Reconfigurable Pixel Antennas Meet Fluid Antenna Systems: A Paradigm Shift to Electromagnetic Signal and Information Processing

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***Abstract*—Traditionally, antennas and wireless communication technologies have been developed separately. While antennas focus on maximizing the received or transmitted signal strength, communication technologies optimize performance through coding, signal processing, and resource allocation. However, strong antenna signals do not guarantee high-quality communication due to factors such as channel fading and interference. Recently, the fluid antenna system (FAS) has emerged as a paradigm that treats the radiating aperture as a flexible, reconfigurable physical-layer resource and integrates it into the physical-layer design, broadening the scope of system and network optimization and inspiring next-generation reconfigurable antennas. This paradigm naturally couples electromagnetic signal and information processing (ESIP). A key enabler is the reconfigurable pixel antenna (RPA), which offers high degrees of reconfigurability via pixel-level switching. This article explores the integration of RPA into the FAS concept and highlights the unique ESIP opportunities and associated challenges. Experimental results are presented to demonstrate the significant potential of RPA-enabled FAS.**

***Index Terms*—6G, antenna coding, fluid antenna system (FAS), reconfigurable pixel antennas (RPA), reconfigurable antennas.**

I. Introduction

A RECONFIGURABLE antenna is any structure capable of altering its radiation characteristics on demand and reverting when necessary. The earliest example may be the electromechanically scannable trough waveguide antenna from the 1960s. Phased arrays used in the 1970s for satellite beamforming also exemplify early reconfigurability but according to a more rigorous definition, reconfigurable antennas are defined by their intrinsic ability to modify fundamental operating parameters such as frequency, polarization, and radiation pattern.

Antenna reconfigurability can be achieved through various approaches. A common method involves the use of switches, such as optical switches, field-effect transistors (FETs), PIN diodes, radio frequency (RF) microelectromechanical systems (MEMS), to selectively connect conductive pads and dynamically change the antenna's topology. Varactor diodes are often used as well to allow smooth rather than discrete changes in the antenna's operating characteristics. Moreover, mechanical modifications to antenna structures provide a broader range of reconfiguration capabilities but often raise concerns regarding slower switching speeds, which is particularly problematic in wireless applications. Changes in the material characteristics are also possible to change the permittivity and permeability that can reconfigure the effective size of an antenna.

Traditionally, research on reconfigurable antennas has been driven solely by the antenna community, with a primary focus on reconfigurability in frequency, polarization, and radiation pattern. Frequency reconfigurability is a fundamental feature in cognitive radio applications while polarization reconfigurability facilitates real-time adaptation to match the polarization of the incoming radio wave, reducing mismatch losses. On the other hand, pattern reconfiguration can be closely linked to an antenna's ability to adapt to different channel conditions.

However, from a system-level perspective, the benefits and implementation costs of reconfigurable antennas remain fundamentally unclear. The complexity of both system architectures and operating environments makes it challenging to directly attribute specific antenna functionalities to improvements in actual communication performance, usually quantified by metrics such as throughput, link reliability, or bit error rate (BER). This has motivated some of the earliest efforts, dating back to 2004 [1], to explore the integration of reconfigurable antennas with multiple-input multiple-output (MIMO) technologies. In particular, the idea was to treat antenna reconfiguration in the form of radiation and polarization properties as an additional degree of freedom (DoF) in the joint optimization of adaptive MIMO systems for beamforming and space-time coding [2]. The spacing between antenna elements can also be optimized to align with channel sparsity, enhancing communication performance [3]. Overall, these early efforts primarily responded to what was technically feasible with reconfigurable antennas at the time, seeking to exploit existing capabilities rather than shaping the development of new antenna technologies tailored for the diverse, fast-changing communication needs.

Crucially, one of the most valuable lessons from MIMO is the power of *spatial diversity*—a principle that underpins the evolution from link-adaptive and multiuser MIMO to massive and cell-free MIMO systems. Spatial diversity originates from antenna position diversity. Recognizing this, in 2020 [4], Wong *et al.* introduced the concept of the fluid antenna system (FAS), highlighting the significance of reconfigurability in both shape and position for antennas. More specifically, FAS abstracts the radiating aperture as a flexible and reconfigurable

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(a) (b)

Fig. 1. Illustration of possible FAS deployments: (a) RPA-FAS used at base stations (BSs), user terminals, vehicles, and building surfaces, etc.; and (b) an E-FAS deployed in an indoor environment, where all reconfigurable surfaces collectively form a large FAS to serve users within the space. In this case, users are served via the shortest possible wireless links, and some may even be served through direct contact with the surfaces [7].

physical-layer resource and integrates it into the physical-layer design, broadening the scope of system and network optimization and inspiring next-generation reconfigurable antennas.[1] FAS is hardware agnostic and reconfigurable antennas such as movable antennas, liquid antennas, and time-modulated arrays (or electronically steerable passive array radiator (ESPAR)), can be implementation examples to realize the concept.

While shape reconfigurability naturally represents the capability of conventional reconfigurable antennas, the inclusion of position reconfigurability calls for innovations in reconfigurable antenna designs. A recent article [5] explored the technical challenges and opportunities associated with FAS while Lu *et al.* [6] most recently offered an interpretation of FAS from an electromagnetic (EM) perspective. An enormous FAS (E-FAS)[2] using reconfigurable waveguides was also envisaged to engineer the wireless environments for more control, less interference and higher propagation efficiency [7].

With the increasing interest in FAS, a key question is how its benefits can be realized practically. A particularly appealing approach is the reconfigurable pixel antenna (RPA) technology, whose foundational principles were first established by Brown in 1998 [8]. The emergence of RPA has motivated the research efforts in [1], [2], [3]. An RPA is a LEGO-based structure composed of numerous small metallic patches, called pixels, which are interconnected by RF switches. Given its versatility, RPA can be regarded as a general form of reconfigurable antennas. The designs of RPA require many switches and the effect of the switches and their control lines on the antenna performance is difficult to deal with. Thus, recent studies have proposed using genetic algorithm [9] and adaptive successive exhaustive Boolean optimization (SEBO) [10] to satisfy the intricate reconfigurable antenna design constraints. In [11], a successful FAS prototype was implemented using RPA.[3]

The integration of RPA and FAS in [11] reveals something intriguing but intricate taking place inside the antenna, which can inform future signal and information processing designs. In particular, the observation made in the RPA design suggests that mutual coupling amongst the pixels can be interpreted as some form of analog signal processing and exploited to the advantage of the antenna to produce a diverse EM response. This parallels the perspective in [13], which integrates information theory with Maxwellian electromagnetics to interpret wireless systems at a fundamental level. Nonetheless, our intent is different. Instead of focusing on the EM propagation in the wireless environments, this article gets inside the antenna structure to provide some interpretation of how RPA works in terms of EM signal and information processing (ESIP) towards FAS. This could, in turn, pave the way for new research directions in the evolution of reconfigurable antenna and wireless communication technologies.

II. RPA-FAS

A. The FAS Concept

FAS embraces the new generation of reconfigurable antenna technologies capable of shape and position flexibility tailored for different applications [5]. FAS can be deployed at base stations (BSs), user devices,[4] vehicles, large surfaces on buildings and so on, as illustrated in Fig. 1(a). On the other hand, [7] recently presented a vision where reconfigurable surfaces can serve as waveguides or radiators depending on the situations. This unique capability allows users to be served with either the shortest wireless links or by direct contact with the surfaces. Fig. 1(b) shows this E-FAS case when all the reconfigurable surfaces together are interpreted as a huge FAS.

[1] It is worth highlighting the emerging tri-hybrid MIMO architecture, which provides a unified framework that integrates conventional hybrid analog-digital signal processing with a third layer based on reconfigurable antennas. This architecture is primarily motivated by the need to reduce the cost and energy consumption associated with fully digital MIMO systems, leveraging both analog processing and state-of-the-art reconfigurable antenna technologies. In contrast, the FAS concept is intentionally not confined to existing reconfigurable antenna designs; rather, it exploits the broader dimensions of shape, position, and aperture reconfigurability to enable the development of next-generation wireless technologies across diverse application scenarios.

[2] This terminology serves to advocate the notion of treating a group of coordinated intelligent surfaces as a gigantic reconfigurable antenna system.

[3] Besides RPA, a metamaterial-based approach can be used to implement FAS [12] but its operating principles are different from the RPA approach.

[4] FAS can add value at handsets because a single FAS element driven by one RF chain can harvest spatial diversity, generating multiple channel realizations without duplicating transceivers or carving extra volume for multiple antennas.

The virtue of FAS is to provide a dynamic, software-defined flexible architecture that can fully utilize the permissible space to obtain the best signals for a given application. Typically, in communications, this usually means that FAS operates at the best position where the channel of the intended signal is the strongest, or the signal-to-interference plus noise ratio (SINR) is maximized when interference is present. It works under the same principle of MIMO except that antennas are not fixed at given locations. For other applications, the antenna position in FAS can be accordingly optimized via a proper metric.

B. Principles of RPA

An RPA consists of a grid of small subwavelength conductive pads, referred to as pixels interconnected by RF switches such as RF MEMS or PIN diodes [9]. The RF switches can be turned 'ON' or 'OFF' to change the antenna geometry and topology so that the EM signal can flow through different paths connecting particular pixels, altering the current distribution and resonance as well as the antenna's radiation characteristics. An important example is the RPA-FAS in [11] which consists of two layers: an E-slot patch antenna as the radiation source on the bottom, and a pixelated metallic layer on top.

Full reconfigurability requires controlling all inter-pixel connections via RF switches, enabling a vast number of potential antenna states. However, not all configurations are practical or operational. The objective of antenna design is not to predetermine a single optimal state because the best configuration depends on real-time channel state information (CSI) during operation. Instead, the design goal is to identify a diverse set of reconfigurable, operational states that can be dynamically selected based on CSI. These states are typically discovered by genetic algorithms in conjunction with EM simulations [9]. Recent advances have enabled RF switches between pixels to be modeled as circuit elements, greatly reducing computational complexity by requiring only a single EM simulation [10]. The resulting configurations exhibit diverse radiation patterns and are selected to ensure good impedance matching.

An example of RPA is given in Fig. 2 to show the basic operating principle [14]. The RPA has 6×5 pixels interconnected by in total 49 RF switches. By controlling the ON/OFF states of RF switches, the current distribution can be adjusted, i.e., how current flows through different pixels, and thus implement the reconfigurable radiation pattern which can be pointed to different directions such as $0^\circ, 30^\circ, 60^\circ, 90^\circ$, and 120°.

C. Interpretation and New Insights

The EM behaviour of the RPA is fundamentally governed by the surface current distribution but the underlying relationship is structurally intricate and analytically intractable due to the complex coupling effects and boundary conditions involved. With that said, it is possible to make some observations from the RPA design to gain insights that could contribute to the advancements of wireless communication technologies.

First, it is useful to understand what a reconfigurable state is in a RPA. A reconfigurable state represents a particular combination of ON/OFF states of the interconnections between the pixels and this state should be operational at a given frequency with good impedance matching. A state may be interpreted as forming one or more antennas with certain shape, polarization and radiating at certain positions on the surface. As a result, RPA ensures shape-and-position reconfigurability.

Moreover, the operation of RPA apparently sees EM signal processing at play. The EM signals together with the coupling effects are mixed according to the surface current distribution, which represents some form of analog signal processing. In other words, ESIP constitutes the intrinsic mechanism through which information signals are processed in the RPA. As mutual coupling effects are already accounted for in the identification of reconfigurable states, they are purposefully utilized to benefit the antenna design, contrary to the traditional perception of mutual coupling as a negative influence.

An interesting observation from [11] is that the identification of reconfigurable states can be done to approach any given correlation structures over the states. In [11], this was done to approximate the Jake's correlation model which is attainable theoretically under rich scattering channel conditions. This is another dimension that ESIP plays a role in RPA.

Additionally, RPA-FAS has a very high switching speed, in microseconds for MEMS and nanoseconds for PIN diodes. If PIN diodes are employed for pixel interconnections, then a fast time-switching RPA-FAS can be viewed as a near-continuous aperture antenna. Given the fast switching speed, it is possible that an RPA can obtain the received signals for all the possible reconfigurable states in each symbol duration. If we interpret each state as an antenna position, then this means that at each symbol period, the RPA can obtain the received signals at all the possible positions, and if the number of states is extremely large, the RPA operates like a continuous aperture antenna on a single RF chain. For fifth generation (5G), the shortest symbol period is 4.46 μs so modern PIN diodes can easily allow RPA to access signals across thousands of states/positions.

III. Opportunities

The structures of RPA enable numerous capabilities that are largely unexplored. This section discusses some of these new possibilities, highlighting the ESIP aspects and potential.

A. Antenna Coding

An RPA with Q RF switches can be modeled as a $(Q+1)$-port circuit network with the Q ports connected to tunable load impedance, each of which is either short-circuit or open circuit (corresponding to ON and OFF states). Through simple circuit analysis, the current through the pixel antenna can be analytically expressed and linked to the antenna characteristics such as impedance, radiation pattern, and polarization. Further leveraging the beamspace channel model, we can build a one-to-one mapping from the ON/OFF states of RF switches to the end-to-end channel with RPA. As such, we can express key performance metrics such as capacity as a function of a binary *antenna coding* vector that represents the states of all the RF switches [15]. By choosing the antenna coding, we effectively optimize the ESIP for communications. This integrated design makes RPA an ideal technology for fully exploiting ESIP.

B. Embedded Hybrid Signal Processing

As the reconfiguration of an RPA can be regarded as some kind of analog EM signal processing through mutual coupling

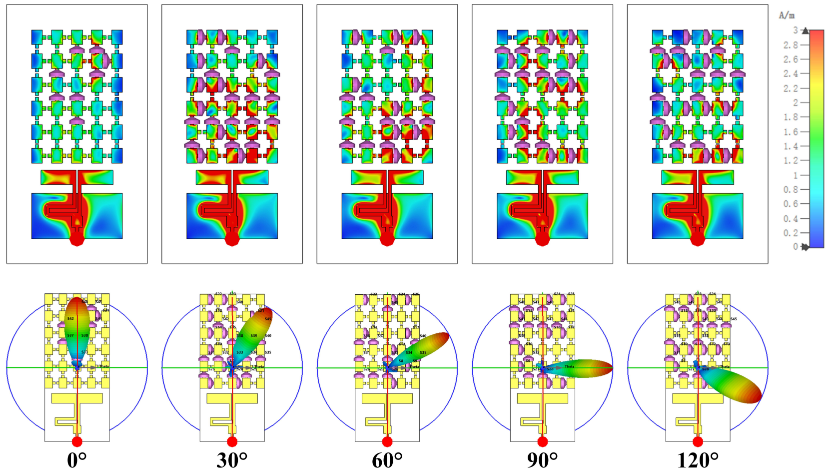


Fig. 2. Current distributions on a pixel antenna which is configured to generate radiation pattern toward $0°, 30°, 60°, 90°$, and $120°$, respectively. In this figure, all switches with ON state (connected) are shown as pink arrows and all switches with OFF state (disconnected) are hidden for clarity of view.

between pixels over certain paths, a MIMO RPA system naturally mixes analog and digital signal processing together. In MIMO using multiple RPAs at both ends, conventional digital beamforming or spatial multiplexing approaches can still be performed but this time done together with antenna coding to switch between states of the RPAs, thereby naturally mixing analog and digital signal processing. Additionally, there is also the scope that an RPA surface with M shared RF chains can perform like $N > M$ fixed-position antennas because the state of the RPA basically includes analog combining over multiple antennas created by the interconnected pixels. Note that unlike conventional hybrid signal processing for MIMO, here, such hybrid processing involves ESIP occurring within the RPA.

C. State-Time Modulation

With high-speed RF switches, RPA can support time modulation.[5] By switching among a series of particular antenna coders with a high speed, an RPA can modulate the waveform in time domain, corresponding to different radiation patterns at each harmonics through Fourier transform. In addition, an RPA can modulate the transmit/receive signal at each symbol period, which enables state-time coding for each symbol. On the other hand, as the reconfigurable states of an RPA can be optimized to fit into certain correlation structures, the RPA can use state-time coding to impose unique correlation signatures for authentication and interference management.

D. Time-Switching RPA as Continuous Aperture Antenna

With RPA time-switching across all the possible reconfigurable states during each symbol period, an RPA approximates a continuous aperture antenna that obtains the received signals at all the possible positions or states over the antenna surface. This then facilitates the operation of fast fluid antenna multiple access (FAMA) schemes that are capable of serving a massive number of users on the same data channel without precoding [5, Section V-C]. Moreover, the RPA-FAS technology makes possible signal processing in the computational domain, which means that the signal dimensionality is no longer limited by the number of RF chains. In the extreme case, the RPA-FAS can operate on a single RF chain to obtain a near-continuous signal series over a given space. Signal processing then takes place in the computational domain, like coding or decoding, after the signal values are stored for computation.

E. Towards a General Approach to ESIP

The capability of RPA can be enhanced if the PIN diodes interconnecting the pixels are replaced by varactor diodes. In so doing, antenna coding is upgraded to continuous antenna coding, which provides a general approach for ESIP. Unlike PIN diodes, varactors offer continuous tuning of capacitance via bias voltage, enabling fine-grained control over phase and resonance characteristics. This enables smooth reconfiguration of radiation patterns, phase shifts, or resonance frequency—rather than just discrete states. The increased DoF is anticipated to need fewer pixels to achieve similar performance targets, thanks to the analog tuning range of varactors.

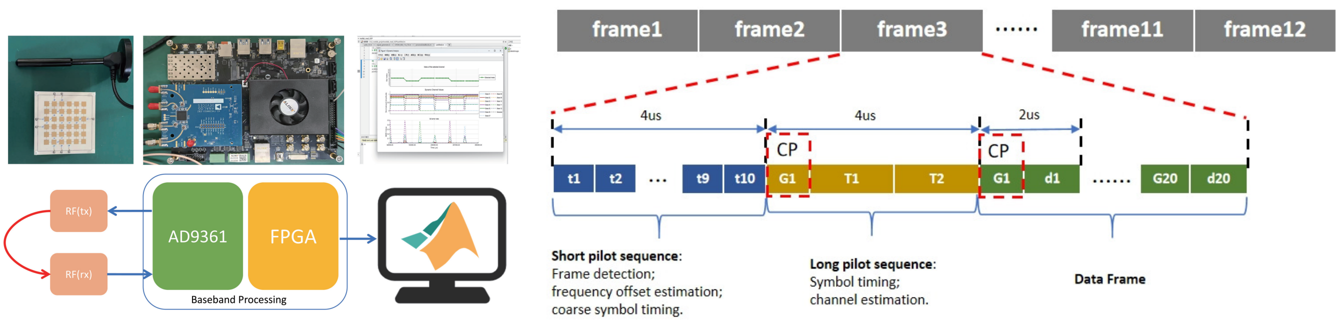
IV. Challenges

In this section, we outline some key challenges involved in the RPA-FAS technology that should be addressed properly.

A. CSI Estimation

CSI is key for FAS to take advantage of its shape and position reconfigurability for best communication performance. Owing to the finite space of FAS, existing channel estimation schemes often utilize spatial correlation to help reconstruct the entire channel knowledge by first estimating the CSI at some positions. This itself is doable but by no means trivial. In the case of RPA, there is an added challenge. Each reconfigurable state can mean more than just a position and the correlation among the states is not well known, meaning that the existing channel estimation schemes for FAS are inapplicable. One way to tackle this is to obtain measurement data characterizing the correlation structures over the states and train the estimator to

[5] This resembles space-time coded modulation in MIMO systems but the spatial domain is generalized to the state domain in RPA. This is not the same as the time modulation for time-modulated arrays where the time-modulated signal is the control signal to tune the array.



(a) (b)

Fig. 3. The experimental setup of RPA-FAS: (a) the FPGA-based system architecture, and (b) the OFDM PPDU.

infer the CSI according to the real data. Another approach is to employ the beamspace channel model and decompose the radiation pattern of RPA into multiple orthogonal bases. As a result, it suffices to estimate a beamspace channel combining the basis pattern, the angle-of-departure (AoD), the angle-of-arrival (AoA), and the gains for multiple paths, which has a reduced dimension for channel estimation.

B. Antenna Coding Optimization

Optimizing the antenna coding for RPA is a binary optimization problem, which is NP-hard. Additionally, the antenna coding optimization becomes even harder when sophisticated objective functions are considered and there are constraints on the optimization variables. Evidently, if antenna coding needs to be jointly optimized with beamforming, then there will be an additional layer of difficulty. To overcome this problem, one promising approach is to leverage machine learning and artificial intelligence (AI) techniques. For example, it is possible to obtain labelled data of the antenna coding solution from traditional stochastic optimization methods and then train a neural network as an antenna coding optimizer in the manner of supervised learning. Reinforcement learning using proximal policy optimization (PPO) for antenna coding optimization is another possible technique that can handle such problems.

Besides, as discussed in Section III-E, when the RF switches are replaced by variable reactive loads, such as varactor diodes, antenna coding can be extended to continuous antenna coding optimization for ESIP. As a consequence, in this case, we can optimize the continuous load impedance, rather than select short/open-circuit, for RPAs. Such continuous antenna coding not only increases the DoF for smoother reconfigurability, but makes the optimization problem more tractable. Nevertheless, varactors can also introduce intermodulation distortion and nonlinear effects, especially under strong RF signals.

C. Hardware Imperfections

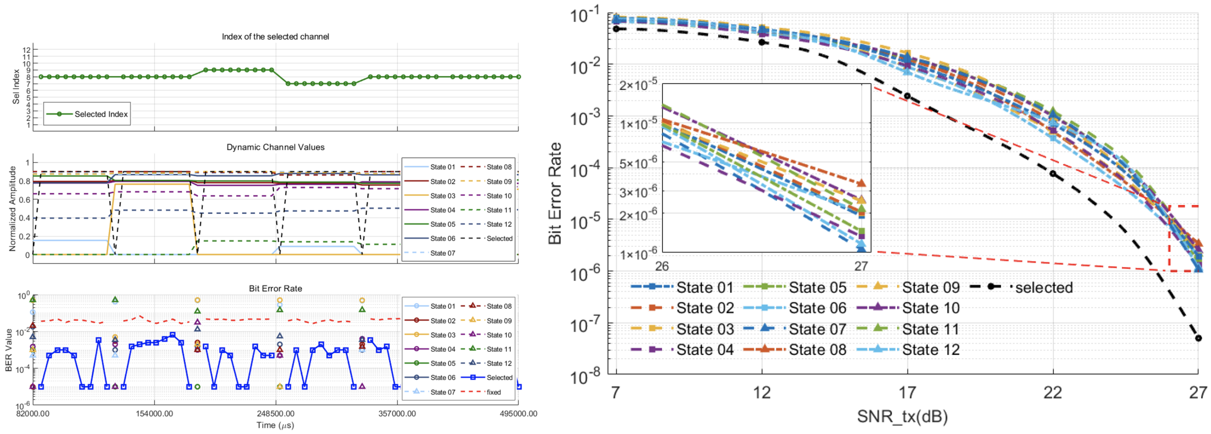
Practical RPAs suffer from hardware imperfections due to limitations in material properties, design constraints, and fabrication processes. These imperfections include:

- **Imperfect impedance matching:** When RPAs are configured using antenna coders optimized for different objectives, their input impedance can vary. This variation causes impedance mismatch, reducing energy efficiency.
- **Non-ideal switch impedance:** RF switches exhibit imperfect short/open-circuit impedance in their ON and OFF states. These imperfections introduce insertion loss, reducing the energy efficiency of pixel-based antennas. Additionally, they affect the accuracy of circuit-analytic methods used to estimate the radiation pattern, thereby degrading antenna coding optimization.
- **Mutual coupling in MIMO setups:** In multi-antenna systems, mutual coupling between adjacent RPAs can occur and is influenced by the chosen antenna coders. This coupling undermines the independence of each RPA and can degrade overall system performance.
- **Challenges in continuous antenna coding:** Continuous coding requires varactors instead of PIN diodes. However, varactor-based control demands precise analog voltage regulation, complicating the biasing network, especially with many pixels. While varactors switch fast enough for many applications, they are slower than PIN diodes (though still significantly faster than MEMS switches).

Overall, while accounting for these hardware imperfections is crucial, it remains a challenging task. An accurate model of pixel-based antennas—one that incorporates impedance mismatch, switch non-idealities, and mutual coupling—may be developed using impedance network analysis techniques.

D. System Implementation and Prototyping

While various RPAs have been designed, prototyped, and experimentally validated, a comprehensive system-level implementation and prototype of RPA-FAS that incorporates continuous antenna coding remains under development. Several key challenges must be overcome to realize such a system. One major obstacle is the efficient control of a large number of RF switches in RPAs, particularly in massive MIMO RPA-FAS architectures, while keeping cost, circuit complexity, and power consumption at acceptable levels. This aspect remains poorly understood. Additionally, integrating low-complexity antenna coding optimization with conventional signal processing tasks, such as precoding, modulation, and waveform design, under current computational constraints poses a significant challenge. Ensuring that the RPA-FAS can adapt to time-varying channels in real time requires novel, resource-efficient solutions. Addressing these challenges will enable the development of new architectures, algorithms, and design methodologies, paving the way for practical prototyping of RPA-FAS systems.



(a) (b)

Fig. 4. The experimental results of RPA-FAS: (a) the real-time results of the experiments, and (b) the BER.

V. Experimental Validation for RPA-FAS

In this section, we present a wireless communication system architecture conducting experiments of an end-to-end RPA-FAS under OFDM settings. Based on the experimental results, we validate that the RPA-FAS obtains significant BER reduction over a fixed-position antenna system.

A. Hardware Platform

We adopt a modular hardware platform that supports both real-time reconfiguration of antenna states and performance evaluation. As shown in Fig. 3(a), the entire system consists of five primary components: (1) a baseband signal processor, (2) an RF transceiver, (3) a conventional fixed-position transmit antenna, (4) an RPA-FAS receiver with 12 reconfigurable states proposed in [11], and (5) a state controller. In addition, the platform is equipped with a dedicated software interface for performance monitoring and data visualization.

To analyze the signal reception performance across different reconfigurable states within a single time slot, the state controller sequentially switches among all predefined configurations via digital I/O control interfaces. In each time slot, the system evaluates reception quality for all candidate states based on some metrics and selects the optimal configuration for data reception, thereby adapting to instantaneous channel conditions and enhancing communication quality.

B. OFDM Physical Layer Protocol Data Unit (PPDU)

We propose an OFDM PPDU based on the IEEE 802.11a protocol.[6] Its frame structure consists of 12 subframes of the same format (frame1, frame2, . . . , frame12). Each subframe contains a short pilot sequence, a long pilot sequence and a data frame part, as depicted in Fig. 3(b). The 12 subframes are used to evaluate the receiving performance of the RPA-FAS under 12 state configurations. The short pilot sequence consists of 10 short symbols of the same format (t1, t2, . . . , t10), of which t1-t7 is mainly used for frame detection, that is, identifying the starting position of the frame; t8-t10 is mainly used for frequency offset estimation and coarse symbol timing. The long pilot sequence consists of a cyclic prefix (G1) and a long symbol (T1, T2). Its function is to achieve symbol timing, ensure that the receiving end can accurately align the starting time of each symbol, and perform CSI estimation. The channel characteristics is understood by analyzing the pilot signal so that the received signal can be processed accordingly. The data frame part consists of 10 time slots of the same format. Each time slot contains two parts: a cyclic prefix and a symbol sequence, which carry the information to be transmitted.

The transmitter consists of several key modules, including modulation mapping, pilot insertion, serial-to-parallel conversion, inverse fast Fourier transform (IFFT), and cyclic prefix insertion. Correspondingly, the receiver includes synchronization, cyclic prefix removal, parallel-to-serial conversion, fast Fourier transform (FFT), channel estimation and equalization, phase tracking, and demodulation mapping. These modules follow the IEEE 802.11a protocol. To isolate and evaluate the performance of the RPA-FAS, certain modules, such as scrambling/descrambling, channel coding/decoding, and interleaving, which are typically used to enhance error resilience, are intentionally disabled. This allows for a clearer assessment of the standalone capability of the RPA-FAS system.

C. Measurement Results

The experiments were carried out on an FPGA-based platform utilizing the Xilinx Zynq UltraScale+ XCZU15EG. The FPGA was employed to configure the AD9361 RF transceiver, which operated at a center frequency of 2.5 GHz, chosen to highlight the pronounced frequency-selective behavior of the RPA-FAS in this band. The system employed a signal bandwidth of 20 MHz and a sampling rate of 40 MHz, enabling efficient data acquisition and processing. To ensure a fair and unbiased comparison across different RPA-FAS antenna state

[6]Unlike conventional systems with fixed antenna configurations, FAS requires a mechanism to evaluate the channel quality across all its possible states within a coherent time period. Therefore, a new PPDU is required that is structured to accommodate 12 identical subframes, each corresponding to one of the 12 predefined antenna patterns (states). Each subframe contains pilot sequences for synchronization, channel estimation, and data symbols. This design allows the receiver to sequentially test all 12 states within a single time slot, measure the received signal quality (e.g., based on the channel gain), and then select the optimal state for data reception.

configurations, no error correction or robustness-enhancement algorithms were applied during signal processing.

The middle panel of Fig. 4(a) illustrates the temporal evolution of the normalized channel response magnitudes across all predefined RPA-FAS states. These fluctuations reflect both the dynamic characteristics of the wireless environment and the frequency-selective behavior of different antenna configurations. At each observation point, the antenna state with the highest normalized channel gain is identified and selected as the optimal configuration. The top panel of Fig. 4(a) shows the time-varying index of this selected state, demonstrating the system's ability to adaptively track the most favorable antenna configuration for signal reception.

The bottom panel presents the BER measurements for all RPA-FAS antenna states, evaluated over short intervals within each time slot. As such, the BER values appear as discrete data points. Notably, the dynamically selected antenna state consistently achieves the lowest BER, outperforming all fixed-state configurations by one to two orders of magnitude.

These results clearly indicate that the optimal RPA-FAS antenna state varies over time and must be updated continuously to maintain performance. In contrast to conventional fixed-state transmission schemes, the dynamic state selection strategy offers a significant advantage in preserving link quality and enhancing communication reliability.

As shown in Fig. 4(b), the dynamic state selection scheme achievable by RPA-FAS consistently outperforms fixed-state configurations across all tested scenarios. Compared to the average BER of multiple predefined antenna states, the dynamically selected configuration yields significantly lower error rates under all SNR conditions. In the SNR range of 7 to $17\ \mathrm{dB}$, BER reductions of approximately 10% to 50% are observed. Notably, beyond $17\ \mathrm{dB}$, the performance gain becomes even more pronounced, with BER improvements reaching one to two orders of magnitude. These results reaffirm that fixed-state designs are insufficient in coping with channel variability, while dynamic selection enables sustained link-level optimization in diverse and changing wireless environments.

Furthermore, experimental results show that even in quasi-static environments, in which the optimal state tends to remain stable over longer periods, real-time evaluation remains necessary. Factors such as hardware imperfections, platform instability, or fluctuating interference can cause gradual performance drift, making continuous monitoring beneficial. These findings emphasize that dynamic state selection is not only critical for time-varying channels but also advantageous in static settings. Overall, the proposed approach is well aligned with emerging trends in 6G research that prioritize intelligent, reconfigurable RF front-ends, and demonstrates the practical viability and adaptability of RPA-FAS antenna architectures with integrated dynamic optimization capabilities.

VI. Conclusion

This article identified RPAs as a key enabler of the shape- and position-reconfigurability envisioned in FAS. By naturally merging analog and digital signal processing, RPA-FAS supports the emerging paradigm of electromagnetic signal and information processing. Our experimental validation confirms that even simple antenna coding in RPA-FAS achieves significant BER reduction over fixed configurations, pointing to its strong potential in future wireless systems.

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