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Design of MEMS Reconfigurable E-Shaped Patch Antenna Design for Cognitive radio

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***Abstract*—Reconfigurable antennas offer attractive potential solutions to solve the challenging antenna problems related to cog-nitive radio systems using the ability to switch patterns, frequency, and polarization. In this paper, a novel frequency reconfigurable E-shaped patch design is proposed for possible applications in cognitive radio systems. This paper provides a methodology to design reconfigurable antennas with radio frequency microelec-tromechanical system (RF-MEMS) switches using particle swarm optimization, a nature-inspired optimization technique. By adding RF- MEMS switches to dynamically change the slot dimensions, one can achieve wide bandwidth which is nearly double the original E-shaped patch bandwidth. Utilizing an appropriate fitness function, an optimized design which works in the frequency range from 2 GHz to 3.2 GHz (50% impedance bandwidth at 2.4 GHz) is obtained. RF-MEMS switch circuit models are incorporated into the optimization as they more effectively represent the actual switch effects. A prototype of the final optimized design is developed and measurements demonstrate good agreement with simulations.**

Index Terms*—Cognitive radio, E-shaped patch, frequency re-configurable, Particle Swarm Optimization, radio frequency mi-cro electromechanical system (RF-MEMS), wideband antenna.

I. INTRODUCTION

THE communication link between two antennas typically suffers from multipath, interference, and fading. These various phenomena can severely restrict the performance of present-day wireless communication systems. In recent years, numerous techniques and solutions to enhance communication links have been devised [1]–[4]. The improvements involving antennas include the usage of *antenna diversity* to overcome limitations imposed on the system performance with a single receiving antenna [1]; *antenna reconfigurability* to enhance a single antenna by adding additional functionalities [2], [3]; and *multiple-input multiple-output* (MIMO) antenna systems to exploit rich multipath environments for a given frequency band [4]. In these methods, the frequency band is typically assumed to be set, and the goal is to improve overall system performance for that given band by exploiting spatial features of the wire-less environment. Another technique that is currently gaining momentum is the use of *software defined radio* in the context of dynamic spectrum access, also known as *cognitive radio* .

In general, cognitive radios refer to full communication system architectures that are able to sense the environment for primary (licensed) users and utilize available spectrum not currently being used [5]. In contrast to the previously mentioned techniques, cognitive radio takes advantage of the frequency and time aspects of the wireless environment. At any given location, time, and direction the frequency spectrum may not be fully utilized as shown in the inset figure in Fig. 1, where less than 6% occupancy is observed for a representative scenario [6]. Thus, enabling dynamic spectrum access offers many benefits to wireless systems, including the opportunity to combat fading and possibly improve channel capacity through wider bandwidths.

The required features of cognitive radio systems provide many unique challenges to antenna designers. Some of these challenges and requirements are detailed in [7]. The antenna requirements for cognitive radio systems can also depend upon the network architecture. Some possible network architectures can be seen in Fig. 1, where a base station infrastructure is depicted as well as an *ad hoc* network with no pre-existing infrastructure [6], [8]. In the architecture with infrastructure, base stations make up the backbone of the network, and often directive arrays are implemented for these systems to provide sectoral coverage. However, in *ad hoc* networks the backbone is made up of select terminals, and hence omnidirectional coverage is often desired. Previous work concerning antenna designs for these systems have often targeted scenarios requiring omnidirectional coverage and extremely wide bandwidth designs using UWB-class antennas as well as reconfigurable antennas [9]. Patch antennas form another class of antennas which have been widely used in many wireless applications such as laptops [10] and base stations, but the effort to investigate their use in cognitive radio systems has been limited, primarily due to their narrow bandwidth. However their bandwidth could be extended through novel patch topologies, such as the E-shaped patch, as well as frequency reconfigurability .In this paper, a novel frequency reconfigurable E-shaped patch antenna (FR-ESPA) design is presented as a new wide-band patch antenna for possible use in cognitive radio systems. **.** RF-MEMS switch circuit models are incorporated into the optimization as they more effectively and clearly represent actual MEMS switch effects.

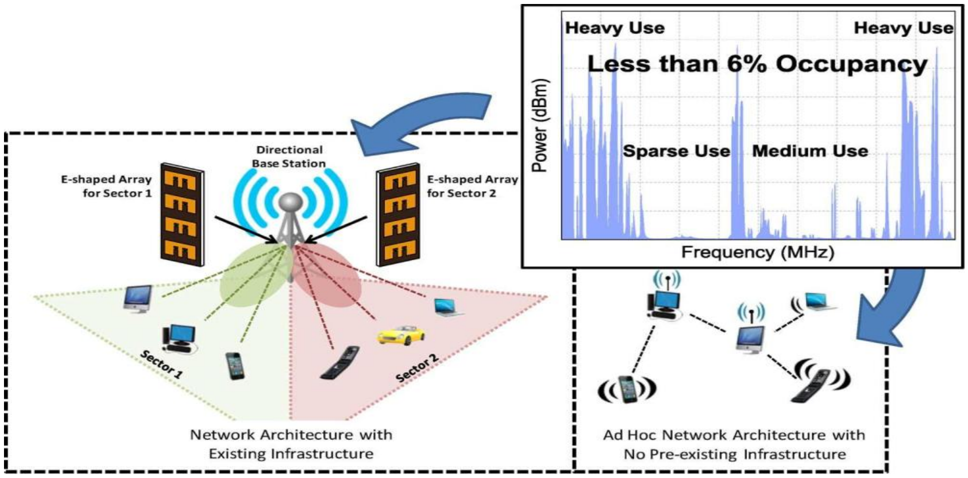

Fig. 1. Two potential network architectures in cognitive radio. The frequency reconfigurable E- shaped patch antenna proposed in this paper could be used as an array element for base station applications for future cognitive radio paradigms. Spectral plot in upper right is adapted from [6].

E-shaped patch design offers a simple single layer single feed structure which is straightforward to manufacture. It also can provide a wide instantaneous bandwidth in comparison to other tuned narrowband systems. To accomplish this, a methodology for the design and optimization of reconfigurable antennas with RF-MEMS switches for cognitive radio systems is presented. The design is analyzed through full-wave electromagnetic solvers, optimized through nature-inspired optimization techniques, and fully fabricated with RF-MEMS switches.

The paper is organized as follows. Section II discusses the frequency reconfigurable concept and introduces our newly proposed design. Section III discusses the application of Particle Swarm Optimization (PSO) [16], a nature inspired optimization technique, in conjunction with the full-wave electromagnetic solver, HFSS, for the design of a frequency reconfigurable E - shaped patch antenna design. The resulting design from the optimization is then fabricated using ideal switches and demonstrated through antenna measurements. Next, Section IV details the different switch models that can be used for modeling the switch (RF-MEMS switch) within HFSS to realize a design which can be implemented using RF-MEMS. Section V describes the final optimized E-shaped RF-MEMS reconfigurable antenna through optimizations, simulations, and measurements. Section VI provides the final design with RF-MEMS switches along with bias lines for switch activation. Both impedance matching and radiation pattern measurements are provided and some observations are made. Section VII provides some concluding remarks.

II. Frequency Reconfigurable E-Shaped Patch Antenna Concept

Some of the more popular techniques in literature for in-creasing the bandwidth of probe-fed patch antennas include the stacked patch [17], L-shaped probe-fed patch [18], U-slotted patch [19], and the E-shaped patch [20]. The E-shaped patch an-tenna is advantageous due to its single layer, single feed structure.

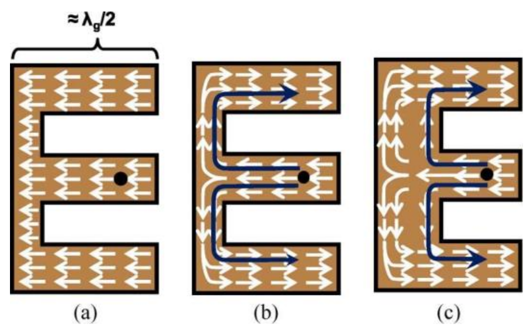

Fig. 2. Frequency reconfigurable E -shaped patch design concept. (a) Currents travelling along the patch length. (b) Currents travelling around the slots. (c) Effect on current by changing slot length.

In the past, the E -shaped patch antenna has been optimized for dual band and wideband de-signs; however, frequency reconfigurability was not incorporated [21]. In a recent conference paper, the authors briefly introduced frequency reconfigurability into the E-shaped patch antenna design [22], and this paper presents the comprehensive and complete study of the FR-ESPA using MEMS.

Typically, the E-shaped patch antenna has dual resonance due to the slots introduced into the patch topology [20]. These slots which create the E-shape allow another mode to resonate at a lower frequency relative to the typical patch mode. This is due to the currents resonating over a longer geometrical path as shown in Fig. 2(b). This mode has strong dependence on the slot geometry [Fig. 2(b)], while the normal patch mode depends primarily on the patch resonant length [Fig. 2(a)]. This patch changing the slot dimensions strongly controls the resonant modes of the E-shaped patch, and therefore they can be altered to provide a desired impedance matching performance. The slot length in Fig. 2(c) is shortened in comparison to Fig. 2(b), and consequently the current has a smaller distance to travel around the slots, giving rise to a higher resonant frequency. By implementing RF switches such as PIN diodes or MEMS, one

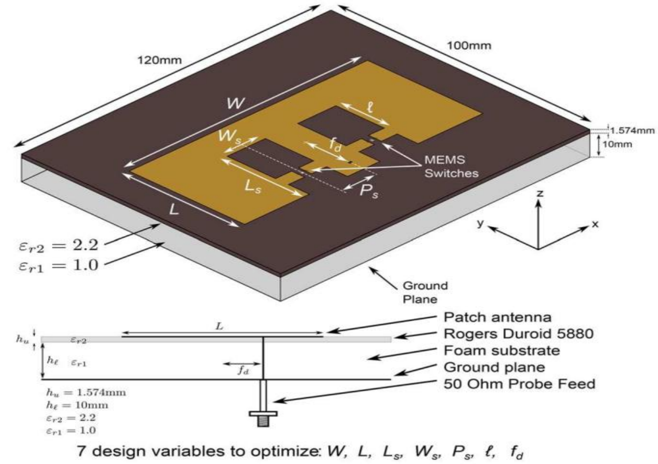

Fig. 3. Frequency reconfigurable E-shaped patch design schematic using RF switches with optimization parameters listed.

TABLE I
SUMMARY OF THE FREQUENCY RECONFIGURABLE E-SHAPED PATCH ANTENNA OPTIMIZATION (ALL DIMENSIONS IN mm)

Fixed parameters	$L_g = 100, W_g = 120,$ $t_1 = 10$, Substrate = foam, $\varepsilon_{r1} = 1$ $t_2 = 1.574$, Substrate = RT/Duroid 5880, $\varepsilon_{r2} = 2.2$
Optimization Parameters	$W, L, L_s, W_s, P_s, \ell, f_d$ (7-dimensional problem space)
Swarm Size	14
Max Iterations	500
Boundaries	$L \in (30,96), W \in (30,96), L_s \in (0,96),$ $W_s \in (0,48), P_s \in (0,48), \ell \in (0,96), f_d \in (-48,48)$
Constraints	$L - L_s > 5\text{mm}, P_s - \frac{W_s}{2} > 2.5\text{mm},$ $\frac{W}{2} - \left(P_s + \frac{W_s}{2}\right) > 5\text{mm}, \lvert f_d \rvert < \frac{L}{2}, L_s - \ell > 5\text{mm}$

can alter the dimensions of the slots. Ultimately, these resonant modes can be manipulated by turning the switches ON and OFF. Many switches can be incorporated in the slot for various resonant mode excitations but we use only two RF MEMS switches for basic proof of concept.

III. DESIGN IMPLEMENTATION USING PARTICLE SWARM OPTIMIZATION

In this section, the frequency reconfigurability concept is realized through the use of Particle Swarm Optimization. The schematic of the FR -ESPA is shown in Fig. 3. A multilayer de-sign was used with a Rogers RT Duroid 5880 substrate with $\varepsilon_r = 2.2$ and 1.574-mm thickness on top of a foam substrate with $\varepsilon \approx 1.0$ and 10-mm thickness. The duroid layer was employed to allow the antenna topology to be etched onto the substrate through photolithography, thus providing satisfactory fabrication accuracy. The foam substrate was used to increase the bandwidth and have an overall effective substrate permittivity close to 1.

In this case, there are seven variables whose values must be chosen. The complexity of the antenna design optimization problem increases drastically with higher parameter space dimensionalities, making this a difficult design problem to solve. Parametric studies for problems of this nature are complicated to quantitatively estimate the effect of each design parameter on the antenna performance. Therefore, the PSO technique was applied to this problem due to its robust convergence for problems that are multimodal, non-differentiable, discontinuous, nonlinear, non-convex, and highly dimensional. PSO is a global optimization technique and is also well known for its simple algorithm based on the social and cognitive mechanisms of bee swarms searching for food [16], [23]. More references on PSO and other nature-inspired optimization techniques can be found listed in [23].

In Fig. 3, L is the length of the patch, W is the width of the patch, L_s is the slot length, W_s is the slot width, P_s is the slot position, Fd is the position of the feed and ℓ is the position of the MEMS switch bars. Table I lists the fixed parameters, optimization parameters, swarm size, number of iterations, and the different boundaries and constraints used in this FR-ESPA implementation. The swarm size was chosen to be double the number of parameters to be optimized based on the implementation in [21]; however, a larger population can always be used. The constraints are formed in order to avoid designs which do not maintain the E -shape. The boundaries and the constraints define the solution space and feasible space and thus account for all the geometrical aspects of the optimization.Here, two simulations are needed to evaluate the given set of parameters. One simulation outputs the OFF state characteristics and the other one outputs the ON state features. For this antenna design problem, our main objective is to obtain good impedance matching $(S_{11} < -10\text{ dB})$ over two specified frequency bands. the fitness if the design parameter set $\vec{x}$ does not satisfy the constraint equations.

PSO was linked with High Frequency Structure Simulator (HFSS) in order to simulate the S_{11} performance, and the port data from HFSS was extracted and processed by the fitness function given in (1). Ideal switch models were used to represent the RF switches as a first-pass proof of concept and to reduce simulation and optimization time, as discussed in Section IV. In this model, we assume that the OFF state can be represented by a simple open circuit, while the ON state can be represented by a short circuit. The termination criterion utilized for our optimization runs was a maximum number of iterations, which was set to 500 iterations. The PSO-HFSS program convergence results showed that the average fitness approaches the global best value, which is typically a good indication that the optimization run has converged, and no significant improvements are to be expected. This can also indicate that the design is tolerable to possible design and fabrication errors if encountered. Ideal switch models were used to represent the RF switches as a first-pass proof of concept and to reduce simulation and optimization time.

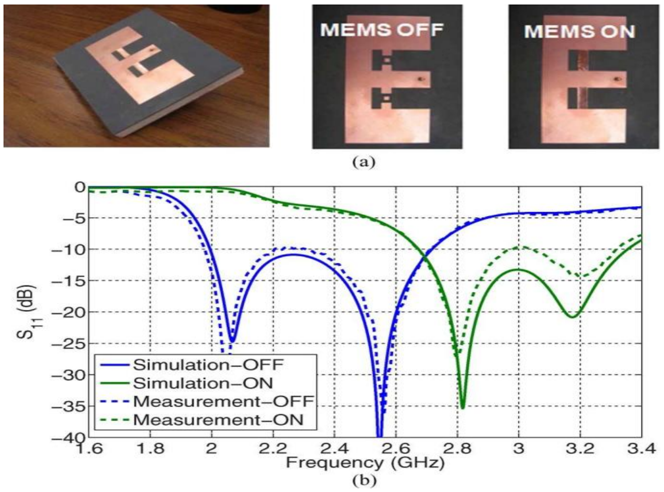

Fig. 4. (a) Prototype using ideal switch model. (b) Simulated and measured S_{11} performance of the prototype with ideal switches.

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IV. RF Switch Modeling

RF-MEMS switches are chosen as the switching elements for antenna reconfiguration due to their satisfactory RF prop-erties including low insertion loss, excellent linearity, good impedance matching, and high isolation [24]–[27]. In this paper, we used Radant MEMS *RMSW100HP* switches due to their availability and good switch performance. RF-MEMS switches were placed and wirebonded on the same fabricated prototype from the previous section in order to test the performance with these switches. Fig. 5 provides a comparison of the measured S_{11} results between the wirebonded MEMS measurement when the MEMS switches are not actuated (OFF state) and the ideal switch model. A ±90 V driver was connected to the switches, and the ON and OFF states were measured by applying 90 and 0 V.

TABLE II
Final Design Parameters for the Ideal Switch Case (All Dimensions in mm)

W	L	L_s	W_s	P_s	ℓ	f_d
92.5	44.1	31.3	14.9	13.6	4.18	16.9

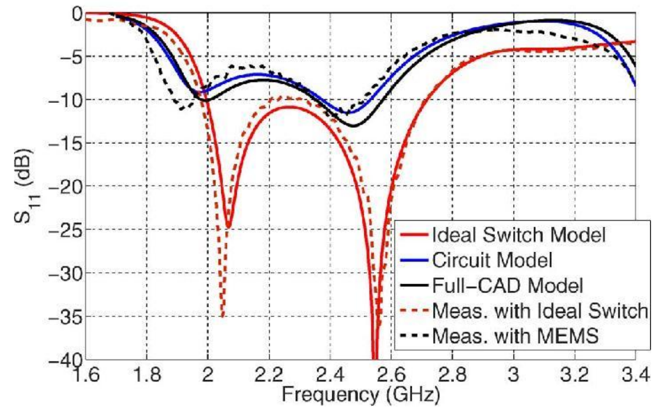

Fig. 5. FR-ESPA OFF state S_{11} response comparison between the simulated MEMS switch models and measurement with ideal switches [Fig. 4(a)] and measurement with wirebonded MEMS. Major differences can be observed be-tween the ideal switch (open circuit) and the wirebonded MEMS.

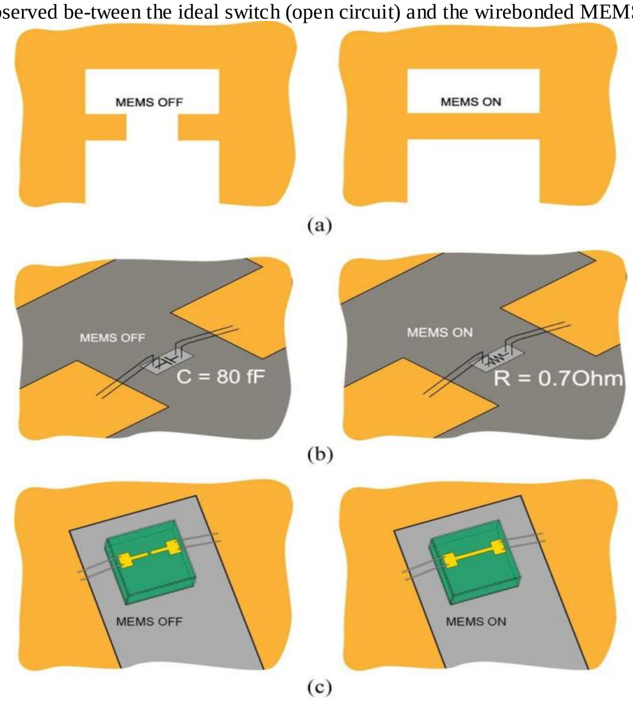

Fig. 6. Different switch models that can be used to implement RF-MEMS switches in simulations. (a) Ideal switch model. (b) Circuit model for the Radant RMSW100HP switch. (c) Full-CAD model for the Radant RMSW100HP switch.

This model implementation is shown in Fig. 6(a). Internal capacitances/reactances of these switches are not considered in this model and in most cases this model has the fastest simulation time.

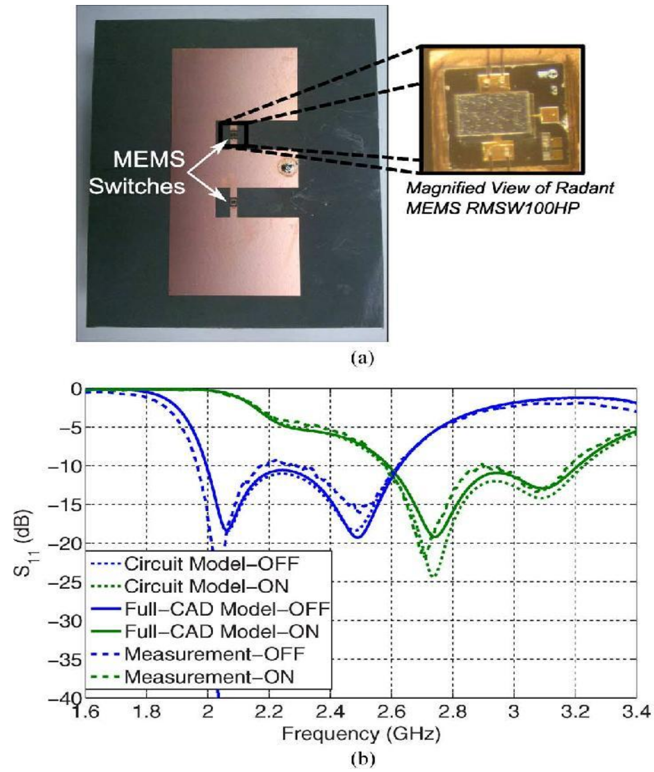

Fig. 7. (a) Fabricated final optimized FR-ESPA which incorporates MEMS switches as shown in the inset figure. (b) Comparison between the simulated circuit model, Full-CAD model, and measured antenna for the final optimized FR-ESPA.

TABLE IV
FINAL DESIGN PARAMETERS FOR THE MEMS SWITCH CASE (ALL DIMENSIONS IN mm)

W	L	L_s	W_s	P_s	ℓ	f_d
95.9	44.3	28.6	11.4	13.1	4.88	18.6

V. OPTIMIZED E-SHAPED PATCH ANTENNA WITH RF-MEMS SWITCHES

With the FR-ESPA concept proven through simulations and measurements of the optimized design with ideal switch models, the final step was the optimization of the E- shaped antenna using the circuit model. Thus, we incorporated the circuit model of the switch in the HFSS simulations, allowing us to proceed directly from optimization to implementation. The same optimization methodology was applied to this design to obtain a final optimized design with accurate switch properties incorporated.

Fig. 7(a) shows the fabricated final optimized prototype, where MEMS switches were used to test the antenna performance. This was done so that radiation patterns for both the states can be measured independently in the UCLA spherical near-field chamber. Fig. 7(b) shows the S_{11} comparison.

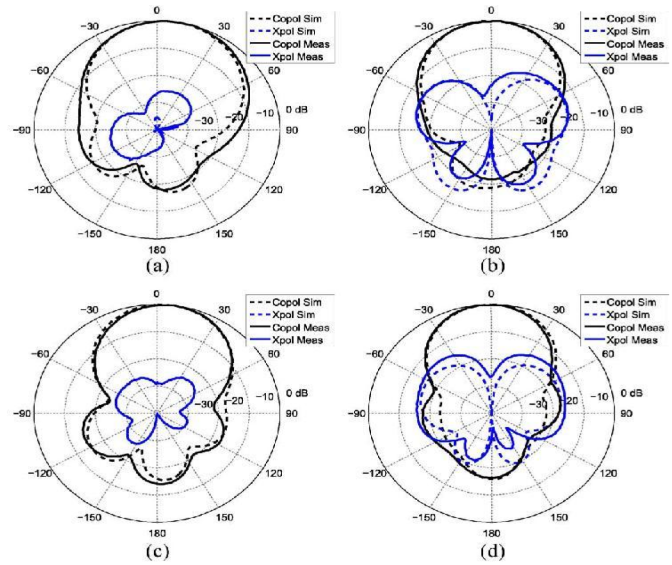

Fig. 8. Comparison between simulated and measured radiation patterns of the final optimized FR-ESPA for the OFF state. (a) E-plane—2.05 GHz. (b) H-plane—2.05 GHz.. (c) E-plane—2.55 GHz. (d) H-plane—2.55 GHz. The boresight directivity for 2.05 and 2.55 GHz are 8.89 and 10.46 dB, respectively.

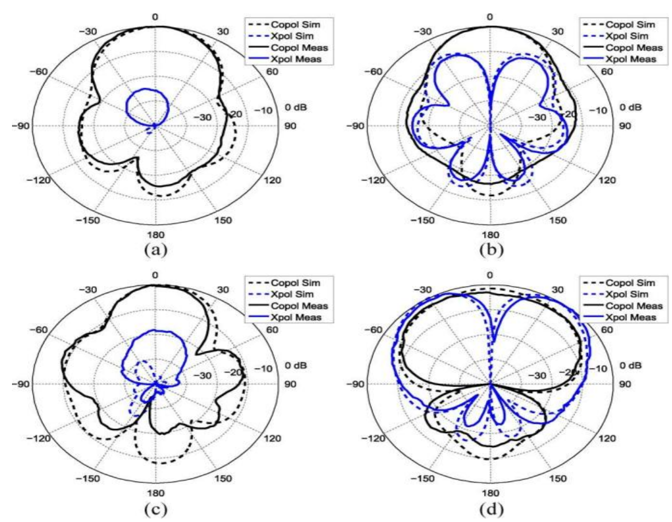

Fig. 9. Comparison between simulated and measured radiation patterns of the final optimized FR-ESPA for the ON state. (a) E-plane—2.8 GHz. (b) H-plane—2.8 GHz. (c) E-plane—3.1 GHz. (d) H-plane—3.1 GHz. The boresight directivity for 2.8 and 3.1 GHz are 7.79 and 5.17 dB, respectively.

The radiation patterns of all different states are given in Figs. 8 and 9 with the orientation of the E- shaped antenna provided in Fig. 3. Fig. 8(a) and (b) shows the E- and H-plane for the OFF state at 2.05 GHz. This frequency corresponds to the mode where the currents travel around the slots for the E-shaped patch. Cross - polarization is observed in the H-plane due to structural asymmetry created by the slots.

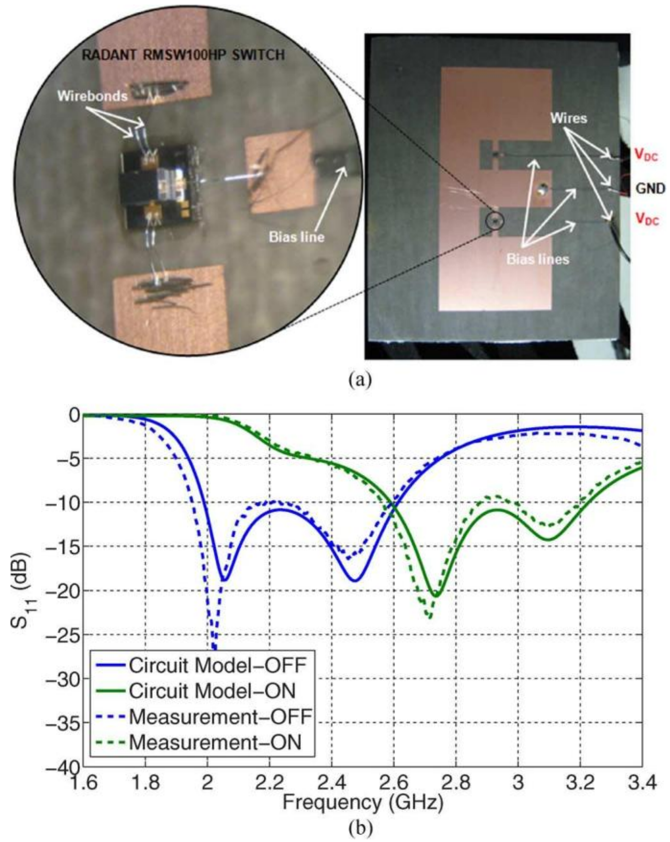

Fig. 10. (a) Final optimized FR-ESPA design with MEMS switches and bias lines. (b) Comparison of S_{11} between the simulated circuit model and measured antenna for the final optimized FR-ESPA including the bias lines.

VII. Conclusion

Cognitive radio is an emerging and promising technology that aims to provide freedom to wireless networks by taking ad-vantage of the unused spectrum. Reconfigurable antenna technology can help address many of the challenges for antenna de-signs for these systems. This paper demonstrates a novel wide-band E-shaped patch antenna with frequency reconfigurability. The proposed design can be used to progress the functionality of larger terminals or access points using patch antennas such as laptops or base station antennas the functionality of larger terminals or access points using patch antennas. This paper detailed the development, design, optimization, and implementation of this antenna. The concept of frequency reconfigurability for E-shaped patch antennas was proposed and the concept verified using PSO. An initial prototype using ideal switches validated the concept. . Different variations of MEMS switch models were presented, and the circuit model was chosen due to its simulation accuracy and rapid optimization time.

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VIII. Acknowledgement

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