Reconfigurable Antennas for Wireless and Space Applications

Basic concepts for designing antennas with reconfigurability in gain, frequency response, radiation patterns, or a combination of several radiation patterns, are discussed in this paper.

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ABSTRACT | Reconfigurable antennas, with the ability to radiate more than one pattern at different frequencies and polarizations, are necessary in modern telecommunication systems. The requirements for increased functionality (e.g., direction finding, beam steering, radar, control, and command) within a confined volume place a greater burden on today's transmitting and receiving systems. Reconfigurable antennas are a solution to this problem. This paper discusses the different reconfigurable components that can be used in an antenna to modify its structure and function. These reconfiguration techniques are either based on the integration of radio-frequency microelectromechanical systems (RF-MEMS), PIN diodes, varactors, photoconductive elements, or on the physical alteration of the antenna radiating structure, or on the use of smart materials such as ferrites and liquid crystals. Various activation mechanisms that can be used in each different reconfigurable implementation to achieve optimum performance are presented and discussed. Several examples of reconfigurable antennas for both terrestrial and space applications are highlighted, such as cognitive radio, multiple-input–multiple-output (MIMO) systems, and satellite communication.

KEYWORDS | Cognitive radio; deployable antennas; ferrites; frequency tuning; liquid crystals; multiple-input–multiple-output (MIMO); photoconductive switches; PIN diodes; polarization; radiation pattern; radio-frequency microelectromechanical systems (RF-MEMS); reconfigurable antennas; satellite communication; varactors

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I. INTRODUCTION

Reconfiguring an antenna is achieved through deliberately changing its frequency, polarization, or radiation characteristics. This change is achieved by many techniques that redistribute the antenna currents and thus alter the electromagnetic fields of the antenna's effective aperture. Reconfigurable antennas can address complex system requirements by modifying their geometry and electrical behavior, thereby adapting to changes in environmental conditions or system requirements (i.e., enhanced bandwidth, changes in operating frequency, polarization, and radiation pattern).

Reconfigurability has become an important and desired feature of modern, agile, radio-frequency (RF) systems for wireless and satellite communications, sensing, and imaging. There is a shift toward incorporating smart, cognitive, and agile RF devices that can both sense the surrounding RF environment and communicate at the same time in any contested/congested environment. Some of the new desired capabilities include frequency-agile, software-defined, and cognitive radios to cope with extendable and reconfigurable multiservice, multistandard, and multiband operation, as well as with efficient spectrum and power utilization. These concepts can significantly reduce the number of components and thus hardware complexity, and cost compared to today's radio technology, which relies on incompatible communications systems with inflexible hardware.

Reconfigurable antennas have been studied in the past ten years for a variety of applications but almost all of them have made use of some kind of a switching mechanism. Once these antennas are constructed and placed on a

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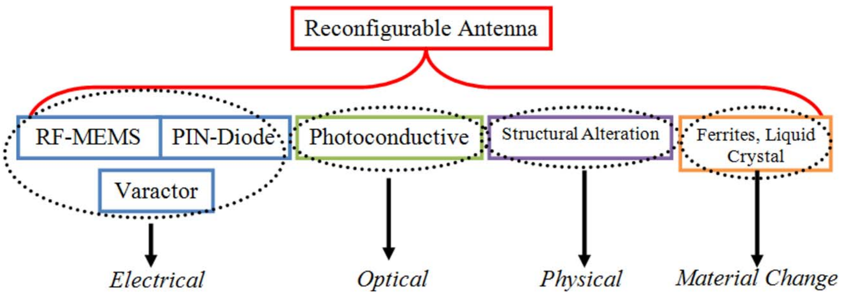


Fig. 1. *Various techniques adopted to achieve reconfigurable antennas.*

certain platform, they can be reconfigured remotely without having to reconstruct the antenna or the platform upon which the antenna structure is mounted.

The first patent on reconfigurable antennas appeared in 1983 by Schaubert [1]. In 1999, the Defense Advanced Research Projects Agency (DARPA) launched a multi-university program between 12 well-known universities, research institutes, and companies in the United States under the name Reconfigurable Aperture Program (RECAP), to investigate reconfigurable antennas and their potential applications [2].

When designing reconfigurable antennas, RF engineers must address three challenging questions.

1) Which reconfigurable property (e.g., frequency, radiation pattern, or polarization) needs to be modified?
2) How are the different radiating elements of the antenna structure reconfigured to achieve the required property?
3) Which reconfiguration technique minimizes negative effects on the antenna radiation/impedance characteristics?

In the sections to follow herein, we discuss the classification of reconfigurable antennas, their various reconfiguration techniques, the advantages and disadvantages of each technique, and some of the most recent applications of reconfigurable antennas.

II. RECONFIGURATION TECHNIQUES AND CLASSIFICATION OF RECONFIGURABLE ANTENNAS

Six major types of reconfiguration techniques are used to implement reconfigurable antennas, as indicated in Fig. 1. Antennas based on radio-frequency microelectromechanical systems (RF-MEMS) [3]–[8], PIN diodes [9]–[20], and varactors [21]–[26] to redirect their surface currents are called electrically reconfigurable. Antennas that rely on photoconductive switching elements are called optically reconfigurable antennas [27]–[31]. A description of the operation of the switches is summarized in Table 1 [32]–[35]. Physically reconfigurable antennas can be achieved by altering the structure of the antenna [36]–[39]. Finally, reconfigurable antennas can be implemented through the use of smart materials such as ferrites and liquid crystals [40]–[43].

Reconfigurable antennas can be classified into four different categories [44].

- *Category 1:* A radiating structure that is able to change its operating or notch frequency by hoping between different frequency bands is called frequency reconfigurable antenna. This is achieved by producing some tuning or notch in the antenna reflection coefficient.
- *Category 2:* A radiating structure that is able to tune its radiation pattern is called radiation pattern reconfigurable antenna. For this category, the antenna radiation pattern changes in terms of shape, direction, or gain.
- *Category 3:* A radiating structure that can change its polarization (horizontal/vertical, ±slant 45°, left-hand or right-hand circular polarized, etc.) is called polarization reconfigurable antenna. In this case, the antenna can change, for example, from vertical to left-hand circular polarization.

Table 1 Different Type of Switches Used in the Design of Electrically and Optically Reconfigurable Antennas

RF MEMS: *They use mechanical movement to achieve a short circuit or an open circuit in a surface current path of an antenna structure. The forces required for the mechanical movement can be obtained using electrostatic, magnetostatic, piezoelectric, or thermal designs.*
PIN Diodes: *They operate in two modes. The "ON" state, where the diode is forward biased and the "OFF" state, where the diode is not biased.*
Varactors: *They consist of a p-n junction diode. As the bias voltage applied to the diode is varied, the varactor capacitance is going to be changed. Typical values are from tens to hundreds of picofarads.*
Photoconductive Elements: *The movement of electrons from the valence band to the conduction band allows the switch to go from "OFF" state to "ON" state. This is achieved by illuminating the switch by light of appropriate wavelength from a laser diode.*

- *Category 4:* This category is a combination of the previous three categories. For example, one can achieve a frequency reconfigurable antenna with polarization diversity at the same time.

The corresponding reconfigurability for each of the four categories can be obtained by a change in the antenna surface current distribution, a change in the feeding network, a change in the antenna physical structure, or a change in the antenna radiating edges. It is essential to note that the change in one parameter in the antenna characteristics can affect the other parameters. Therefore, an antenna engineer should be careful during the design process to analyze all the antenna characteristics simultaneously in order to achieve the required reconfigurability.

There are several advantages in using reconfigurable antennas as summarized below [45]–[47].

1) Ability to support more than one wireless standard →
    a) minimizes cost;
    b) minimizes volume requirement;
    c) simplifies integration;
    d) good isolation between different wireless standards.
2) Lower front end processing →
    a) no need for front end filtering;
    b) good out-of-band rejection.
3) Best candidate for software-defined radio →
    a) capability to adapt and learn;
    b) automated via a microcontroller or a field programmable gate array (FPGA).
4) Multifunctional capabilities →
    a) change functionality as the mission changes;
    b) act as a single element or as an array;
    c) provide narrow band or wideband operation.

While reconfigurable antennas represent a potential candidate for future RF front ends for wireless and space applications, there is definitely a cost for adding tunability to the antenna behavior in both systems. This cost can be linked to different parameters as summarized below:

1) design of the biasing network for activation/deactivation of the switching elements which add complexity to the antenna structure;
2) increase in the required power consumption due to the incorporation of active components which augments the system cost;
3) generation of harmonics and inter modulation products;
4) need for fast tuning in the antenna radiation characteristics to assure a correct functioning of the system.

III. ELECTRICALLY RECONFIGURABLE ANTENNAS

An electrically reconfigurable antenna relies on electronic switching components (RF-MEMs, PIN diodes, or varactors) to redistribute the surface currents, and alter the antenna radiating structure topology and/or radiating edges. The integration of switches into the antenna structure makes it easier for designers to reach the desired reconfigurable functionality.

The ease of integration of such switching elements into the antenna structure has attracted antenna researchers to this type of reconfigurable antennas despite the numerous issues surrounding such reconfiguration techniques. These issues include the nonlinearity effects of switches, and the interference, losses, and negative effect of the biasing lines used to control the state of the switching components on the antenna radiation pattern. Next, three different examples of electrically reconfigurable antennas are described. Each example discusses the use of a different reconfiguration technique to reach the corresponding function.

A. Reconfigurable Antennas Based on RF-MEMS

The antenna shown in Fig. 2 is a reconfigurable rectangular spiral antenna with a set of RF-MEMs switches, which are monolithically integrated and packaged onto the same substrate. The antenna is printed on a printed circuit board (PCB) substrate with a dielectric constant of 3.27 and fed through a coaxial cable at its center point. The structure consists of five sections that are connected with four RF-MEMS switches. The spiral arm is increased by discrete steps in the following manner: U, 2U, 2U, 3U, 3U, . . ., NU, where U is the length of the first segment of the rectangular spiral and N is an integer. It is increased following the right-hand direction to provide right-hand circular polarization for the radiated field. The location of switches is determined such that the axial ratio and gain of the antenna are optimum at the frequency of interest. Based on the status of the integrated RF-MEMS, the antenna can change its radiation beam direction [3].

B. Reconfigurable Antennas Based on PIN Diodes

A frequency and pattern reconfigurable antenna based on PIN diodes is discussed in [9]. The activation of the switches is automated via an FPGA. The antenna structure consists of three layers. The bottom layer is a ground plane that covers the entire substrate. The middle substrate has a dielectric constant of 4.2 and a thickness of 0.235 cm. The upper layer is the metal patch composed of a main midsection and four surrounding smaller sections, as shown in Fig. 3(a). A side view of the antenna is shown in Fig. 3(b). The variations in configuration are achieved through individually controllable switches, each implemented as a PIN diode. The fabricated antenna prototype is shown in Fig. 3(c). The antenna tunes its operating frequency/radiation pattern according to the four switch combinations.

C. Reconfigurable Antennas Based on Varactors

Single- and dual-polarized slot-ring antennas with wideband tuning using varactor diodes have been

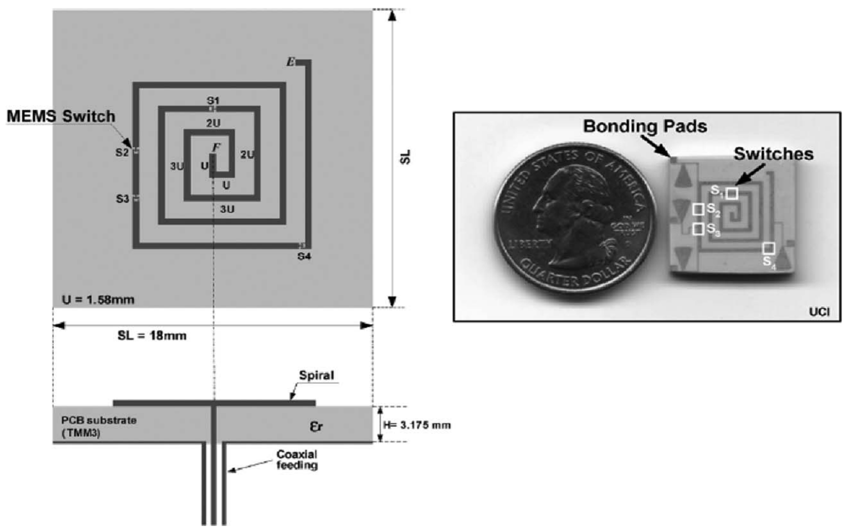
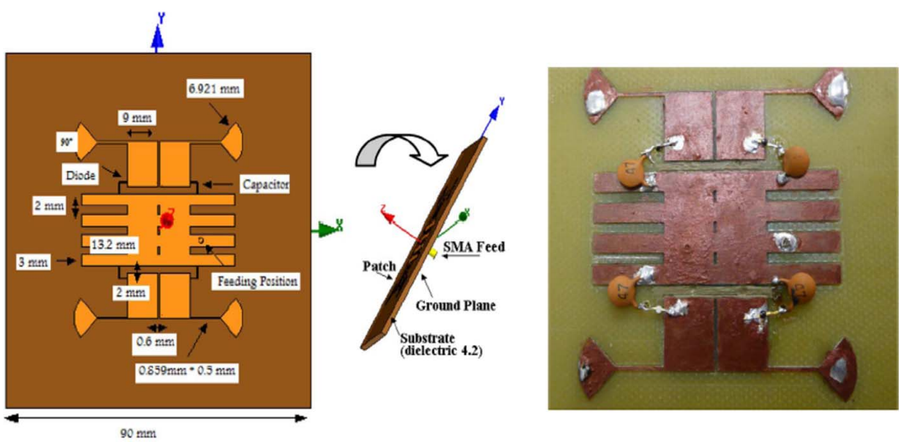


Fig. 2. *(Left) A radiation pattern reconfigurable antenna. (Right) Fabricated prototype with the biasing line [3].*

demonstrated in [24]. The single-polarized antenna tunes from 0.95 to 1.8 GHz with better than 13-dB return loss. Both polarizations of the dual-polarized antenna tune from 0.93 to 1.6 GHz, independently, with better than 10-dB return loss and greater than 20-dB port-to-port isolation over most of the tuning range. The capacitance of the varactor diodes varies from 0.45 to 2.5 pF. The antennas are printed on 70 × 70 × 0.787 mm^3 substrates with a dielectric constant of 2.2. The dual-polarized slot-ring antenna can either be made both frequency and polarization agile simultaneously, or can operate at two independent frequencies on two orthogonal polarizations. The corresponding antenna structure for single- and dual-polarized slot-ring antennas is shown in Fig. 4.

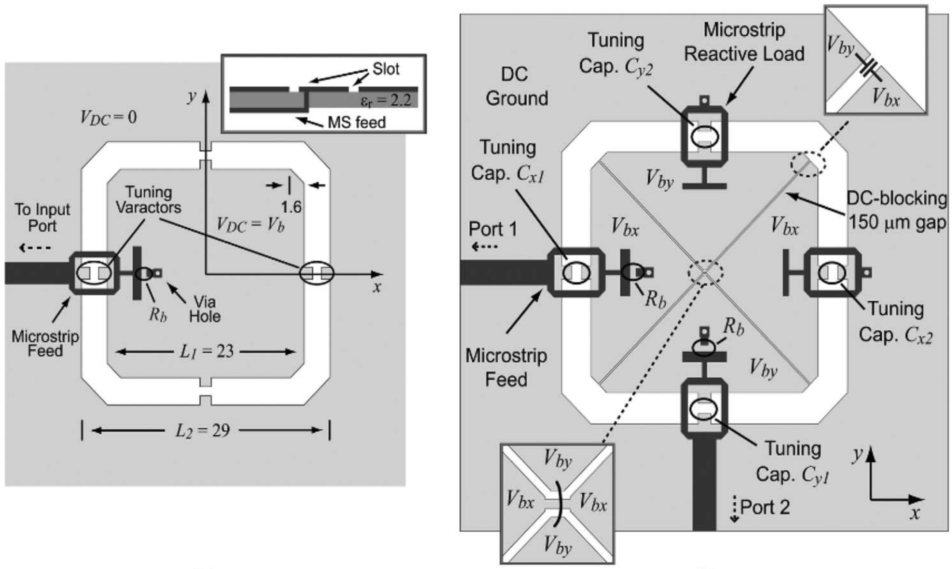
IV. OPTICALLY RECONFIGURABLE ANTENNAS

An optical switch is formed when laser light is incident on a semiconductor material (silicon, gallium arsenide). This results in exciting electrons from the valence to the conduction band and thus creating a conductive connection [35]. Integrating such a switch into an antenna structure and using it to reconfigure the antenna behavior is called an "optically reconfigurable antenna." The linear behavior of optical switches, in addition to the absence of biasing lines, compensates for their lossy aspect and the need for laser light to activate them. The main issue focuses on the activation mechanism of such switches on the antenna structure. In this section, we present examples of three



(a) (b) (c)

Fig. 3. *(a) Frequency reconfigurable antenna. (b) Side view of the antenna. (c) Fabricated prototype [9].*



(a) (b)

Fig. 4. ***(a) Single-polarized slot-ring antenna. (b) Dual-polarized slot-ring antenna [24].***

optically reconfigurable antennas with different activation techniques.

A. First Activation Technique: Nonintegrated Optical Fiber

The schematic of the antenna structure is shown in Fig. 5. It consists of a printed dipole with two gaps. A 1 mm × 1 mm × 0.3 mm silicon dices are then placed over the gaps and are held in place using silver loaded epoxy, which ensures good contact between the copper and silicon. To activate the silicon switches, two 980-nm lasers operating at 200 mW are coupled to two glass fiber optic cables, which are then angled over the silicon wafers using plastic clamps. When both switches are turned off, the silicon acts as an insulator and the dipole resonates at its shorter length of 33.5 mm. When both lasers are operating at 200 mW, the silicon conducts and the gaps are bridged, increasing the dipole arm lengths to 62.3 mm and hence reducing the resonance frequency. Activating each switch individually results also in a near 50° shift in beam nulls [28].

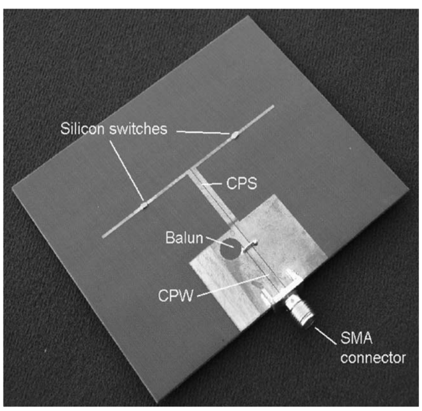


Fig. 5. ***Optically reconfigurable antenna for the first activation technique [28].***

B. Second Activation Technique: Integrated Optical Fiber

The antenna structure for this case consists of an outer circular annular ring [region 1 of Fig. 6(a)] and an inner circular patch [region 2 of Fig. 6(a)]. Both structures are separated via a 1-mm gap and connected together via two silicon pieces that act as the RF switches. The dimensions of the different parts of the antenna structure are shown in Fig. 6(a). The top view of the fabricated antenna topology is shown in Fig. 6(b). The bottom view of the antenna structure is shown in Fig. 6(c). The chosen substrate is Rogers Duroid 5880 with a dielectric constant of 2.2 and a height of 1.6 mm. The antenna can tune its operating frequency based on the status of the silicon switch. To activate the silicon pieces, light from an 808-nm laser diode is delivered to the switches via an optical fiber cable. It is placed underneath the substrate and held via a plastic fixture. To couple light into the silicon switches, two holes of radius 1 mm each are drilled into the substrate, as shown in Fig. 6(c) [30].

C. Third Activation Technique: Integrated Laser Diode

Optically reconfigurable antennas can also be implemented by integrating laser diodes directly into the

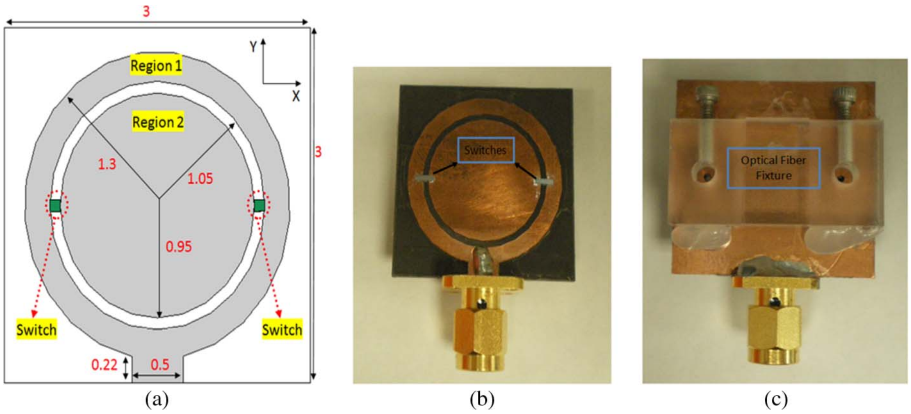


Fig. 6. ***(a) Optically reconfigurable antenna for the second activation technique. (b) Top view of the fabricated prototype. (c) Bottom view of the fabricated prototype [30].***

antenna substrate [31]. A copper piece is attached to the back of the antenna ground, as shown in Fig. 7. This piece has a minimal effect on the antenna radiation pattern since it has a small depth and a smaller width and height as the antenna ground plane. This technique eliminates the use of optical fiber cables for light delivery which enables easier integration of the optically reconfigurable antenna. The laser diodes are activated via a current driver to generate the required output optical power.

An example of this type of reconfigurable antenna is shown in Fig. 7(a) [31]. The antenna top layer is the radiating patch while the bottom layer represents the antenna ground plane. Two silicon switches (indicated as S_1 and S_2) are included to allow the antenna to tune its resonant frequency. To activate the silicon switches, laser diodes are integrated within the antenna substrate by attaching a small copper piece to the ground of the antenna, as shown in Fig. 7(b). Two holes are drilled throughout the substrate in order to allow the light from the laser diode to be delivered to the silicon switches. These copper pieces are also used as a heat sink for the laser diodes. The fabricated antenna top layer is also shown in Fig. 7(c).

V. PHYSICALLY RECONFIGURABLE ANTENNAS

Antennas can also be reconfigured by physically altering the antenna radiating structure. The tuning of the antenna is achieved by a structural modification of the antenna radiating parts. The importance of this technique is that it does not rely on any switching mechanisms, biasing lines, or optical fiber/laser diode integration. On the other hand, this technique depends on the limitation of the device to be physically reconfigured.

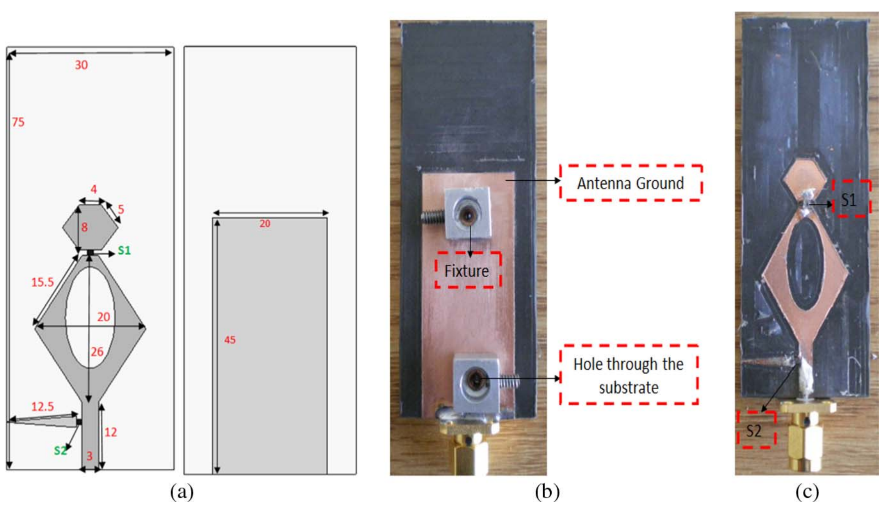


Fig. 7. ***(a) Optically reconfigurable antenna for the third activation mechanism. (b) Laser diode integration with copper fixture. (c) Fabricated prototype [31].***

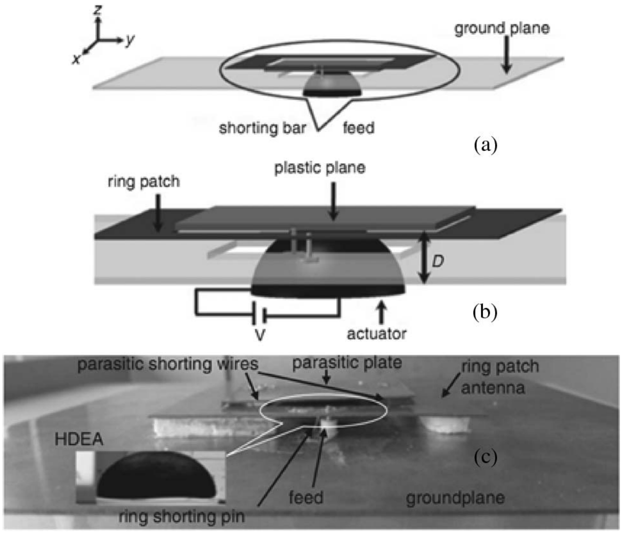


Fig. 8. ***(a) Representation of the mechanically reconfigurable system. (b) Antenna structure after actuation (parasitic above ring). (c) Fabricated antenna prototype [36].***

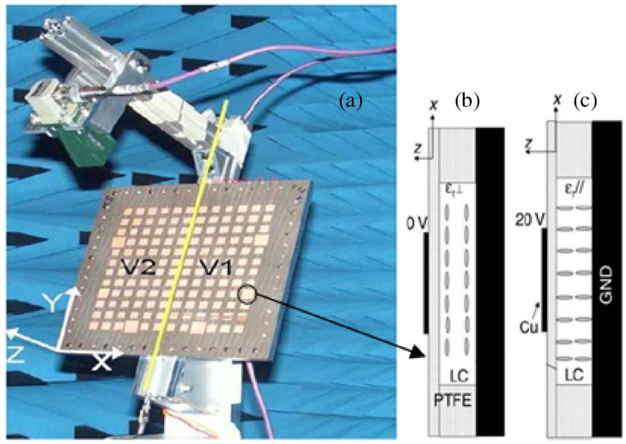


Fig. 9. ***(a) Reconfigurable reflectarray antenna with liquid crystal substrate. (b) Liquid crystal molecules under 0 V. (c) Liquid crystal molecules under 20 V [40].***

In this section, we present a pattern reconfigurable square ring patch antenna based on a movable parasitic plate within the ring patch [36]. The plate is actuated using a hemispherical dielectric elastomer actuator (HDEA). Small variations of the height of the parasitic plate can significantly alter the antenna radiation pattern while maintaining reasonable impedance matching. The actuator is used in the antenna by placing it below the parasitic conductor plate. An electric field across the electrodes causes a radial expansion in the actuator, and as a result, the height of the parasitic plate is varied, as summarized in Fig. 8(a)–(c).

The fabricated antenna prototype shown in Fig. 8(c) has a copper square ring patch in the *XY*-plane with inner and outer side lengths of 52 and 81 mm, respectively, at a height (*z*-direction) of 4.5 mm from a 180 mm $\times$ 180 mm copper ground plane. A square copper parasitic plate is located in the middle of the ring patch with a side length of 51.2 mm and thickness of 1 mm. The parasitic plate is shorted to the ground plane with two thin shorting wires located at the two sides of the parasitic plate at a distance of 22 mm along the *x*-axis from its center. A square slot with a side length of 38 mm is cut out of the middle of the ground plane to provide space for the HDEA. The parasitic plate is kept parallel to the ground plane and ring by its adhesion to the HDEA [36].

VI. RECONFIGURABLE ANTENNAS BASED ON SMART MATERIALS

Antennas are also made reconfigurable through a change in the substrate characteristics by using materials such as liquid crystals [40], [41] or ferrites [42], [43]. The change in the material is achieved by a change in the relative electric permittivity or magnetic permeability. In fact, a liquid crystal is a nonlinear material whose dielectric constant can be changed under different voltage levels, by altering the orientation of the liquid crystal molecules. As for a ferrite material, a static applied electric/magnetic field can change the relative material permittivity/permeability.

As an example, a liquid-crystal-based reflectarray antenna with a switchable pattern is shown in Fig. 9(a) [40]. The antenna structure can generate a beam that can be electronically switched from a sum to a difference radiation pattern based on the voltage supplied to the liquid crystal material. The antenna consists of a 12 $\times$ 12 array of patch elements. Six columns, each containing 12 patches, were positioned on either side of the line of symmetry on a 125-μm-thick 18 cm $\times$ 18 cm glass reinforced PTFE substrate. A 500-μm-thick tunable liquid crystal layer is inserted between the printed array and the ground plane. Bias lines of width 0.2 mm were used to connect the 12 patches in each row, and two power supplies were employed to provide the biasing voltage on the left and right halves of the reflectarray. Fig. 9(b) shows that for the unbiased state the liquid crystal molecules are mainly aligned perpendicular to the fringing field of the patches. On the other hand, parallel alignment of the molecules occurs when a voltage is applied to create an electrostatic field in the substrate, as shown in Fig. 9(c).

VII. COMPARISON BETWEEN DIFFERENT RECONFIGURATION TECHNIQUES

Electronic switching components have been widely used to reconfigure antennas, especially after the appearance of RF-MEMS in 1998 [48]. One of the major advantages of such components is their good isolation and low-loss

Table 2 Electrical Properties for Electrically and Optically Switching

Electrical Property	RF MEMS	PIN Diode	Optical Switch (Si)
Voltage [V]	20-100	3-5	1.8-1.9
Current [mA]	0	3-20	0-87
Power Consumption [mW]	0.05-0.1	5-100	0-50
Switching Speed	1-200 μsec	1-100 nsec	3-9μsec
Isolation [1-10 GHz]	Very High	High	High
Loss (1-10 GHz) [dB]	0.05-0.2	0.3-1.2	0.5-1.5

property. While RF-MEMS represent an innovative switching mechanism, their response is slower than PIN diodes and varactors which have a response on the order of nanoseconds [32]–[34]. All these switches and especially varactors add to the scalability of reconfigurable antennas.

The ease of integration of such switches into the antenna structure is matched by their nonlinearity effects (capacitive and resistive) and their need for high voltage (RF-MEMS, varactors) [49]. The activation of such switches requires biasing lines that may negatively affect the antenna radiation pattern and add more losses. The incorporation of switches increases the complexity of the antenna structure due to the need for additional bypass capacitors and inductors which will increase the power consumption of the whole system.

Even though optical switches are less popular, they definitely present a reliable reconfiguration mechanism especially in comparison to RF-MEMS. The activation or deactivation of the photoconductive switch by shining light from the laser diode does not produce harmonics and intermodulation distortion due to their linear behavior. Moreover, these switches are integrated into the antenna structure without any complicated biasing lines which eliminates unwanted interference, losses, and radiation pattern distortion. Despite all these advantages, optical switches exhibit lossy behavior and require a complex activation mechanism. Table 2 shows a comparison of the characteristics for the different switching techniques used on electrically (RF-MEMS/PIN diodes) and optically reconfigurable antennas [50], [51].

The advantages of using physical reconfiguration techniques lie in the fact that they do not require bias lines or resort to laser diodes or optical fibers. However, their disadvantages include slow response, cost, size, power source requirements and the complex integration of the reconfiguring element into the antenna structure.

As for ferrite-based reconfigurable antennas, one major advantage is their small size that is due to the ferrites' high relative permittivities and permeabilities. The main disadvantage is their low efficiency that is a common inconvenience for liquid-crystal-based antennas as well, especially at microwave frequencies [41].

The trivial question one may ask is: "What is the best reconfiguration technique to use for wireless and space applications?" In fact, there is no single answer to this question. The best reconfiguration technique is always the one that is more satisfying to the constraints of the application for which the antenna is designed. For space applications, for example, RF-MEMS switches or physical changes in the structure may be more desirable, since they will not include radiation hardened electronics. For terrestrial wireless communications, all options are used depending on the required speed of operation and the overall system requirements.

VIII. APPLICATIONS

Reconfigurable antennas are required to cover different wireless services that are spanned over a wide frequency range. In this section, we present three major wireless applications that use reconfigurable antennas to improve spectrum efficiency. The first one discusses the use of frequency reconfigurable antennas for a cognitive radio environment. The second one utilizes a radiation pattern reconfigurable antenna array for multiple-input–multiple-output (MIMO) channels. The third application is intended for satellite communication.

A. Frequency Reconfigurable Antenna for a Cognitive Radio System

A cognitive radio system is able to communicate efficiently across a channel by altering its frequency of operation based on the constant monitoring of the channel spectrum. This system is able to continuously monitor gaps (white spaces) in the finite frequency spectrum occupied by other wireless systems, and then dynamically alter its transmit/receive characteristics to operate within these unused frequency bands, thereby minimizing interference with other wireless systems and maximizing throughput. The monitoring of the wireless spectrum is the key in cognitive radio since the spectrum can be idle for 90% of the time [52]. Therefore, we should differentiate in such systems between a primary user that owns the spectrum and a secondary user that wants to access the spectrum whenever it is idle [53].

This capability requires an "ultrawideband (UWB) sensing antenna" that continuously monitors the wireless channel searching for unused carrier frequencies, and a "reconfigurable transmit/receive antenna" to perform the data transfer [54]–[58]. A general view of a cognitive radio antenna structure is shown in Fig. 10.

A cognitive radio antenna designer has to consider three key parameters:

1) the isolation between the two ports of the sensing and the reconfigurable antennas (the operation of one antenna should not affect the other);

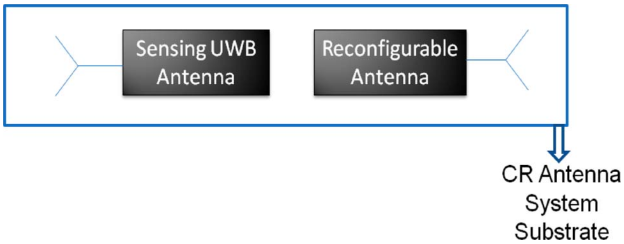


Fig. 10. ***A cognitive radio antenna system.***

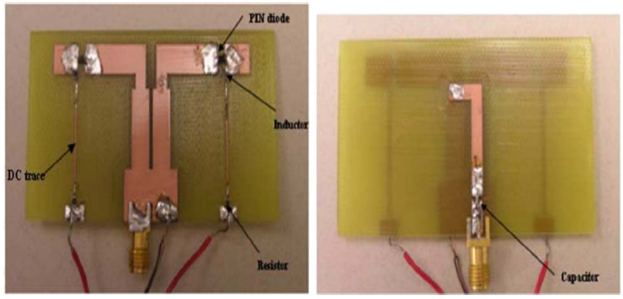


Fig. 12. ***A pattern diversity reconfigurable antenna array [59].***

2) the dimension of the cognitive radio antenna system substrate (the space needed to accommodate both antennas should be minimal);
3) omnidirectional/reconfigurable radiation pattern (both antennas should be able to receive a signal at any given direction; also both antennas should be able to produce reconfigurable nulls in their radiation pattern in case interferers and jammers are present).

Fig. 11 shows a cognitive radio antenna system based on physically reconfigurable antenna structure [54]. The left module in Fig. 11(a) is the sensing antenna while the right part is the reconfigurable section. Frequency tuning is achieved by physically altering the patch shape. A circular substrate section holding five different antenna patches is rotated via a stepper motor. A 50-Ω stripline overflows the rotating section in order to guarantee contact between the rotating circular patch and the feeding line. At each rotation stage, the stripline excites a different patch and a different frequency is achieved. The fabricated antenna is shown in Fig. 11(b). The stepper motor is incorporated in the back of the reconfigurable rotating antenna section. Cognitive radio antenna systems using other types of reconfiguration techniques can be found in [56]–[58].

B. Pattern Reconfigurable Antenna for MIMO Systems

A MIMO system employs multiple antennas at both the transmitter and the receiver front ends. The advantage from using such configurations is that different information can be sent simultaneously, thereby increasing the communication spectral efficiency in a multipath environment. According to the varying channel conditions and user's need, a MIMO system can adjust the modulation level, coding rate, and the transmission signaling schemes. Radiation pattern/polarization reconfigurable antennas add an additional degree of freedom in a MIMO environment and thus improve the system performance. The use of such type of antennas increases significantly the capacity by allowing the selection between different pattern diversity and polarization configurations. Reconfigurable antenna arrays are also an attractive solution for MIMO systems to maintain good communication links, especially for handheld devices where space is an important constraint [59]–[63].

As an example, we present a pattern reconfigurable antenna array. The antenna structure consists of an array of two microstrip dipoles, as shown in Fig. 12 [59]. A quarter-wavelength microstrip balun acts as an unbalanced-to-balanced transformer from the feed coaxial line to the two printed dipole strips. The length of the dipole-arm strip can be changed using two PIN diodes. The setting of the two switches results in different geometries of the antenna structure. This produces different levels of inter-element mutual coupling and therefore different radiation pattern. Such antenna behavior decreases the MIMO spatial channel correlation and subsequently maximizes link capacity [59].

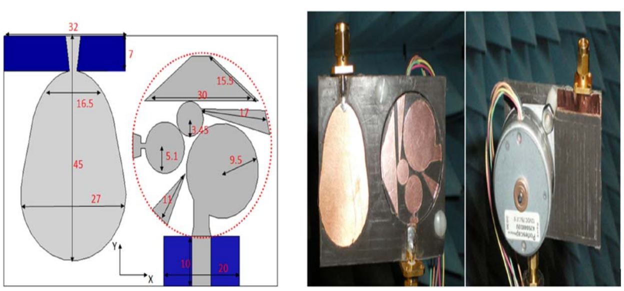


Fig. 11. ***(a) Rotatable reconfigurable antenna for cognitive radio. (b) Fabricated prototype [54].***

C. Reconfigurable Antennas for Satellite Applications

The need for dynamic space applications has led to the realization of reconfigurable antennas for satellite communication. In such systems, it is necessary to reconfigure the antenna radiation pattern to serve a new coverage zone, limit fading in rainy areas, and maintain high data rate at all possible frequency bands of operation [64]–[68].

An example of an antenna structure for satellite applications is discussed in [64] and [65]. It generates an elliptical beam ranging from 10.95 to 14.5 GHz using an 85-cm aperture. Using a rotational and zooming mechanism, the

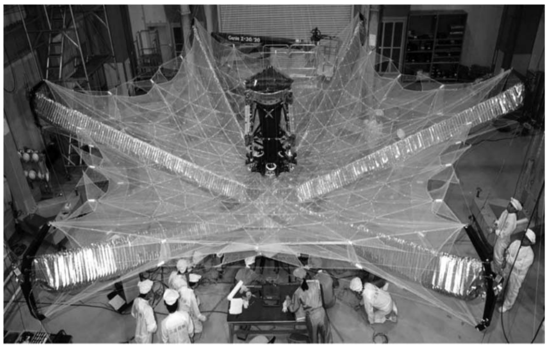


Fig. 13. ***Deployable antenna for satellite communication [70].***

antenna can tune its radiated beam from a "small ellipse" of $2.3^{\circ} \times 3.6^{\circ}$ to a "large ellipse" of $6^{\circ} \times 9^{\circ}$.

Reconfiguration in space has also been achieved through the use of deployable antennas. These antennas change their shape from compact, small structures to large blooming antennas in space. The objectives are to realize high gain and high directivity, which are primarily determined by the size of an antenna aperture. The antenna itself can be reconfigurable to cover several frequency bands as the mission of the satellite changes. Since the antenna must fit with the volume of a launch vehicle fairing, a deployment antenna is often required. A picture of a large deployable antenna is shown in Fig. 13 in the unfolded state [70].

IX. CONCLUSION AND FUTURE OF RECONFIGURABLE ANTENNAS

In this paper, a detailed study about the different types of reconfigurable antennas was presented. The study was based on the different reconfiguration techniques used to obtain the required reconfigurability. Reconfigurable antennas were mainly divided into electrically, optically, physically, and smart-material-based tunable structures. A comparison between the different techniques used to implement such type of antennas was presented. The use of reconfigurable antennas in applications such as cognitive radio, MIMO systems, and satellite communication was also discussed.

We expect future smart reconfigurable antennas to be completely multifunctional and software controlled with machine learning capabilities that can detect changes in their RF environment and react accordingly. Applications such as cognitive radio will be implemented based on a new generation of communication protocols and antenna systems. The key advantage for such application will be the efficient use of frequencies and even the utilization of radiation pattern reconfigurability and polarization diversity to transmit over already "busy" frequencies. The use of reconfigurable antennas in MIMO channels will not only improve the channel capacity but also will increase the efficiency of such channels and reduce their costs. Finally, the merging of deployable and reconfigurable antennas will open new frontiers in the design of antennas for space communications. ■

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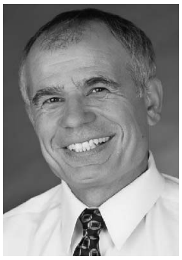

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