Reconfigurable Antennas and Apertures: State-of-the-Art and Future Outlook

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ABSTRACT

The future proliferation of truly high-speed wireless systems will require more functionality from antennas than can be provided by classic designs. One approach to this challenge is to develop reconfigurable antennas. The goal of a reconfigurable radiator – one that can adjust its operating frequency, bandwidth, and/or radiation pattern to accommodate changing requirements – poses significant challenges to both antenna and system designers. This paper highlights some of the recent advances in the area of antenna reconfiguration, at the University of Illinois and elsewhere, as well as discusses some of the barriers that still need to be overcome to arrive at realizable technologies. These barriers include the development of reliable, mass-manufacturable RF MEMS switches, the design of switch bias networks that will not interfere with antenna operation, and the expansion of signal processing and feedback algorithms to fully exploit this new antenna functionality.

Keywords: reconfigurable antenna, reconfigurable aperture

1. INTRODUCTION

The future proliferation of truly high-speed wireless systems will require more functionality from antennas than can be provided by classic designs. One approach to expand system capability is to develop reconfigurable antennas and apertures. The idea of antenna reconfiguration is not a recent one. Indeed, it is already more than two decades old. However, we are coming into an era where new functionality in antennas is not a novelty but rather a requirement to enable future communication and sensing systems. For instance, current planar phased array technology is fundamentally limited in both scan angle and frequency bandwidth as a result of the limitations of the individual array elements. As another example, simple single antennas deployed on portable wireless data devices are usually minimally functional and limit noise immunity, battery life, and, ultimately, data throughput. Both of these examples illustrate the fact that limited antenna functionality could have a significant impact on performance of high-speed communication links in the future.

1.1 What constitutes reconfigurability?

Reconfigurability, when used in the context of antennas, is the capacity to change an individual radiator's fundamental operating characteristics through electrical, mechanical, or other means. Under this definition, then, the traditional phasing of signals between elements in an array to achieve beam forming and beam steering does not make the antenna "reconfigurable," since the antenna's basic operating characteristics remain unchanged in this case.

Ideally, reconfigurable antennas should be able to alter their operating frequencies, impedance bandwidths, polarizations, and radiation patterns independently to accommodate changing operating requirements. However, the development of these antennas poses significant challenges to both antenna and system designers. These challenges lie not only in obtaining the desired levels of antenna functionality, but also in integrating this functionality into complete systems to arrive at efficient and cost-effective solutions. As in many cases of technology development, the majority of the system cost will come not from the antenna but the surrounding technologies that enable reconfigurability.

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1.2 Organization

This paper provides a brief review of some specific reconfigurable antenna designs as well as a discussion of the barriers that still need to be overcome to arrive at realizable systems. State-of-the-art reconfigurable antennas and apertures, developed at the University of Illinois and elsewhere, are organized here according to their capabilities rather than their method of reconfigurability. Section 2 discusses frequency/bandwidth reconfigurable antennas, Section 3 describes polarization reconfigurable antennas, and Section 4 presents individual antennas with radiation pattern reconfigurability. In many cases, reconfigurable antennas possess more than one property that can change, but not independently (this happens, for example, when changes in operating frequency are coupled with changes in radiation patterns that cannot be avoided). In these cases, the antennas are grouped according to their dominant characteristics. In contrast, Section 5 addresses radiating “pixel” apertures that can change in more than one operating dimension in controlled, independent ways – that is, changes in the fundamental operating characteristics are largely de-coupled. Section 6 offers a discussion of some supporting technologies that must be fully realized before reconfigurable antennas can proliferate. These technologies include reliable, mass-manufacturable RF MEMS switches, non-interfering switch and control bias networks, and expanded signal processing and feedback algorithms that exploit this new antenna functionality.

2. FREQUENCY RECONFIGURABILITY

Frequency reconfigurability is by far the area of antenna reconfigurability that has seen the most development. The following subsections are roughly organized according to the degree to which the operating frequency and/or its impedance bandwidth can be reconfigured.

2.1 Frequency Tuning

The use of the term “tuning” rather than “reconfigurability” in this subsection is simply an indicator that this method generally changes the antenna’s operating frequency in relatively small steps around a central operating point. The development of the first frequency-tunable antennas gained attention through a groundbreaking paper in 1982[1]. In Reference 1, wide-band operation of an inherently narrow-band structure, the rectangular microstrip patch antenna, was achieved using varactors (variable capacitance devices) to vary the structure’s effective electrical length and, as a result, its resonant frequency. Researchers have since applied the concept to resonant frequency tuning for other microstrip and wire antennas[2-7], including some that use ferrite substrate material[4] and others that use optically variable capacitors or other optical tuning means[6,7]. Using the same tuning concept as in Reference 1, researchers have demonstrated a patch antenna integrated with microelectromechanical system (MEMS) actuators[8]. These actuators are used to create capacitances at the edges of the patch that then shifts the operating frequency by about 1.6% (from 25 GHz to 24.6 GHz) without significant changes in any other operating parameter.

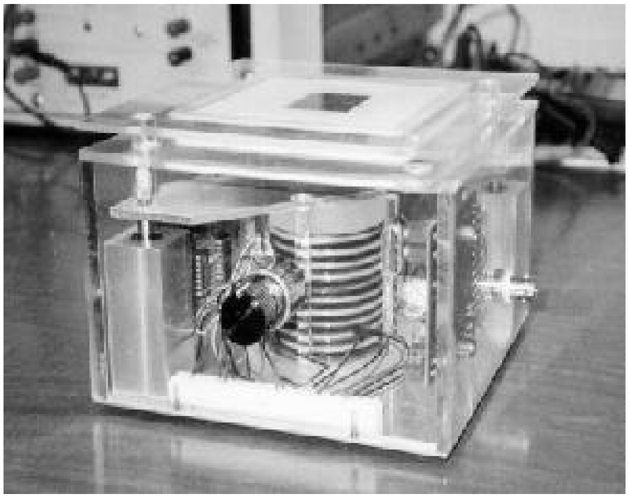

Figure 1: Mechanically-actuated reconfigurable microstrip antenna with moveable parasitic element from Reference 11.

Larger but continuous frequency shifts have been achieved with physical rather than electrical changes in antenna structure. One of these was first demonstrated in 1998, where a piezoelectric actuator system was employed to vary the spacing between a microstrip antenna and a parasitic radiator to change the operating frequency of the antenna [9-11]. A picture of the antenna is presented in Figure 1. While normally possessing a very narrow bandwidth (1%), controlled movement of the parasitic element delivered an effective bandwidth of about 9%. The bandwidth and gain of the structure also change as a function of parasitic element spacing, but these changes are directly coupled to the changes in operating frequency.

Continuous frequency changes have also been demonstrated in a magnetically-actuated microstrip antenna[12]. Using a micromachining process called plastic deformation magnetic assembly (PDMA)[13], the antenna research group at Illinois has developed a new out-of-plane microstrip antenna. A microstrip antenna designed for operation around 26 GHz was covered with a thin layer of magnetic material and released from the substrate. Application of an external DC magnetic field causes plastic deformation of the antenna at the boundary point where it is attached to the microstrip feed line, resulting in a patch positioned at an angle over the substrate. A photograph of one prototype is given in Figure 2. Small changes of the angle at which the structure resides results in changes in operating frequency that preserve radiation characteristics, while larger angles result in frequency shifts accompanied by significant changes in the antenna's radiation pattern. In particular, as the elevation angle between the patch and the horizontal substrate increases past 45 degrees, the antenna's radiation is more characteristic of a horn antenna, and changes toward the pattern of a monopole antenna as the angle approaches 90 degrees.

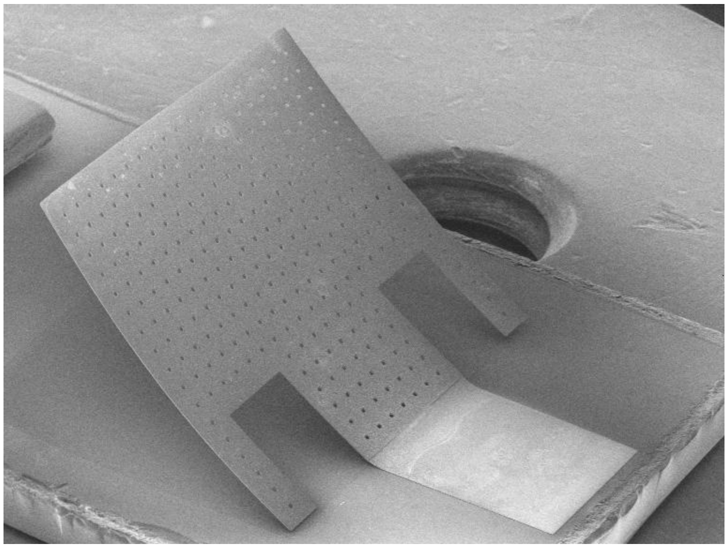

Figure 2: An out-of-plane magnetically-actuated microstrip antenna from Reference 12.

2.2 Switched multiple frequency reconfiguration

Another approach to frequency reconfiguration is the use of switched connections, implementing either diode switches or proposed MEMS switches, that results in operation at two or more discrete frequency bands. One recent application of this approach for frequency tuning is found in Reference 14. In this work, control of bias across a number of PIN diode switches changes the resonant frequency of a radiating slot structure. While this approach to tuning works well as lower frequencies, the losses and parasitics inherent in diodes and varactors limit their use as the frequency of operation increases. For operation at higher frequencies, a number of researchers have proposed the use of RF MEMS switches rather than diodes to achieve apparent changes in an antenna's length or size. For instance, K.C. Gupta proposes use of switches to change the electrical length of rectangular slot ring antennas[15], Ali and Wahid propose switched lengths in a Yagi antenna[16], Weedon et al. propose a two-dimensional grid of switchable patches to form large or small microstrip radiators[17], and Vinoy and Varadan propose switched fractal antennas[18]. In prototype tests, all of these antennas succeed in maintaining

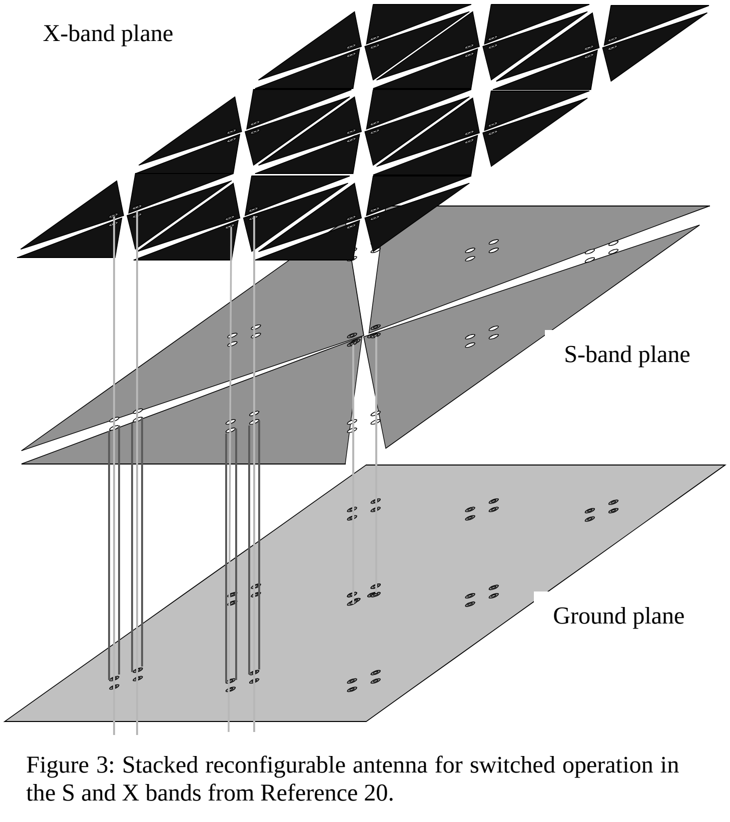

Figure 3: Stacked reconfigurable antenna for switched operation in the S and X bands from Reference 20.

radiating properties while changing their operating frequency. Each of these examples, however, is poorly suited to operation in a uniform periodic array environment, since element spacing at the highest frequencies (requiring the smallest antennas) will create grating lobes in the observed array pattern.

Another approach to frequency reconfigurability is to combine a number of different antennas designed for different frequencies in a single structure and then using switches or other mechanisms to control the operating frequency. One example of this approach is the stacked reconfigurable antenna developed at the University of Illinois[19,20]. A diagram of the stacked reconfigurable antenna is shown in Figure 3. In this structure, two relatively broad frequency bands (with approximately 40% bandwidth) are alternately achieved in the S and X bands. The basic antenna structure consists of a microstrip bowtie with a mixed dielectric substrate. Polarization variability at each feed point is supported by orthogonal placement of two balanced bowtie elements that can be driven to produce linear, elliptical, or circular polarization. Array operation in the lower band requires that the upper-band elements be disconnected via switches below the ground plane. In this stacked configuration, the upper-band elements act as floating parasitic elements for the lower-band elements, slightly broadening the impedance bandwidth. Operation of the upper-band elements requires that the lower-band elements be grounded via switches. In this configuration, the lower-band elements act as the ground plane for the upper-band elements.

Researchers at UCLA have developed a reconfigurable leaky-wave/patch microstrip array that can operate over a range of frequencies[21]. Each of several leaky-wave apertures can be segmented into several smaller patch antenna apertures operating at discrete frequencies between 4 and 8 GHz through activation of switched connections. Additionally, the leaky-wave structures operating between 8 and 10 GHz are arrayed so that they can be frequency scanned with gain up to 12 dB.

3. POLARIZATION RECONFIGURABILITY

Several antennas have also been developed that have reconfigurable polarization characteristics. From a design standpoint, this kind of reconfigurability can be more difficult to achieve than frequency reconfigurability, since the structure of the antenna has to change in ways that alter the way current flows on the antenna without affecting the operating frequency. Polarization reconfiguration could be useful for achieving more reliable wireless connections by adjusting to changing environmental conditions, in effect, acting as a form of switched antenna diversity.

One example of such a polarization-agile antenna is that presented in Reference 22. In this design, a MEMS actuator is located within a simple microstrip patch antenna designed to support two orthogonal modes when excited in the corner. The actuator consists of a moveable metal strip suspended over a metal stub. When the strip is suspended above the stub, the antenna radiates a circularly polarized wave. Using electrostatic actuation, the metal strip can be lowered to create an antenna with dual linear polarization.

Another reconfigurable antenna is the “patch antenna with switchable slots,” or PASS antenna developed at UCLA[23]. In general, the PASS antenna consists of a microstrip antenna with one or more slots cut out of the copper patch. A switch (either diode or RF MEMS) is inserted in the center of the slot to control how currents on the patch behave. When the switch is open, currents must flow around the slot. When the switch is closed, the current can follow the shorter path created by the closed switch. Polarization reconfigurability is achieved by including two orthogonal slots on the surface of the patch. Alternate activation of the switches yields either right-hand or left-hand circular polarization. The broader concept of the PASS has also been applied to achieve switched dual-band frequency reconfigurability as well[24].

4. RADIATION PATTERN RECONFIGURABILITY

A diverse set of designs has emerged to date to deliver radiation pattern reconfigurability while maintaining other operating characteristics. This section is organized according to basic antenna type, since the mechanism for radiation pattern configuration relies heavily on specific antenna design.

4.1 Pattern reconfigurable microstrip antennas

The ability to change radiation patterns on microstrip antennas while maintaining operating frequency is one of the most challenging areas of antenna reconfigurability. This is because the significant changes in the antenna structure necessary to produce changes in radiation characteristics are usually closely coupled to the input impedance of the antenna. Manipulation of an antenna's radiation pattern can be used to avoid intentional or non-intentional jamming sources, to act as a switched pattern diversity system, and to direct signals only toward intended users[25].

At the University of Illinois, we have developed radiation reconfigurable microstrip antennas that maintain their frequency and bandwidth characteristics[25]. The basic antenna structure consists of a single turn square spiral antenna, shown in Figure 4, which exhibits a broadside radiation pattern in fundamental state. Two switches (either solid state or RF MEMS) can be activated – one between the spiral and ground (shown on the left of Figure 4) and the second that opens a small gap in the spiral arm (shown on the right of Figure 4). In this configuration, a 45-degree main beam tilt from broadside is achieved at the same operating frequency (shown in Figure 5). While a scaled version of this antenna is being implemented in phased arrays, it is also being investigated as a single element on portable computers to improve data communication link reliability and noise immunity[26].

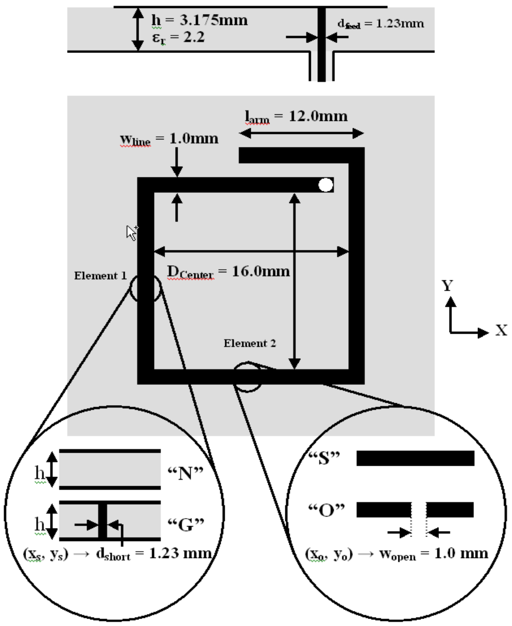

Figure 4: Pattern reconfigurable microstrip spiral antenna from Reference 25.

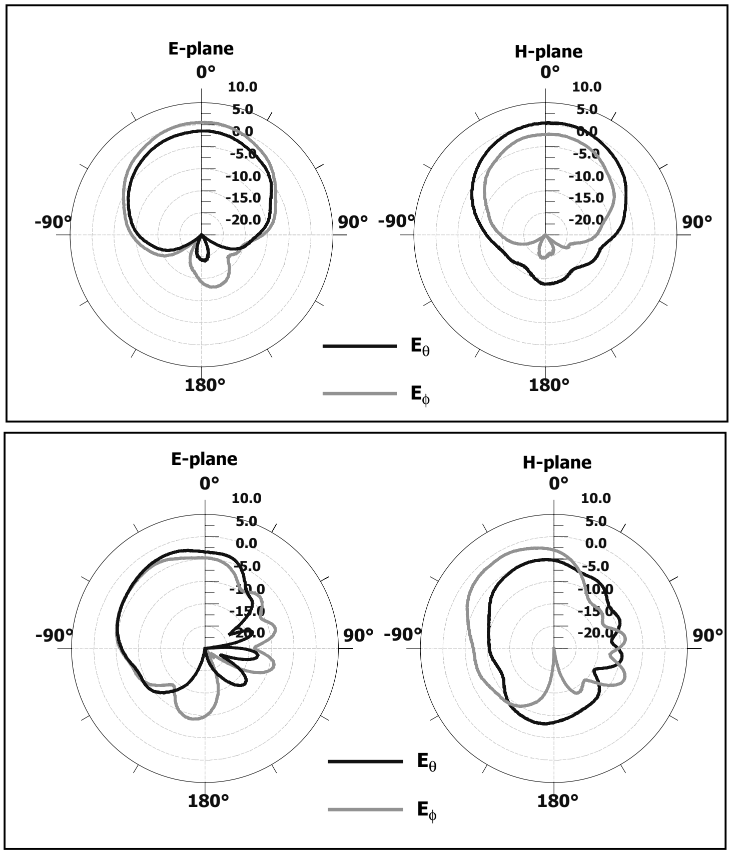

Figure 5: (Top) Dual-linear polarized broadside patterns with fundamental configuration of antenna in Figure 4. (Bottom) Reconfigured dual linear polarized patterns shifted by 45 degrees in each plane with two switches activated[25].

4.2 Pattern reconfigurable reflector antennas

Clarricoats and his colleagues were some of the first to demonstrate radiation pattern reconfigurability with aperture antennas by actively changing the structure of a mesh reflector[27,28]. Initially, changes in the reflector shape were achieved by manually adjusting each meshed region of interest[27]. Later, the process of reconfiguration was achieved by implementing computer-controlled stepper motors to pull strings attached to specific points on the reflector mesh[28].

A related, but certainly more compact and accurate approach to reflector antenna pattern reconfigurability has been demonstrated by researchers at Ohio State University[29]. In this case, however, it is the shape of the subreflector that is changed for satellite applications. The main reflector of this system has a fixed shape. The subreflector is made with a thin flexible material such that it deforms by movement of a set of piezoelectric linear point actuators attached on its back surface. When the subreflector is deformed, the electromagnetic field illuminating the main reflector can be changed, leading to a different far-field radiation pattern. Actuation points are successively added to the structure by using an iterative electromagnetic finite element algorithm to determine where the errors between the desired and actual subreflector shape is greatest[29].

Changes in reflector behavior have also been demonstrated using high impedance surfaces[30]. High impedance surfaces are created using a lattice of small resonant elements. This lattice produces high surface impedance near the resonant frequency of the elements, creating, in effect, an artificial ground plane. By inserting varactors between the resonant elements, the resonant frequency is tuned and the phase of a signal reflected from the surface is changed. Electronic control of the applied voltage across the varactors in the surface then allows reconfigurable beam shaping and steering[30].

4.3 Pattern reconfigurable horn-type structures

A MEMS planar antenna was developed in 1999 that also uses mechanical changes in antenna structure to achieve reconfigurable radiation patterns[31]. In this structure, the basic antenna consists of co-planar strip transmission line feed into a planar “V” structure. Rotational hinges fixed to the substrate material holds the interior points of each arm in place. Each arm of the “V” is moveable by pulling or pushing by MEMS actuators, resulting in lateral movement of the arms. This lateral movement is then used to change the beam direction and beam shape of the radiated signal. Operating at 17.5 GHz, these antennas were able to achieve beam shaping as well as E-plane beam steering up to 45 degrees from boresight[31].

Another group has implemented a flared planar dipole antenna with a tuned high impedance surface to achieve beam steering in the elevation plane[32]. Preliminary results on this design indicate that beam steering of at least 30 degrees is possible through tuning of the resonant elements that make up the high impedance surface[32], in a similar manner as discussed in Reference 30.

4.4 Pattern reconfigurable array structures

Other novel approaches to beam steering have been developed by a research group at Texas A&M University[33]. Rather than conventional ferrite or solid-state phase shifters, these techniques steer beams through perturbations in propagation constants in a number of different transmission line and antenna configurations. One of these is a moveable grating antenna array fed by a dielectric image line that operates at millimeter-wave frequencies[33]. The widths of the gratings on a thin, moveable film placed over a dielectric image line are designed to gradually perturb the propagation constant along the line. Physical shifts of the grating film change the apparent grating spacings and result in a scanned beam. Scan angles of up to 53 degrees have been demonstrated with this design at 35 GHz[33], with lower scan angles achievable over an operating band between 30 and 40 GHz.

5. RECONFIGURABLE APERTURES

Instead of reconfiguring a specific antenna, the two reconfigurable apertures discussed here take a unique approach – creating whatever antenna is necessary to achieve specific frequency, bandwidth, polarization, and radiation characteristics. The first, developed at the Georgia Tech Research Institute, is an antenna that uses hundreds or thousands of switches to connect small non-resonant conductive pads that create a large antenna aperture[34]. To achieve any specified performance goal, a genetic search algorithm determines the combination of switch states across the aperture. For each pass through the genetic algorithm, a finite-difference time-domain electromagnetic simulation is used to evaluate candidate designs. In general, narrowband configurations achieve more gain than wideband configurations, and high frequency operation degrades as a result of the pad density and the solid-state switch capacitance[34].

Another antenna aperture concept, developed by researchers at the Sarnoff Corporation, uses semiconductor plasmas to form antenna structures[35]. This "pixel" approach to a reconfigurable aperture relies on high conductivity plasma islands that are formed and controlled by injected DC currents into silicon-based diode structures. This approach has several unique and attractive features, one of which is that when turned off, the aperture possesses extremely low radar cross section. In addition to forming specific antenna structures, it can also be used to reconfigure holograms for holographic antennas that promise to deliver performance comparable to traditional phased arrays without the need for expensive phase shifters[35].

6. ENABLING RECONFIGURABILITY

While research and development of reconfigurable antenna and aperture designs has seen tremendous growth in the past five years, their deployment in real applications will take much longer. This is due to the fact that there are several technological barriers that must be overcome to make reconfigurability both practical and affordable. The first issue is the device that makes the antenna reconfigurable, whether it is electrical, magnetic, or mechanical. While there are continual advances in the development of RF MEMS switches and other devices, they still suffer from a number of drawbacks that prevent their deployment in actual systems. Some of these include power handling capability, response time, high frequency behavior, and packaging/integration strategies. While these drawbacks are being addressed in the coming years, antenna designers must wait or develop reconfigurable structures in the mean time that use more mature technologies. (Interested readers are referred to References 36-42 for a more complete picture of the evolution and the state of the art of enabling RF MEMS).

The second issue is the actuation of the devices. Most reconfigurable antenna designers will acknowledge that the greatest engineering challenge for these antennas lies not in the design of the antenna but rather in the physical control infrastructure for the devices[34]. This barrier is particularly acute for reconfigurable designs that rely on hundreds or thousands of switches. A popular choice for overcoming this situation is some kind of optical signaling and control which does not interfere with normal antenna operation[7,34], but this approach will not work for all applications.

Finally, the most serious barrier to adoption of reconfigurable antennas may lie in the areas of signal processing and control. Without links back to system-level performance requirements and measures, antenna reconfigurability may be ignored or underutilized. It is imperative that members of the reconfigurable antenna community collaborate with researchers and developers in signal processing and control so that future systems can reach their full potential.

7. FUTURE OUTLOOK

New multi-function reconfigurable antennas have the potential to dramatically reduce the number and size of large array-based antenna systems, improve system efficiency, and decrease system cost and weight. They also have the potential to revolutionize the way we think about antennas, antenna systems, and their roles in national defense, communication, and sensing. The age of the reconfigurable antenna is just beginning. With the requisite development of supporting technology and interactions with system designers, antenna reconfigurability promises to provide not only dramatic improvements in current system performance but also new degrees of freedom that will enable future systems with capabilities that previously were thought impossible.

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