INVITED PAPER

Reconfigurable Antennas: Design and Applications

This paper discusses design, manufacture, and control concepts for antennas that employ programmable features.

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ABSTRACT | The advancement in wireless communications requires the integration of multiple radios into a single platform to maximize connectivity. In this paper, the design process of reconfigurable antennas is discussed. Reconfigurable antennas are proposed to cover different wireless services that operate over a wide frequency range. They show significant promise in addressing new system requirements. They exhibit the ability to modify their geometries and behavior to adapt to changes in surrounding conditions. Reconfigurable antennas can deliver the same throughput as a multiantenna system. They use dynamically variable and adaptable single-antenna geometry without increasing the real estate required to accommodate multiple antennas. The optimization of reconfigurable antenna design and operation by removing unnecessary redundant switches to alleviate biasing issues and improve the system's performance is discussed. Controlling the antenna reconfiguration by software, using Field Programmable Gate Arrays (FPGAs) or microcontrollers is introduced herein. The use of Neural Networks and its integration with graph models on programmable platforms and its effect on the operation of reconfigurable antennas is presented. Finally, the applications of reconfigurable antennas for cognitive radio, Multiple Input Multiple Output (MIMO) channels, and space applications are highlighted.

KEYWORDS | Actuators; Arduino microcontrollers; cognitive radio; CubeSats; field programmable gate array (FPGA); Filtenna; graph models; graphene; Infra-Red; laser diodes; liquid crystals; micro-electromechanical systems (MEMS); multiple input multiple output (MIMO); neural networks; photoconductive switches; p-i-n diodes; plasmonics; reconfigurable antennas; thermal switches; varactors

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I. INTRODUCTION

The reconfiguration of an antenna is achieved by altering the radiated fields of the antenna's effective aperture [1]–[4]. It is based on a purposeful rearrangement of the antenna currents or a reconfiguration of the antenna's radiating edges [1]–[4]. This redistribution of properties results in a change in the antenna's functionalities. Such change of functions allows users to propose reconfigurable antennas for various wireless communication platforms.

Antenna designers are faced with difficult questions when it comes to the design of reconfigurable antennas. Such a process is tedious and requires the consideration of multiple factors, such as achieving a good gain, stable radiation, and a good impedance match throughout all the antenna's operation states.

Designing a reconfigurable antenna requires that the reconfiguration property as well as the reconfiguration technique are determined at the beginning of the design process.

There are four reconfiguration properties that a reconfigurable antenna can achieve. An antenna can exhibit a reconfigurable frequency of operation, a reconfigurable radiation pattern, a reconfigurable polarization behavior, or a combination of any of these properties [1], [2].

As for the selection of the reconfiguration technique, it is based on the reconfigurable antenna property. An antenna designer selects a technique that satisfies the imposed constraints and at the same time completes the antenna design task efficiently. There are several reconfiguration techniques that have been proposed since the rise of reconfigurable antennas. The proposed reconfiguration techniques are divided into four major categories: electrical, optical, mechanical, and material change [1], [2].

Electrical reconfiguration techniques are based on the use of switches to connect and disconnect antenna parts as well as to redistribute the antenna currents. Radio frequency micro-electromechanical systems (RF-MEMS) have been proposed for integration into reconfigurable antennas since 1998 [5]. Many designs have resorted to RF MEMS to reconfigure their performance [6]–[12]. RF-MEMS based reconfigurable antennas rely on the mechanical movement of these switches to achieve reconfiguration. The isolation of RF-MEMS is very high and they require minimal power consumption. The switching speed of RF-MEMS is in the range of 1–200 μsec which may be considered low for some applications [2].

P-i-n diodes or varactors have appeared to be a faster and a more compact alternative to RF-MEMS. The switching speed of a p-i-n diode is in the range of 1–100 nsec [2]. Reconfigurable antennas using to p-i-n diodes [13]–[23] have a more dynamic reconfiguration ability. Other reconfigurable antennas resort to varactors [24]–[32] where varying the biasing voltage can result in varying the capacitance of the corresponding varactor. Such antennas enjoy a vast tuning ability that is based on integrating a variable capacitance into the antenna structure. It is important to indicate that while electrical switching components may present an efficient reconfiguration ability, they require an appropriate design of their biasing networks.

Optical reconfiguration techniques have been proposed based on photoconductive switches [33]–[38]. These switches incorporated into an antenna structure become conductive once they are subjected to a laser beam. The laser beam originates from integrated laser diodes [35]. Integration and power issues constitute a difficulty in such a technique.

Antennas with thermal switches [39] have also been proposed as reconfigurable antenna candidates. Other reconfiguration techniques are based on graphene plasmonics [40], liquid crystals [41] and mechanical reconfiguration techniques [42]–[45].

Antenna designers have used various optimization algorithms to smooth the state transition in a reconfigurable antenna's operation. Genetic algorithms, simulated annealing, ant-colony optimization, self-organized maps, particle swarm optimization, the cross entropy method, and self-adaptive induced mutation algorithm are proposed by antenna designers to smooth transitions between various states of a reconfigurable antenna [46]–[54]. These algorithms also minimize the negative effect of any reconfiguration technique on the antenna performance. A comparison between these optimization techniques shows that a particular optimization algorithm cannot be separated from the rest as the best fit, before selecting a specific reconfigurable scheme [55].

The process of designing a reconfigurable antenna allows antenna researchers to resort to various reconfiguration techniques. However, the complexity of such designs is another aspect that requires consideration. An increased complexity results in unwanted costs and losses [1]. Several approaches have been proposed to reduce the complexity without affecting the reliability of any reconfigurable antenna system [56]–[61]. Most of these approaches are based on applying various techniques or models that are already known in other fields of study [1]. Learning state selection approaches can be used to learn the antenna behavior for various reconfiguration states and then regenerate them on demand [62]. Neural networks constitute a great example of such learning approaches. Neural Networks can be used as an antenna behavioral predictor that allows the generation of various antenna states based on a previous learning experience [63]. The merging of neural networks and graph models have resulted in computational reduction and optimal antenna reconfiguration [64].

On the other hand, the advancement in wireless communication applications requires a new generation of antennas that are able to cater for the needs of such applications. The new era of antenna design must generate antennas that are cognitive, and adjust to the environment and ever changing surrounding conditions. There is a need for antennas that can overcome failures and swiftly respond to new developments. Cognitive radio, Multiple Input Multiple Output (MIMO) channels, on body networks, satellites and space communication platforms are all venues for the application of highly versatile, reliable and efficient reconfigurable antennas.

In this paper, the design process of reconfigurable antennas is detailed. In Sections II and III, switch-based and nonswitch-based reconfigurable antennas, are discussed respectively. Section IV introduces graphs as tools to transform reconfigurable antennas into software accessible devices, while reducing their complexity and maintaining their reliability. Software control of reconfigurable antennas is discussed in Section V. Section VI discusses the use of neural networks on reconfigurable antenna platforms and its application in cognitive communication protocols. Reconfigurable antennas for cognitive radio and MIMO applications are highlighted in Section VII. The deployment of reconfigurable antennas for space applications is discussed in Section VIII. Section IX concludes the paper.

II. SWITCH-BASED RECONFIGURABLE ANTENNAS

Switch-based reconfigurable antennas are proposed with electrical [5]–[32], optical [33]–[38], or thermal switching

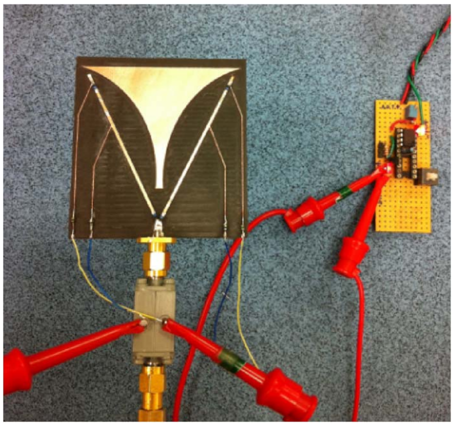

Fig. 1. ***P-i-n diode based frequency and radiation pattern reconfigurable antenna with the appropriate p-i-n diode biasing network [65].***

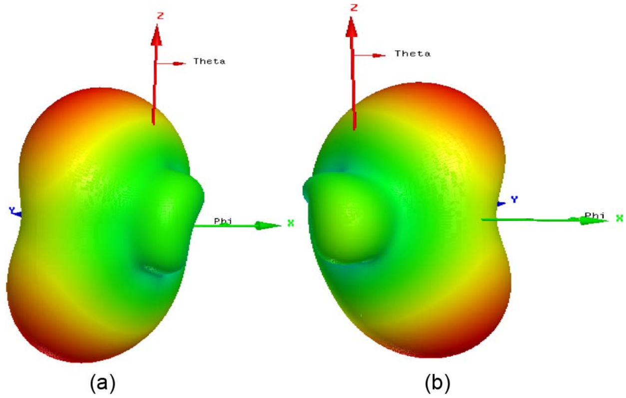

Fig. 2. ***The 3D antenna radiation pattern at*** $f = 3.24$ ***GHz when (a)*** $S_{1,\mathrm{Left}}$ ***is ON, (b)*** $S_{1,\mathrm{Right}}$ ***is ON [65].***

components [39]. Reconfiguration is achieved by integrating switches into the antennas' radiating surfaces or feeding networks. This requires an appropriate biasing network that is designed specifically to supply an appropriate voltage or current. P-i-n diodes for example require a constant DC current that is supplied usually by a current driver. An example of such integration can be found in the antenna shown in Fig. 1 [65]. The antenna structure is composed of two monopoles that are tilted from each other by an angle of 30° [65]. A printed reflector is positioned between the two directed monopoles in order to achieve pattern diversity. The two monopole arms are connected to a tapered feeding line by two p-i-n diodes $S_{1,\mathrm{Left}}$ and $S_{1,\mathrm{Right}}$. Once activated, each p-i-n diode feeds separately an antenna arm. The individual activation of each of the two switches is done by printing a high impedance biasing line on the side of each monopole arm. When either of these two switches are activated, the antenna resonates at $f = 3.24$ GHz.

Two additional p-i-n diodes $S_{2,\mathrm{Left}}$ and $S_{2,\mathrm{Right}}$ are then added on each monopole in order to increase its length on demand as shown in Fig. 1 [65]. The increase in the monopole length as a result of the activation of any of the p-i-n diodes $S_{2,\mathrm{Left}}$ or $S_{2,\mathrm{Right}}$, allows the antenna to lower its resonant frequency to 2.96 GHz. The antenna also achieves pattern diversity through the placement of the printed reflector. The reflector directs the radiated beam to either the left or the right when the left or right monopole is activated by the appropriate switches. The shape and size of the printed reflector has been optimized in order to obtain the desired mode of operation. Thus, the antenna achieves for each frequency of operation two radiation directions. The activation of the p-i-n diodes [66] is achieved using a current driver and a bias tee. The radiation pattern diversity is shown in Fig. 2 when the corresponding switches are activated [65]. Fig. 3 shows the corresponding frequency reconfiguration [65].

The effect of the p-i-n diodes in terms of nonlinearity as well as interference of biasing lines are also taken into consideration during the design process. In order to overcome such drawbacks some antenna designers integrate p-i-n diodes into the feeding network of the antenna. An example of such integration is shown in Fig. 4 [67], where two p-i-n diodes are used to reconfigure a feeding network that can be connected to one or multiple antennas at a later stage. The reconfiguration of the feeding network allows the reconfiguration of the antenna operation.

Varactors can also be incorporated into the antenna structure, either on its radiating surface or into its feeding network. The activation of a varactor requires a direct supply of a DC voltage. The variation of the voltage levels

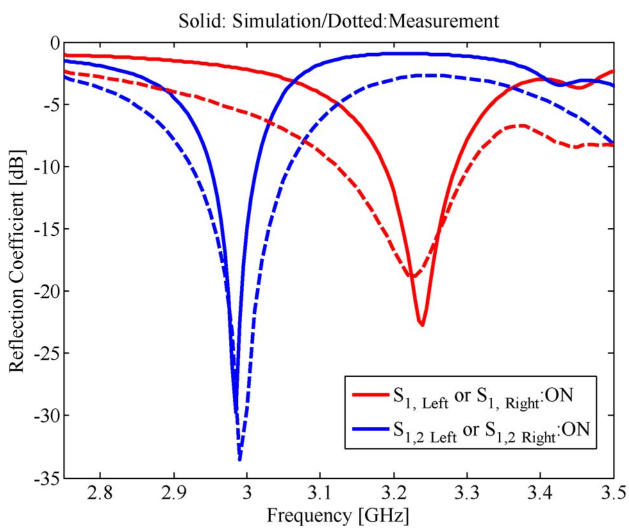

Fig. 3. ***The simulated and measured antenna reflection coefficient for various switch cases [65].***

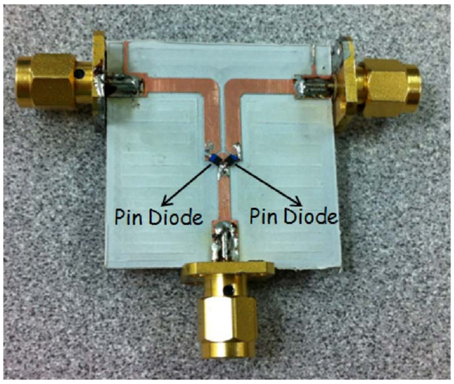

Fig. 4. ***Reconfigurable feeding network with two integrated p-i-n diodes [67].***

allows the varactor to change its capacitance and thus tunes the antenna operation. The integration of a varactor into an antenna structure requires the connection of that varactor to a DC voltage source.

A varactor based reconfigurable "Filtenna" is shown in Fig. 5 [32]. A "Filtenna" is a term used to express the end result of merging a filter into the feeding line of an antenna. A varactor based tunable hexagonal shaped bandpass filter is integrated within the feeding line of a printed antipodal wideband dipole antenna. The combination of both the filter and the antenna achieves frequency tuning without distorting the antenna's radiation characteristics. This technique allows the tuning of frequency filtering without additional and unwanted interferences. Moreover, all the biasing lines of the varactor do not reside on the antenna radiating plane but rather in its feeding line, which will minimize the effect on the antenna radiation characteristics [32]. The frequency tuning in the operation of the "Filtenna" is shown in Fig. 6 [32].

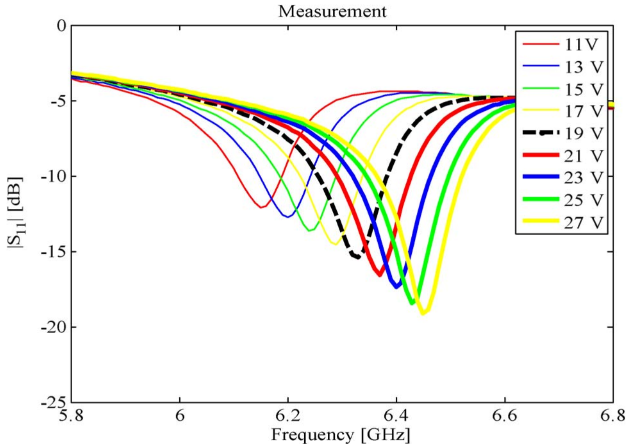

Fig. 6. ***Tuning of the reflection coefficient of the "Filtenna" for different voltage levels [32].***

Optical switching, through the means of silicon photoconductive switches, can also be used to reconfigure an antenna operation. An optically pumped reconfigurable antenna is shown in Fig. 7 [34] where a new light delivery technique is used to activate the silicon switches. The light delivery is based on integrating an optical fiber fixture into the ground plane of the antenna just below the targeted silicon switch [34]. A hole is then drilled through the substrate to allow an easy light delivery to the silicon switch. Once the switch is illuminated by a laser diode it conducts and thus allows the reconfiguration of the antenna operation. The antenna shown in Fig. 7 relies on two silicon switches to reconfigure its operation.

Other types of switches can also be used to reconfigure an antenna's operation, however, it is important to identify the appropriate application for each switch integration. For example, a fast response requires p-i-n diode based switching while a tunable response requires a varactor based one. A low power response allows the integration of

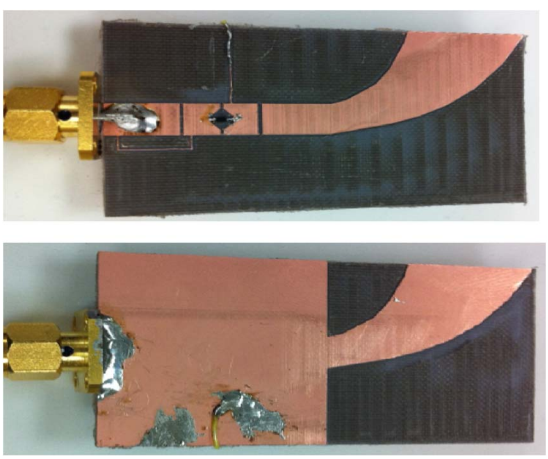

Fig. 5. ***Front and back of the reconfigurable "Filtenna" [32].***

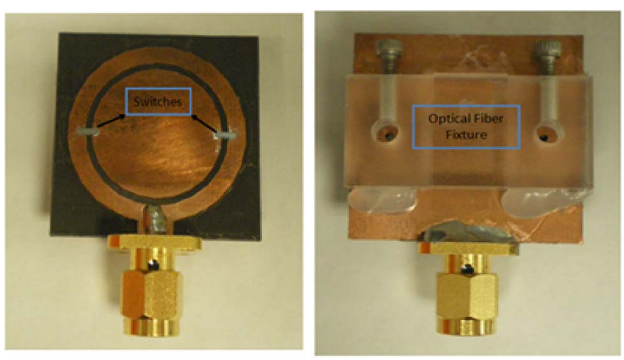

Fig. 7. ***The top and bottom layers of the antenna in [34].***

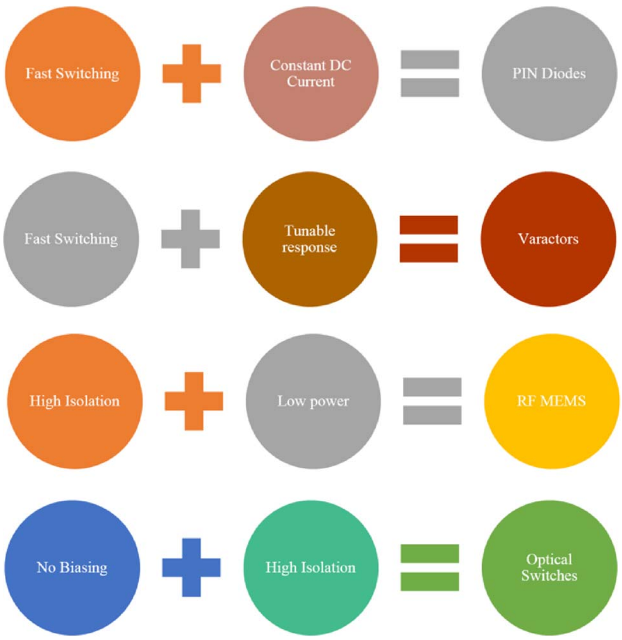

Fig. 8. ***An illustration of the various properties of Switches.***

RF-MEMS instead. An antenna designer needs to make an informed decision when it comes to choosing the appropriate switching mechanism for a reconfigurable antenna design. Fig. 8 depicts an illustration that compares the different properties of the various switching techniques for operation between 1 and 10 GHz.

III. NON-SWITCH-BASED RECONFIGURABLE ANTENNAS

In this section, we discuss reconfigurable antennas that rely on alternative techniques to achieve antenna reconfiguration. These techniques do not resort to switching components, however, they use actuators, motors, or other tools to move some parts in the antenna structure, or change the electrical properties of the antenna's substrate [42]–[45]. The movement of any part of the antenna results in a reconfiguration of the antenna's radiating edges which alters the antenna operation on demand. The antenna shown in Fig. 9 [45] resorts to two actuators to move and tilt the ground plane of its radiating patch. The antenna structure is composed of a microstrip line fed patch, two fixed and one moving ground planes. Two asymmetric rectangular slots are etched on the patch. The feeding line and the slots dimensions are optimized for a better impedance matching. The slots positions improve the antenna matching and allow a multiband operation. The moving ground plane is controlled by two actuators [68] that allow its vertical movement as well as its tilting position. The reconfigurable antenna is designed to cover various frequency bands between 2 GHz and 6 GHz for different ground plane positions and tilt angles.

The entire antenna system is controlled by an Arduino Uno R3 Microcontroller [69]. The Arduino board receives orders from a parallax switch [70]. It outputs controls to an LCD screen and two actuators that drive the ground plane of the antenna. As a result, the antenna is transformed into a suspended microstrip

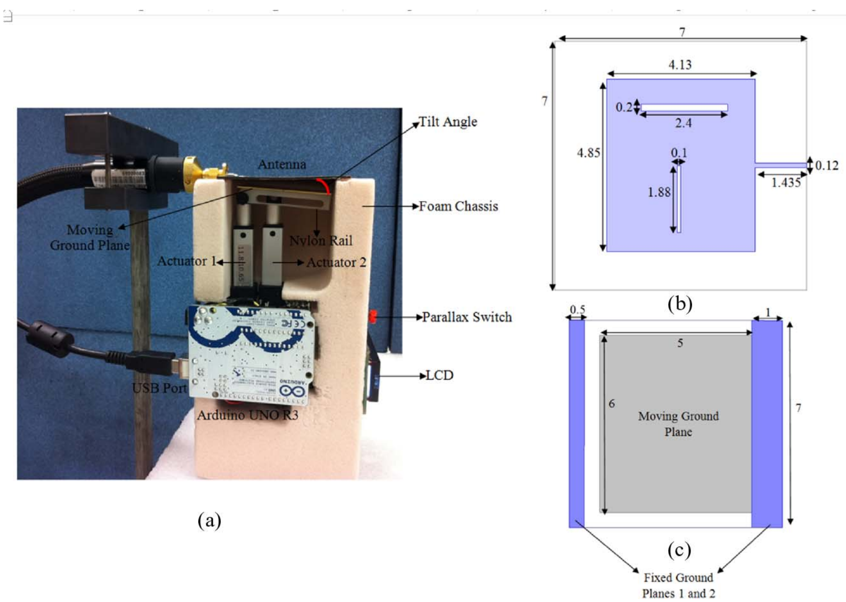

Fig. 9. ***(a) Antenna system. (b) Antenna patch. (c) Antenna ground planes [45].***

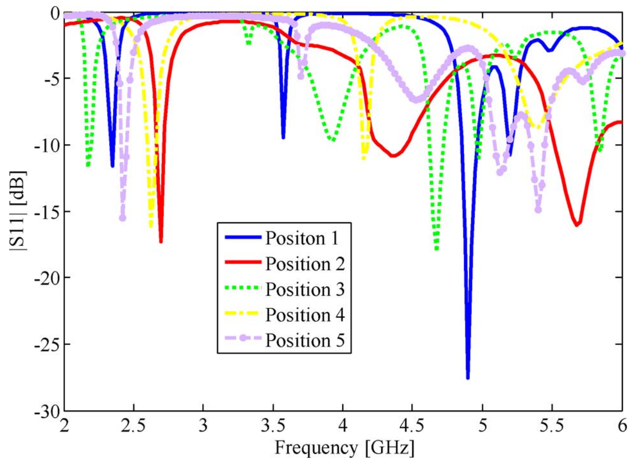

Fig. 10. ***Reconfiguring the antenna's operating frequencies for different ground plane positions [45].***

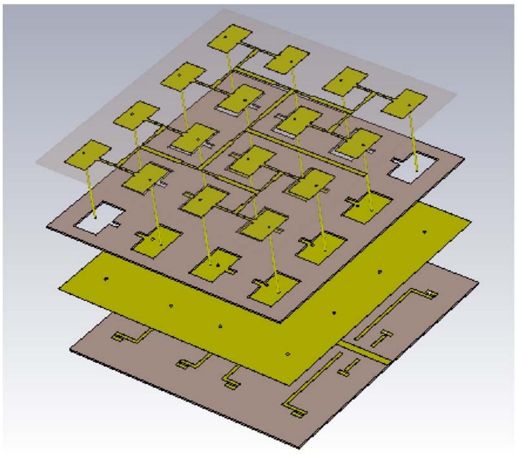

Fig. 11. ***The reconfigurable antenna array structure [71].***

antenna with a variable height [45], resulting in reconfiguring its frequency of operation. Fig. 10 shows the antenna's frequency response for various positions of the ground plane.

Antenna researchers have also resorted to specific material properties such as graphene plasmonics [40], or liquid crystals [41] to reconfigure antenna operations. A 4×4 liquid crystal based planar antenna array is shown in Fig. 11 [71]. Liquid crystal resides as a substrate underneath each of the 16 patches. A Rogers's 3003 substrate with a thickness of 0.5 mm constitutes the structure's substrate elsewhere [71]. A narrow gap is inserted in the feeding line at the input of each patch to block DC from flowing from patch to patch. DC voltage reaches each patch through a pin that goes through the liquid crystal cavity and the ground plane. RF chokes are also used between pins and the feeding connection for isolation purposes. Varying the supplied DC voltage results in varying the dielectric properties of the liquid crystals which results in tuning the operation of the antenna array [71].

The control of mechanically reconfigurable antennas results in driving actuators which can be power consuming. However, the miniaturization of these actuators is possible for future antenna reconfigurable antenna integration. Actuators' tuning speed is definitely slower than any switching component; however, their speed has proven to be sufficient for most applications. Mechanical reconfiguration techniques can also be robust and easily integrated as part of a mechanical system that requires an RF front end for communication purposes. The change in material properties is also another promising technique that is getting more attention. However, its slow tuning speed, high voltage requirements, and small reconfiguration capabilities may constitute some of the drawbacks that need to be addressed.

IV. GRAPH MODELING RECONFIGURABLE ANTENNAS

In this section, graph models are discussed as tools to transform antennas from their bulky state into software accessible devices. Graph models allow the optimization of the automation and software control of the tuning process of any reconfigurable antenna [1]. The advancement in reconfigurable antennas, development is due to the fact that these antennas are software controlled and can be automated easily. Graph models [72] allow the employment of various algorithms into the antennas' automation and optimization process [1].

Graphs are mathematical illustrations of various systems; they are symbolic representations of relationships between different points in a system. A graph can also be a description of a communication protocol; in particular, a suitably designed graph can precisely describe and direct the changing network topology of a self-organizing system [74]–[77], thus the use of graphs to model reconfigurable antennas.

A graph is a collection of vertices that are connected by lines called edges [59]. Each vertex can represent a part of an antenna or an end-point of a switch [1]. The connection between the different antenna parts or the activation of the switch is represented by the presence of an edge connecting the corresponding vertices [1]. Several rules are introduced to model reconfigurable antennas [1]. These rules allow the designer to relate each possible topology to a corresponding electromagnetic performance. Once a graph is drawn, an adjacency matrix can be formed based on this graph. Thus, the graph has transformed an antenna into a matrix where various algorithms can be applied [73].

Graph models can also be used to determine the presence of redundant components in an antenna structure. An element is defined as redundant if its presence gives the antenna more functions than required and its removal does not affect the antenna's performance [59]. A redundancy

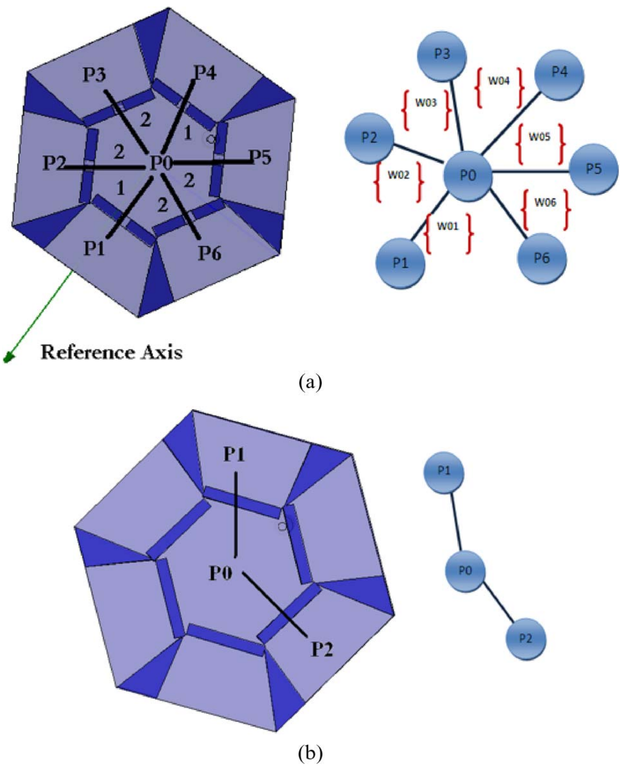

Fig. 12. ***(a) Reconfigurable antenna before the redundancy reduction approach. (b) Reconfigurable antenan after the redundancy reduction approach [59].***

reduction approach is proposed in [59] to eliminate redundant components from reconfigurable antenna structures for more efficient designs. Removing redundant components from an antenna structure reduces its complexity and allows for a more efficient antenna reconfiguration. For instance, eliminating redundant switches in a switch reconfigurable antenna reduces the nonlinearity effects and the interference from the corresponding biasing lines. The planar antenna shown in Fig. 12 [59] is built out of a hexagonal main patch and six trapezoidal parts placed around it. Each trapezoidal part is connected to the main patch by a switch. Thus, this antenna originally utilizes six switches to tune its frequency operation. The antenna is designed on an FR4 epoxy substrate with a height of 3.2 mm. The graph model of this antenna shown in Fig. 12(a), is composed of six vertices $(P_1, P_2, P_3, P_4, P_5, P_6)$ representing the trapezoidal parts connected by six edges to the seventh vertex (P_0) that represents the main patch [59]. After the application of the graph based redundancy reduction approach, the number of used switches is transformed from six to two as shown in Fig. 12(b). It is important to note that the functioning of the antenna is preserved and its optimized response is compared with the original redundant antenna response [59]. Antennas with a larger number of switches can also benefit from the redundancy reduction approach to improve their efficiency and to allow an easier system control and integration [59], [73].

Reconfigurable antennas can achieve the same frequency operation with several switch configurations. These configurations are defined as "Equivalent Configurations" [60]. Eliminating unnecessary and undesired switches from the antenna structure reduces its general complexity as well as the number of equivalent configurations. The effect that this reduction has on the reliability of the antenna needs to be addressed especially in the case of a switch failure.

It is shown that while the physical antenna redundancy is reduced, the equivalent configurations present are sufficient to maintain an acceptable antenna reliability [60].

The reliability of a reconfigurable antenna mainly depends on the number of antenna configurations at a certain frequency and, the probability to achieve them. However, it is inversely proportional to the number of edges needed [73].

The solution is to design reconfigurable antennas with several equivalent configurations but only with a small number of connections. Thus, the reliability of a reconfigurable antenna can be calculated as in (1) [60]. On the other hand, an antenna's general complexity is represented by the total number of edges in a graph as shown in (2) [60]. Antenna's frequency dependent complexity is the measure of the maximum number of edges in a particular configuration as defined in (3) [60]. It can be deduced from these equations that the reliability of a reconfigurable antenna is inversely proportional to its frequency dependent complexity [60]. An antenna designer that wishes to maximize the reliability of an antenna while reducing its complexity must take this conclusion into consideration at the initial stage of the design process.

$$R(f) = \frac{\sum_{i=1}^{Nc(f)} \sum_{j=1}^{NE_i(f)} P(E_{ij})}{\sum_{i=1}^{Nc(f)} NE_i(f)} \times 100 \tag{1}$$

where

R(f)	The reconfigurable antenna reliability at a particular frequency f
NC(f)	The number of configurations achieving the frequency f
NE(f)	The number of edges for different configurations at the frequency f
P(E)	Probability of achieving the edge $E = 1 - P$ (a switch failing)

$$C = NE \tag{2}$$

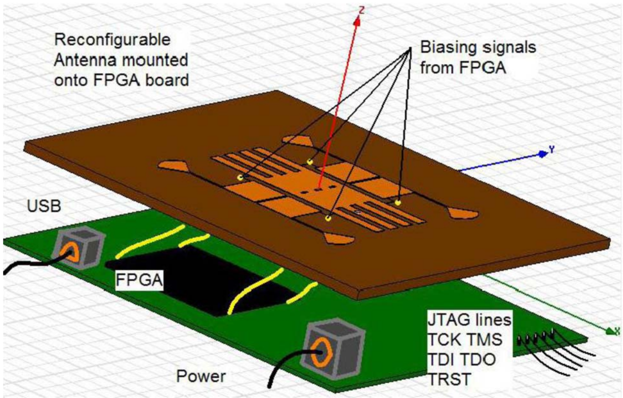

Fig. 13. ***FPGA controlling a p-i-n diode frequency reconfigurable antenna [1].***

where NE represents the total number of edges in a graph for all possible connections.

$$C(f) = \operatorname*{Max}_{i=1,NC(f)} (NE_i(f)) \tag{3}$$

where

C(f) represents the complexity of the antenna system at a frequency f

NC(f) represents the number of equivalent configurations at a frequency f

NE_i (f) represents the number of edges at the configuration i for a frequency f

The graph based analysis can also be extended to reconfigurable antenna arrays where their complexity, reliability, and switch failure correction techniques are correlated and analyzed [61].

It is important to note that this graph based analysis of reconfigurable antennas is executed so that optimal designs are created with less redundancy. Reducing redundant components while maintaining reliability creates systems that have less loss, less costs, efficient, are easy to control and automate [73].

V. SOFTWARE CONTROL OF RECONFIGURABLE ANTENNAS

Controlling a reconfigurable antenna with software can be done using many platforms suchs as Field Programmable Gate Arrays (FPGAs), Microcontrollers, or Arduino Boards [69]. For example, the antenna discussed in [16] uses an FPGA to activate and de-activate p-i-n diodes that connect different parts of its structure as shown in Fig. 13 [1]. In another example, Labview and an NPN Darlington array control the rotation mechanism of a stepper motor that is used to reconfigure an antenna structure [78]. The software control using an FPGA or Labview for example, constitutes a simple approach that is accessible to any antenna designer without complicated programming skills. This allows the automation of reconfigurable antennas to become easily integrated into the antenna design procedure.

Arduino boards also allow antenna designers to program their antenna systems, control and automate them in a compact setting as shown in Fig. 9(a) [45]. The user in such systems controls the operation of the antenna and, decides when and how to change its function. In other cases, detection of surrounding activities is needed to change an antenna's operation. An example of such system is one where a change in temperature triggers thermal switches installed onto the antenna structure [39]. Motion detection is also a trigger mechanism that can be used to bias and tune a reconfiguring component. An Infra-Red (IR) motion detection sensor is connected to the biasing network of a varactor, incorporated onto a reconfigurable antenna as shown in Fig. 14 [79]. Once a movement is detected in a predetermined area, the biasing circuit changes voltage levels. This action results in antenna frequency tuning [79].

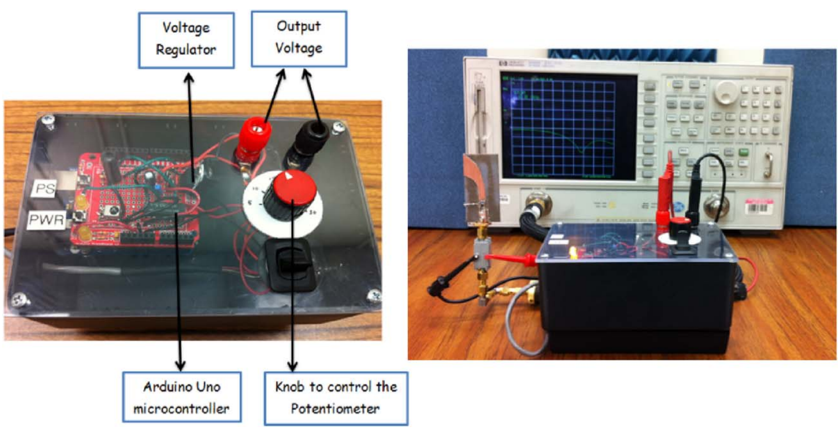

Fig. 14. ***The motion detection circuit connected to the varactor based reconfigurable "Filtenna" [79].***

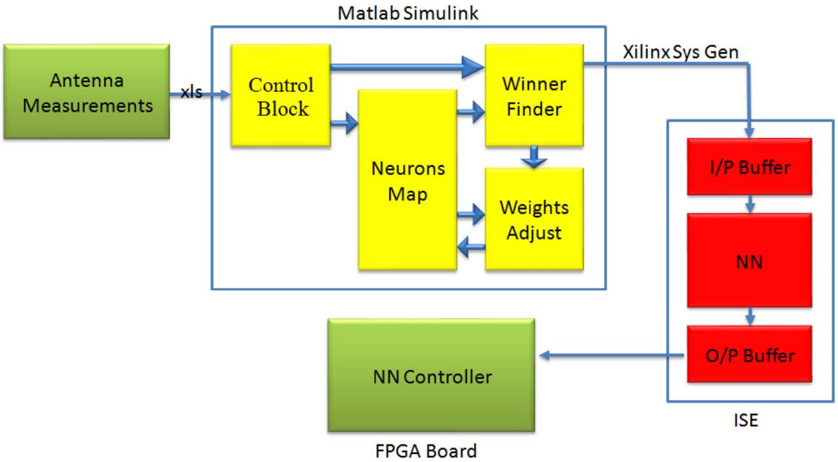

Fig. 15. ***Block diagram of the NN operation [64].***

Graph models based redundancy reduction approach minimizes the number of components that need to be controlled. It also allows the application of algorithms such as the shortest path algorithm. Such algorithm applied to a mechanically reconfigurable antenna insures the fastest possible reconfiguration process in the present setting [1].

VI. NEURAL NETWORKS APPLIED ON RECONFIGURABLE ANTENNAS

Neural Networks (NN) can be used on FPGA based software controlled reconfigurable antennas to drive the antenna state reconfiguration. NNs are proposed to be implemented on reconfigurable antennas as antenna synthesizers. A NN is trained to associate all the different configurations of a reconfigurable antenna with its different operating frequencies [64].

NNs can be designed using a standard back-propagation technique, which steers the design to convergence [80]. Applying NNs to reconfigurable antennas results in the association of different antenna configurations with different frequency responses called clusters. The association of such frequency clusters with corresponding antenna configurations trains the NN to be able to configure the antenna and regenerate frequency responses on demand.

The NN architecture has three layers: Input layer, Hidden layer and Output layer. The input layer represents, in the case a switch-reconfigured antenna, the number of switches existing in that antenna. The number of hidden neurons in the hidden layer represents the accuracy needed to regenerate the frequency response of the antenna in question. The number of output layer neurons is determined depending on the number of points needed to recreate to an acceptable accuracy the return loss of the antenna [81].

The application of Neural Networks requires a considerable amount of data training and software handling. The general methodology is summarized in the block diagram of Fig. 15 [64]. A neural network is built and trained in Matlab Simulink. Training the NN requires adjusting the connection weights and specifying the number of hidden neurons. Error Back-propagation (BP) is used to train the NN in this case. BP compares neural networks' output to the measured antenna response and calculates an error adjustment for each of the nodes in the network. The neural network adjusts the connection weights according to the error values assigned to each node [81]. After the weight adjustment process, a Xilinx system generator creates the NN VHDL code to be used to control an FPGA [81].

As an example, applying neural networks to a reconfigurable antenna with six switches such as the one shown in Fig. 12(a) results in six input neurons, 11 hidden neurons, and 51 output neurons. The NN structure for this antenna is shown in Fig. 16. After removing the redundant components from this antenna as shown in Fig. 12(b), the input layer of the neural network shrinks from six to two and the number of hidden neurons will have to shrink from 11 to 8 [64]. As a result the training process requires less

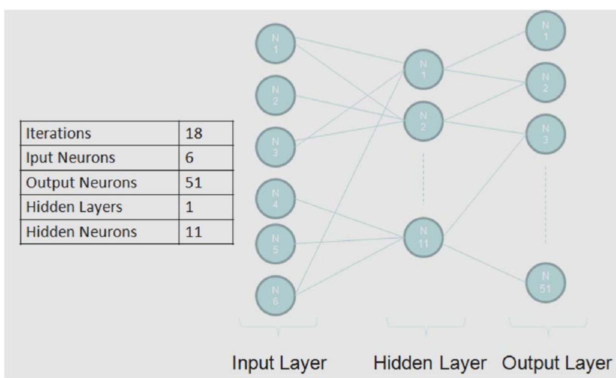

Fig. 16. ***The NN structure of the antenna in Fig. 12(a) [64].***

time and the regeneration of antenna states based on NNs is faster and more efficient [73].

VII. RECONFIGURABLE ANTENNAS FOR COGNITIVE RADIO AND MIMO APPLICATIONS

Cognition and the ability to identify changes in a communication setting require antennas to be able to react to these changes. In a cognitive radio setting, a channel is monitored and idle frequencies in the spectrum are determined. Idle frequencies can also be called unused spaces or white spaces. Once unused spaces are identified, a reconfigurable antenna is ordered to tune its operation to broadcast accordingly; thus increasing the communication efficiency [82].

A wideband or a reconfigurable narrowband antenna can be used for channel sensing. The communication process on the other hand requires a reconfigurable antenna to be able to tune its operation in order to manage the dynamically discovered white spaces in the spectrum. A cognitive radio device's operation is based on a cycle that is shown in Fig. 17 [82]. This cycle starts by observing the channel activity, which is achieved by a sensing antenna. In the second step of the cycle, a cognitive processor decides which part of the spectrum is suitable for communication. In the following step, the processor orders the communicating antenna to act appropriately to achieve the required mode of communication. In the last step, the processor achieves cognition by learning from previous channel activities. This cycle allows the cognitive radio device to self-decide and optimally self-reconfigure its hardware to physically realize the selected mode of communication [82], [83].

It is critical to understand that adding cognition to antenna systems and, allowing them to communicate over unused frequency gaps, does not solve other issues in the spectrum. Hence, it is important to design antennas that also address spectrum concerns such as fading or multipath. A MIMO based antenna can be proposed for cognitive radio applications as shown in Fig. 18 [84]. The reason

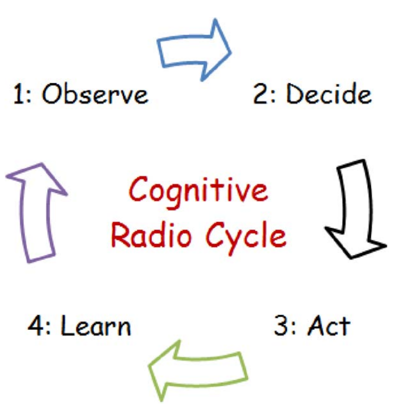

Fig. 17. *The cognitive radio cycle [82].*

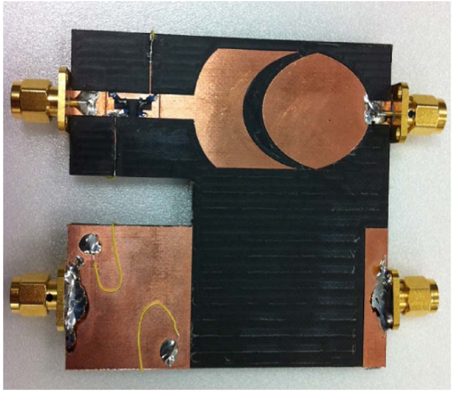

Fig. 18. *MIMO based cognitive radio antenna [84].*

behind adopting a MIMO based antenna for cognitive radio, is to combat fading, ensure reliable communication between end users, and improve the spectrum usage efficiency [73].

The MIMO based cognitive radio antenna system shown in Fig. 18, consists of two sensing antennas as well as two reconfigurable "Filtennas" packed all together on the same substrate [84]. The reconfigurable antennas use p-i-n diodes to tune their frequency band-pass operation. A reconfigurable antenna, in a cognitive radio setting, is able to react to the observations of the wideband sensing antenna, based on the recommendations of the cognitive processor as described in Fig. 17. The evaluation of the performance of the proposed antenna systems in mitigating fading in a rich multipath environment is done by observing the values of the envelope correlation coefficient ρ_e and the mean effective gain (MEG) [84], [85]. It is essential to ensure that the signals received from either the two sensing antennas or the two communicating "Filtennas" satisfy the corresponding criterion as discussed in [84], [85].

VIII. RECONFIGURABLE ANTENNAS FOR SPACE APPLICATIONS

Antennas designed for space communication have to be packed during the launch phase and then deploy once in space. Many types of deployable antennas have been used on orbit. Reflector types constitute the widest category [86]. Other deployable structures made with folded hoops or ribs are also used for space communications [87]. Some researchers have also resorted to tape springs and neutrally stable material to design their structures [88]. Helical antennas [89] are also a popular choice of satellite antennas due to their natural circular polarization and wide bandwidth [90].

Traditional deployable antennas present valid options for space communication. However, the rise of small satellites' development and the launch of clusters of CubeSats have increased the need for more agile antennas. Currently

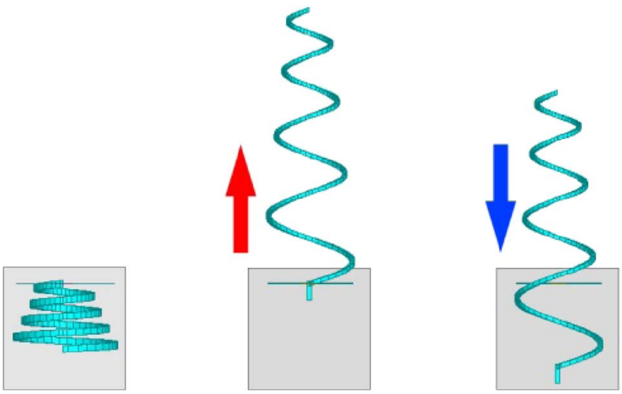

Fig. 19. ***Helical antenna deployed in progression [95].***

dipole antenna arrays in various configurations constitute the most common antennas deployed on CubeSats [91]. The merging of reconfigurable and deployable antennas appears to be a solution to the increased demand for communication agility in space [73].

When proposing a suitable reconfiguration technique for antennas in space, antenna designers need to utilize the deployment process as part of their reconfiguration process. Thus, mechanical reconfiguration techniques come to mind as first choice. However some electrical reconfiguration means can also be addressed especially with the advancement in satellite power handling technology.

Many types of actuators can be used to achieve mechanical reconfiguration. The choice of such actuators depends on the nature of the antenna and its material composition. For example, the reconfiguration of deployable antennas that are designed with bi-stable composite tape springs can be achieved using one-way linear or rotary actuator [92]–[94]. Antennas made with Neutrally Elastic Mechanism (NEM) tape springs require two-way actuators to be reconfigured [92]–[94].

Another reconfiguration technique can be based on deploying an antenna in progression. For example, a helical antenna shown in Fig. 19 [95], deploys in stages by resorting to actuators. The sequential deployment tunes the antenna's operating frequency. The concept is based on the fact that only the part of the antenna that is above the deployed ground plane radiates [95].

The introduction of reconfigurability to space communication antennas constitute a great addition to space technology despite the difficulty in achieving such task. Reconfigurable deployable antennas allow major advancement possibilities in available communication technology and constitute a suitable addition to the evolving world of space communication.

IX. CONCLUSION

In this paper a summary of the techniques and methodologies used to design, optimize and apply reconfigurable antennas is presented. Reconfigurable antennas constitute a major part of current communication systems. They are the basis for many future applications that are based on cognition and reaction to evolving/changing conditions. A static communication system that relies on one or more fixed antennas, no longer caters for the evolving needs of today's communication technology.

Several techniques are proposed to achieve the reconfiguration mechanism of antennas. These techniques are based on electrical, optical, or mechanical means. However, no matter which technique is used, the end result is the same: a re-arrangement of the antenna's radiating aperture.

The operation of reconfigurable antennas can be automated, controlled and optimized using many techniques, such as graph models or neural networks. These techniques embedded on FPGAs, microcontrollers, or any programmable processor, allow a reconfigurable antenna to optimally operate within the design's existing objectives.

Finally, one must keep in mind that the future of reconfigurable antennas is filled with self-adaptation, learning, reacting, overcoming failures and achieving a very efficient communication link that is highly dynamic and ever-changing. ■

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REFERENCES

[1] J. Costantine, Y. Tawk, and C. G. Christodoulou, *Design of Reconfigurable Antennas Using Graph Models*. San Rafael, CA, USA: Morgan and Claypool, 2013.

[2] C. G. Christodoulou, Y. Tawk, S. A. Lane, and S. R. Erwin, "Reconfigurable antennas for wireless and space applications," *Proc. IEEE*, vol. 100, no. 7, pp. 2250–2261, Jul. 2012.

[3] C. A. Balanis, *Modern Antenna Handbook*. Hoboken, NJ, USA: Wiley, 2011.

[4] J. T. Bernhard, *Reconfigurable Antennas*. San Rafael, CA, USA: Morgan and Claypool, 2007.

[5] E. R. Brown, "RF-MEMS switches for reconfigurable intgrated circuits," *IEEE Trans. Microw. Theory Tech.*, vol. 46, no. 11, pt. 2, pp. 1868–1880, 1998.

[6] X.-S. Yang, B.-Z. Wang, S. H. Yeung, Q. Xue, and K. F. Man, "Circularly polarized reconfigurable crossed-yagi patch antenna," *IEEE Antennas Propag. Mag.*, vol. 53, no. 5, pp. 65–80, 2011.

[7] A. Zohur *et al.*, "RF MEMS reconfigurable two-band antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 72–75, 2013.

[8] G. H. Huff and J. T. Bernhard, "Integration of packaged RF-MEMS switches with radiation pattern reconfigurable square spiral microstrip antennas," *IEEE Trans. Antennas Propag.*, vol. 54, no. 2, pp. 464–469, Feb. 2006.

[9] B. A. Cetiner, G. R. Crusats, L. Jofre, and N. Biyikli, "RF MEMS integrated frequency reconfigurable annular slot antenna," *IEEE Trans. Antennas Propag.*, vol. 58, no. 3, pp. 626–632, Mar. 2010.

[10] A. Grau *et al.*, "A dual linearly polarized MEMS-reconfigurable antenna for narrowband MIMO communication systems," *IEEE Trans. Antennas Propag.*, vol. 58, no. 1, pp. 4–16, Jan. 2010.

[11] S. Nikolaou, N. D. Kingsley, G. E. Ponchak, J. Papapolymerou, and M. M. Tentzeris, "UWB elliptical monopoles with a reconfigurable band notch using MEMS switches actuated without bias lines," *IEEE Trans. Antennas Propag.*, vol. 57, no. 8, pp. 2242–2251, Aug. 2009.

[12] E. Erdil, K. Topalli, M. Unlu, O. A. Civi, and T. Akin, "Frequency tunable patch antenna using RF MEMS technology," *IEEE Trans. Ant. Propag.*, vol. 55, no. 4, pp. 1193–1196, Apr. 2007.

[13] D. Piazza, P. Mookiah, M. D'amico, and K. Dandekar, "Experimental analysis of pattern and polarization reconfigurable circular patch antennas for MIMO antennas," *IEEE Trans. Antennas Propag.*, vol. 59, no. 5, pp. 2352–2362, 2010.

[14] P. Quin, Y. J. Guo, A. R. Weily, and C. Liang, "A pattern reconfigurable U-Slot antenna and its applications in MIMO systems," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pt. 1, pp. 516–528, 2012.

[15] L. Hinsz and B. D. Braaten, "A frequency reconfigurable transmitter antenna with autonomous switching capabilities," *IEEE Trans. Antennas Propag.*, vol. 62, no. 7, pp. 3809–3813, 2014.

[16] S. Shelley, J. Costantine, C. G. Christodoulou, D. E. Anagnostou, and J. C. Lyke, "FPGA-controlled switch-reconfigured antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 355–358, 2010.

[17] S.-H. Chen, J.-S. Row, and K.-L. Wong, "Reconfigurable square-ring patch antenna with pattern diversity," *IEEE Trans. Antennas Propag.*, vol. 55, no. 2, pp. 472–475, Feb. 2007.

[18] S.-J. Wu and T.-G. Ma, "A wideband slotted bow-tie antenna with reconfigurable CPW-to slotline transition for pattern diversity," *IEEE Trans. Antennas Propag.*, vol. 56, no. 2, pp. 327–334, Feb. 2008.

[19] B. Kim *et al.*, "A novel single-feed circular microstrip antenna with reconfigurable polarization capability," *IEEE Trans. Antennas Propag.*, vol. 56, no. 3, pp. 630–638, Mar. 2008.

[20] R.-H. Chen and J.-S. Row, "Sing-fed microstrip patch antenna with switchable polarization," *IEEE Trans. Antennas Propag.*, vol. 56, no. 4, pp. 922–926, Apr. 2008.

[21] J. Sarrazin, Y. Mahe, S. Avrillon, and S. Toutain, "Pattern reconfigurable cubic antenna," *IEEE Trans. Antennas Propag.*, vol. 57, no. 2, pp. 310–317, Feb. 2009.

[22] J. Perruisseau-Carrier, P. Pardo-Carrera, and P. Miskovsky, "Modeling, design and characterization of a very wideband slot antenna with reconfigurable band rejection," *IEEE Trans. Antennas Propag.*, vol. 58, no. 7, pp. 2218–2226, Jul. 2010.

[23] P.-Y. Qin, A. R. Weily, Y. J. Guo, T. S. Bird, and C.-H. Liang, "Frequency reconfigurable quasi-yagi folded dipole antenna," *IEEE Trans. Antennas Propag.*, vol. 58, no. 8, pp. 2742–2747, Aug. 2010.

[24] Y. Bai, S. Xiao, C. Liu, X. Shuai, and B. Wang, "Design of pattern reconfigurable antennas based on a two-element dipole array model," *IEEE Trans. Antennas Propag.*, vol. 61, no. 9, pp. 4867–4871, 2013.

[25] S. Onodera, R. Ishikawa, A. Saitou, and K. Honjo, "Multi-band reconfigurable antennas embedded with lumped-element passive components and varactors," in *Proc. Asia-Pacific Microw. Conf.*, 2013, pp. 137–139.

[26] A. H. Ramadan *et al.*, "Tunable filter-antennas for cognitive radio applications," *Progress Electromagn. Res. B*, vol. 57, pp. 253–265, 2014.

[27] E. A. Daviu, M. C. Fabres, M. F. Bataller, and A. V. Jimenez, "Active UWB antenna with tunable band-notched behavior," *IEEE Electron. Lett.*, vol. 43, no. 18, pp. 959–960, Aug. 2007.

[28] W.-S. Jeong, S.-Y. Lee, W.-G. Lim, H. Lim, and J.-W. Yu, "Tunable band-notched ultra wideband (UWB) planar monopole antennas using varactor," in *Proc. 38th Eur. Microw. Conf.*, 2008, pp. 266–268.

[29] H. Jiang, M. Patterson, C. Zhang, and G. Subramanyan, "Frequency tunable microstrip patch antenna using ferroelectric thin film varactor," in *Proc. IEEE Nat. Aerospace Electron. Conf.*, Jul. 2009, pp. 248–250.

[30] S.-S. Oh, Y.-B. Jung, Y. -R. Ju, and H.-D. Park, "Frequency-tunable open ring microstrip antenna using varactor," in *Proc. Int. Conf. Electromagn. Adv. Appl.*, Sep. 2010, pp. 624–626.

[31] S. L.-S. Yang, A. A. Kishk, and K.-F. Lee, "Frequency reconfigurable U-slot microstrip patch antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 127–129, Jan. 2008.

[32] Y. Tawk, J. Costantine, and C. G. Christodoulou, "A varactor based reconfigurable filtenna," *IEEE Antennas Wireless Propag.*, vol. 11, pp. 716–719, 2012.

[33] G. P. Jin, D. L. Zhang, and R. L. Li, "Optically controlled reconfigurable antenna for cognitive radio applications," *IET Electron. Lett.*, vol. 47, no. 17, pp. 948–950, 2011.

[34] Y. Tawk, A. R. Albrecht, S. Hemmady, G. Balakrishnan, and C. G. Christodoulou, "Optically pumped frequency reconfigurable antenna design," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 280–283, Mar. 2010.

[35] Y. Tawk *et al.*, "Demonstration of a cognitive radio front end using an optically pumped reconfigurable antenna system (OPRAS)," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pt. 2, pp. 1075–1083, 2012.

[36] V. Sathi, N. Ehtheshami, and J. Nourinia, "Optically tuned frequency reconfigurable microstrip antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1018–1020, 2012.

[37] S. Pendharker, R. K. Shevgaonkar, and A. N. Chandorkar, "Optically controlled frequency-reconfigurable microstrip antenna with low photoconductivity," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 99–102, 2014.

[38] D. Patron, A. S. Daryoush, and K. R. Dandekar, "Optical control of reconfigurable antennas and application to a novel pattern-reconfigurable planar design," *IEEE J. Lightw. Technol.*, 2014, Early access article.

[39] Z. Jiang and F. Yang, "Reconfigurable sensing antennas integrated with thermal switches for wireless temperature monitoring," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 914–917, 2013.

[40] J. Perruisseau-Carrier, M. Tamagnone, J. S. Gomez-Diaz, M. Esquius-Morote, and J. R. Mosig, "Resonant and leaky-wave reconfigurable antennas based on graphene plasmonics," in *Proc. Int. Symp. Antennas Propag.*, 2013, pp. 136–137.

[41] L. Liu and R. J. Langley, "Liquid crystal tunable microstrip patch antenna," *IET Electron. Lett.*, vol. 44, no. 20, pp. 1179–1180, 2008.

[42] D. Rodrigo, L. Jofre, and B. Cetiner, "Circular beam-steering reconfigurable antenna with liquid metal parasitics," *IEEE Trans. Antennas Propag.*, vol. 60, no. 4, pp. 1796–1802, 2012.

[43] A. Mehdipour *et al.*, "Mehcanically reconfigurable antennas using an anisotropic carbon-fibre composite ground," *IET Microw. Antennas Propag.*, vol. 7, no. 13, pp. 1055–1063, 2013.

[44] R. A. Liyakath, A. Takshi, and G. Mumcu, "Multilayer stretchable conductors on polymer substrates for conformal and reconfigurable antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 603–606, 2013.

[45] J. Costantine, Y. Tawk, J. Woodland, N. Floam, and C. G. Christodoulou, "Reconfigurable antenna system with a movable ground plane for cognitive radio," *IET Microw., Antennas Propag.*, 2014, early access.

[46] J. A. Bossard, D. H. Werner, T. S. Mayer, and R. P. Drupp, "A novel design methodology for reconfigurable frequency selective surfaces using genetic algorithms," *IEEE Trans. Antennas Propag.*, vol. 53, no. 4, pp. 1390–1400, Apr. 2005.

[47] Z. Min, X.-W. Luo, and G.-H. Wang, "Preliminary research of the reconfigurable antenna based on genetic algorithms," in *Proc. 3rd Int. Conf. Comput. Electromagn. Appl.*, 2004, pp. 137–140.

[48] D. E. Skinner, J. D. Connor, S. Y. Foo, M. H. Weatherspoon, and N. Powell, "Optimization of multi-band reconfigurable microstrip line-fed rectangular patch antenna using self-organizing maps," in *Proc. IEEE 10th Annu. Wireless Microw. Technol. Conf.*, 2009, pp. 1–4.

[49] A. Akdagli, K. Guney, and B. Babayigit, "Clonal selection algorithm for design of reconfigurable antenna array with discrete phase shifters," *J. Electromagn. Waves Appl.*, vol. 21, no. 2, pp. 215–227, 2007.

[50] C. M. Coleman, J. E. Rothwell, and J. E. Ross, "Investigation of simulated annealing, ant-colony and genetic algorithms for self-structuring antennas," *IEEE Trans. Antennas Propag.*, vol. 52, no. 4, pp. 1007–1014, 2004.

[51] J. D. Connor, "Antenna array synthesis using the cross entropy method," Ph.D. dissertation, Florida State Univ., Tallahassee, FL, USA, 2008.

[52] S. Song and R. D. Murch, "An efficient approach for optimizing frequency reconfigurable pixel antennas using genetic algorithms," *IEEE Trans. Antennas Propag.*, vol. 62, no. 2, pp. 609–620, 2014.

[53] K. Cao, H. Jiang, G. Chen, P. Cui, and T. Xiong, "Self-adaptive induced mutation algorithm for reconfigurable antenna systems," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 237–240, 2014.

[54] N. Jin and Y. Rahmat-Samii, "Advances in particle swarm optimization for antenna designs: Real-number, binary, single-objective and multiobjective implementations," *IEEE Trans. Antennas Propag.*, vol. 55, no. 3, pp. 556–567, 2007.

[55] D. Langoni, M. H. Weatherspoon, E. Ogunti, and S. Y. Foo, "An overview of reconfigurable antennas: Design, simulation, optimization," in *Proc. IEEE 10th Annu. Wireless Microw. Technol. Conf.*, Apr. 2009, pp. 1–5.

[56] R. Mehmood, J. W. Wallace, and M. A. Jensen, "Key establishment employing reconfigurable antennas: Impact of antenna complexity," *IEEE Trans. Antennas Propag.*, 2014, early access article.

[57] R. Mehmood and J. W. Wallace, "Diminishing returns with increasing complexity in reconfigurable aperture antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 299–302, 2010.

[58] K. A. Obeidat, B. D. Raines, R. G. Rojas, and B. T. Strojny, "Design of frequency reconfigurable antennas using the theory of network characteristic modes," *IEEE Trans. Antennas Propag.*, vol. 58, no. 10, pp. 3106–3113, 2010.

[59] J. Costantine, S. al-Saffar, C. G. Christodoulou, and C. T. Abdallah, "Reducing redundancies in reconfigurable antenna structures using

graph models," *IEEE Trans. Antennas Propag.*, vol. 59, no. 3, pp. 793–801, 2011.

[60] J. Costantine *et al.*, "Analyzing the complexity and reliability of switch-frequency-reconfigurable antennas using graph models," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pt. 2, pp. 811–820, 2012.

[61] J. Costantine, Y. Tawk, and C. G. Christodoulou, "Complexity versus reliability in arrays of reconfigurable antennas," *IEEE Trans. Antennas Propag.*, vol. 60, no. 11, pp. 5436–5441, 2012.

[62] N. Gulati and K. R. Dandekar, "Learning state selection for reconfigurable antennas: A multi-armed bandit approach," *IEEE Trans. Antennas Propag.*, vol. 62, no. 3, pp. 1027–1038, 2013.

[63] A. Patnaik, D. E. Anagnostou, C. G. Christodoulou, and J. C. Lyke, "Neurocomputational analysis of a multiband reconfigurable planar antenna," *IEEE Trans. Antennas Propag.*, vol. 53, no. 11, pp. 3453–3458, 2005.

[64] J. Costantine, Y. Tawk, E. Al-Zuraiqi, S. E. Barbin, and C. G. Christodoulou, "Applying graph models and neural networks on reconfigurable antennas for cognitive radio applications," in *Proc. IEEE APS Topical Conf. Antennas Propag. Wireless Commun.*, 2011, pp. 909–912.

[65] Y. Tawk, J. Costantine, and C. G. Christodoulou, "A frequency reconfigurable printed monopole with pattern diversity," *IEEE Trans. Antennas Propag.*, 2015.

[66] Infineon Technologies. [Online]. Available: http://www.infineon.com

[67] Y. Tawk, J. Costantine, and C. G. Christodoulou, "A reconfigurable feeding network," in *Proc. 8th Eur. Conf. Antennas Propag.*, The Hague, The Netherlands, 2014, pp. 1534–1536.

[68] Firgelli Technologies Inc., *Miniature Linear Motion Series L12*, Jun. 25, 2013. [Online]. Available: http://www.firgelli.com/pdf/L12_datasheet.pdf

[69] Arduino, *Arduino Uno*, May 20, 2013. [Online]. Available: http://www.arduino.cc/en/Main/arduinoBoardUno

[70] Parallalx Inc., *5-Position Switch (#27801)*, Feb. 3, 2010. [Online]. Available: http://www.parallax.com/Portals/0/Downloads/docs/prod/sens/27801-5PositionSwitch-v1.1.pdf

[71] F. N. Ayoub *et al.*, "Frequency-tunable patch array using highly anisotropic liquid crystal," in *Proc. IEEE Int. Symp. Antennas Propag.*, 2014.

[72] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introductions to Algorithms*. Cambridge, MA, USA: MIT Press, 2001.

[73] Z. N. Chen, *Handbook of Antenna Technologies*. New York, NY, USA: Springer Publishing, 2015.

[74] E. Klavins, "Programmable self assembly," *IEEE Control Syst. Mag.*, vol. 27, no. 4, pp. 43–56, Aug. 2007.

[75] E. Klavins, "Programmable self assembly," *IEEE Control Syst. Mag.*, vol. 27, no. 4, pp. 43–56, Aug. 2007.

[76] N. Napp, S. Burden, and E. Klavins, "The statistical dynamics of programmed assembly," in *Proc. IEEE Int. Conf. Robotics Autom.*, May 2006, pp. 1469–1476.

[77] E. Klavins, "Self-assembly from the point of view of its pieces," in *Proc. Amer. Control Conf.*, Jun. 2006, p. 7.

[78] Y. Tawk, J. Costantine, K. Avery, and C. G. Christodoulou, "Implementation of a cognitive radio front-end using rotatable controlled reconfigurable antennas," *IEEE Trans. Antennas Propag.*, vol. 59, no. 5, pp. 1773–1778, May 2011.

[79] J. Costantine, Y. Tawk, and C. G. Christodoulou, "Motion-activated reconfigurable and cognitive radio antenna systems," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1114–1117, 2013.

[80] J. Lyke, "A cellular automata FPGA architecture that can be trained with neural networks," in *Proc. Aerospace Conf.*, 2002, vol. 5, pp. 2347–2354.

[81] E. A. Zuraiqi, "Neural network field programmable gate array (FPGA) controllers for reconfigurable antennas," Ph.D. dissertation, Dept. Elect. Comput. Eng., Univ. New Mexico, Albuquerque, NM, USA, 2012.

[82] Y. Tawk, J. costantine, and C. G. Christodoulou, "Cognitive radio antenna functionalities: A tutorial," *IEEE Antennas Propag. Mag.*, vol. 56, no. 1, pp. 231–243, 2014.

[83] S. K. Jayaweera and C. G. Christodoulou, "Radiobots: Architecture, algorithms and real-time reconfigurable antenna designs for autonomous, self-learning future cognitive radios," Univ. New Mexico, Tech. Rep. EECE-TR-11-0001, Mar. 2011.

[84] Y. Tawk, J. Costantine, and C. G. Christodoulou, "Reconfigurable filtennas and MIMO in cognitive radio applications," *IEEE Trans. Antennas Propag.*, vol. 62, no. 3, pp. 1074–1083, 2014.

[85] R. G. Vaughan and J. B. Andersen, "Antenna diversity in mobile communications," *IEEE Trans. Veh. Technol.*, vol. 36, pp. 149–172, Nov. 1987.

[86] T. Tadashi *et al.*, "Deployable antenna with 10-m maximum diameter for space use," *IEEE Trans. Antennas Propag.*, vol. 52, no. 1, pp. 2–11, 2004.

[87] F. Zheng, M. Chen, W. Li, and P. Yang, "Conceptual design of a new huge deployable antenna structure for space application," in *Proc. IEEE Aerospace Conf.*, 2008, pp. 1–7.

[88] T. W. Murphey and S. Pellegrino, "A novel actuated composite tape-spring for deployable structures," Tech. Rep., AIAA, TR-1528, Apr. 2004.

[89] C. A. Balanis, *Antenna Theory: Analysis and Design*. Hoboken, NJ, USA: Wiley, 2012.

[90] H. King and J. Wong, "Characteristics of 1 to 8 wavelength uniform helical antennas," *IEEE Trans. Antennas Propag.*, vol. 28, pp. 291–296, Mar. 1980.

[91] P. Muri, C. Obulpathi, and J. McNair, "Enhancing small satellite communication through effective antenna system design," in *Proc. Military Commun. Conf.—Unclassified Program*, San Jose, CA, USA, Nov. 2010.

[92] J. Costantine, Y. Tawk, C. G. Christodoulou, J. Banik, and S. Lane, "CubeSat deployable antenna using bistable composite tape-springs," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 285–288, 2012.

[93] T. W. Murphey, S. Jeon, A. Biskner, and G. Sanford, "Deployable booms and antennas using bi-stable tape-springs," in *Proc. 24th AIAA/USU Conf. Small Satellites*, Logan, UT, USASSC10-X-6.

[94] S. Jeon and T. W. Murphey, "Design and analysis of a meter-class CubeSat boom with a motor-less deployment by bi-stable tape springs," in *Proc. 52nd AIAA Structures, Structural Dynamics, Materials Conf.*, Palm Springs, CA, USA, Apr. 4–7, 2011, AIAA-2011-1731.

[95] J. Costantine, Y. Tawk, and C. G. Christodoulou, "Reconfigurable deployable antennas for space communications," in *Proc. Int. Workshop Antenna Technol.*, 2014.

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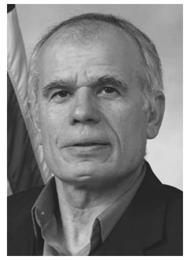

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