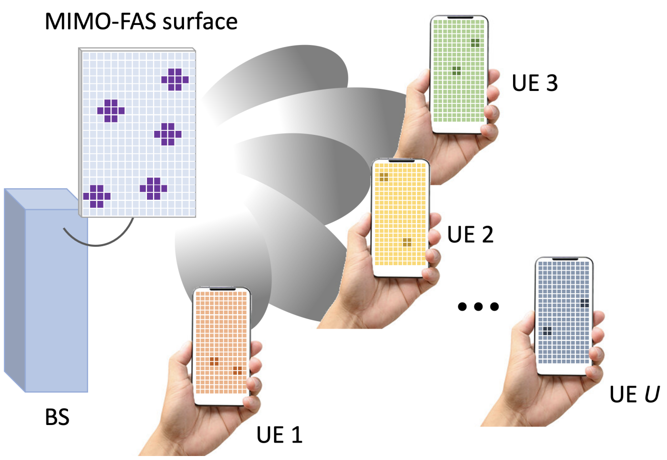

Fig. 2. FAMA with MIMO-FAS at the BS and UEs.

Fig. 2 shows a downlink system where the BS is equipped with a 2D multi-port FAS[10] to transmit signals to U UEs each with a 2D multi-port FAS. In this case, (6) can be extended to express the received signals at the u-th UE as

$$\tilde{\mathbf{r}}_u = \mathbf{W}_{\rm R}^{(u)}\mathbf{A}_{\rm R}^{(u)}\mathbf{H}_u\mathbf{A}_{\rm T}\left(\sum_{\tilde{u}=1}^{U}\mathbf{W}_{\rm T}^{(u)}\mathbf{s}_u\right)+\mathbf{W}_{\rm R}^{(u)}\mathbf{A}_{\rm R}^{(u)}\boldsymbol{\eta}_u, \tag{7}$$

in which all the variables follow the same definitions as before except the index u is introduced to specify the UE. Note that all the UE signals share the same port selection $\mathbf{A}_T$ at the BS. A typical problem is to maximize the sum-rate by optimizing the port selection and beamforming matrices jointly, see (8) at the top of next page. The beamforming matrices come with standard norm constraints to limit their power.

This optimization problem assumes the availability of CSI at the BS. Evidently, the CSI estimation problem alone deserves future work to make the whole process practical. Even with perfect CSI, unfortunately, the problem is NP-hard. To tackle this, one might structure the optimization into two parts. One focuses on interference elimination via port selection and then next is to optimize MIMO beamforming matrices for lifting the achievable performance of each UE's channel. It would be important to come up with a simple metric for port selection at each UE before the beamforming matrices are even optimized. Additionally, the port selection at the BS is trickier since the selected ports are shared by all the UEs and hence should be 'good' for all. The sense of 'goodness', however, is difficult to define. In summary, much needs to be researched for FAMA when MIMO-FAS is employed at both the BS and UEs. Also, machine learning is expected to help with the optimization.

C. FAS for Wireless Power Transfer Systems

Since the pioneering work of [27], wireless communications does not just include information transmission but also power transfer. Nonetheless, both have different goals that are often conflicting. For example, interference signals can contribute to higher received power for energy harvesting but will damage communication. Conventional approaches also tend to handle simultaneous wireless information and power transfer through power allocation and/or beamforming to prevent the power signal from interfering too much the information receiver.

With a multi-port FAS, this problem can be easily handled. In Fig. 3, we demonstrate how a 2-port FAS can assist in this application. As we can see, the SINR and received power over the ports do not follow the same trend. As a result, it would be ineffective to try to do both based on one single received signal point. FAS can address this by having two activated ports, one maximizing the SINR for information reception and another maximizing the total received power reception. Note that FAS improves wireless power transfer at the receiver side whereas the emerging RIS utilizes its large aperture for passing power onto nearby UEs as a power transmitter. Their complementary features should innovate wireless power transfer systems.

D. FAS for Physical-Layer Security

Another advantage of FAS can be on achieving security over wireless channels. It is understood that wireless communications is more vulnerable to security threats because the channel is an open medium [28]. Great efforts have been spent on using physical-layer approaches to modify the wireless channel that ruins the reception at potential eavesdroppers. The side effect, however, is that it normally compromises the signal reception of the legitimate receiver. This is especially the case when the CSI of the eavesdropper is not known.

FAS can help by encouraging the network operating under interference-limited conditions, as depicted in Fig. 4. From the FAMA perspective, it is known that a UE with FAS can avoid the interference by activating a favourable port. In fact, this feature was recently exploited in [29] where the BS used one antenna to transmit the information signal and another to send an artificial noise to harm a potential eavesdropper. The merit is that the legitimate UE is clear of the artificial noise utilizing FAS while the eavesdropper is made difficult to retrieve the signal. It was illustrated in [29] that FAS without CSI at the BS could even outperform a zero-forcing based BS in terms of secrecy rate if the BS CSI was not perfect. This motivates future study on the secrecy performance of FAMA.

E. Others

There are many more opportunities than we can cover in this letter. For example, the potential of FAS to reduce latency, how FAS works in a multi-carrier setting, how the actual radiation pattern of FAS affects its diversity performance and more, are other ones that deserve proper investigation in the future.

IV. CONCLUSION

In this letter, we have discussed briefly the classical problems and presented several opportunities in FAS, with the hope to trigger more interest in this emerging research area. In the finale of a series of three letters, we will study a new paradigm where FAS innovates RIS to deliver massive connectivity.

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[10] Depending on the situations, it may be desirable to adopt many distributed single-port fluid antenna surfaces than a single multi-port FAS at the BS.

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$$\max_{\mathbf{A}_T,\left\{\mathbf{A}_R^{(u)},\mathbf{W}_T^{(u)}\right\}_{\forall u}} \sum_{u=1}^{U} \log_2 \det\left[\sigma_\eta^2\mathbf{I}+\sigma_s^2\left(\mathbf{A}_R^{(u)}\mathbf{H}_u\mathbf{A}_T\right)\mathbf{W}_T^{(u)}\left(\mathbf{W}_T^{(u)}\right)^\dagger\left(\mathbf{A}_R^{(u)}\mathbf{H}_u\mathbf{A}_T\right)^\dagger \right.$$
$$\left. \times\left(\sigma_\eta^2\mathbf{I}+\sigma_s^2\sum_{\substack{\tilde{u}=1\\ \tilde{u}\neq u}}^{U}\left(\mathbf{A}_R^{(u)}\mathbf{H}_u\mathbf{A}_T\right)\mathbf{W}_T^{(\tilde{u})}\left(\mathbf{W}_T^{(\tilde{u})}\right)^\dagger\left(\mathbf{A}_R^{(u)}\mathbf{H}_u\mathbf{A}_T\right)^\dagger\right)^{-1}\right] \tag{8}$$

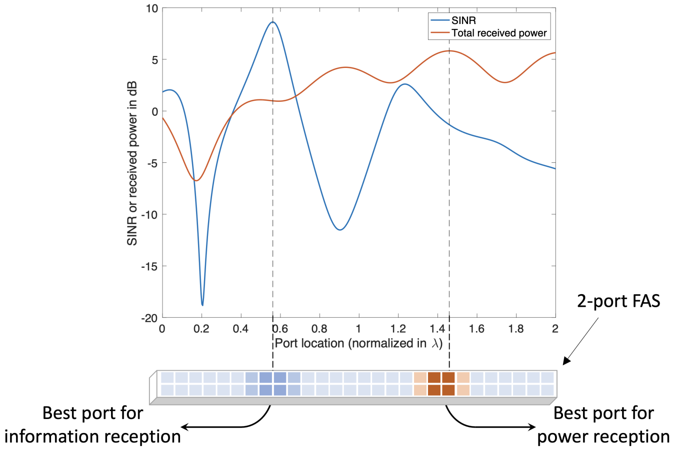

Fig. 3. A 2-port FAS for wireless information and power reception.

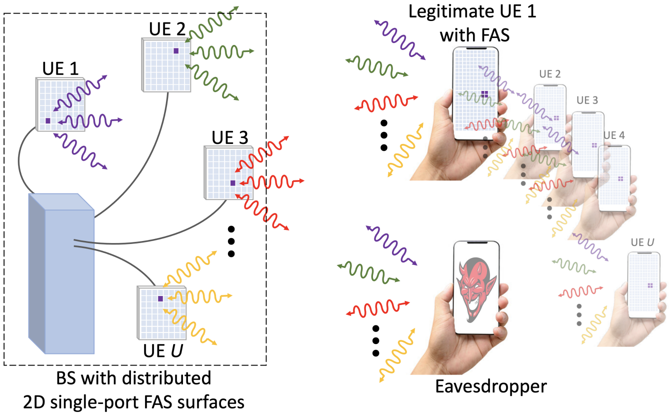

Fig. 4. A FAMA-based secure wireless system by encouraging interference.

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