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A Beam-Steering Reconfigurable Antenna for WLAN Applications

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Abstract—A multifunctional reconfigurable antenna (MRA) capable of operating in nine modes corresponding to nine steerable beam directions in the hemispheric space \([-30^\circ, 0^\circ, 30^\circ] ; \phi \in \{0^\circ, 45^\circ, 90^\circ, 135^\circ\}\) is presented. The MRA consists of an aperture-coupled driven patch antenna with a parasitic layer placed above it. The surface of the parasitic layer has a grid of $3 \times 3$ electrically-small square-shaped metallic pixels. The adjacent pixels are connected by PIN diode switches with ON/OFF status to change the geometry of the parasitic surface, which in turn changes the current distribution on the antenna, thus provides to change the geometry of the parasitic surface, which in turn changes the current distribution on the antenna, thus provides controllable reconfigurability in beam steering direction. The MRA operates in the IEEE 802.11 frequency band (2.4—2.5 GHz) in each mode of operation. The antenna has been fabricated and measured. The measured and simulated impedance and radiation pattern results agree well indicating an average of $\sim 6.5$ dB realized gain in all modes of operation. System level experimental performance evaluations have also been performed, where an MRA equipped WLAN platform was tested and characterized in typical indoor environments. The results confirm that the MRA equipped WLAN systems could achieve an average of 6 dB Signal to Noise Ratio (SNR) gain compared to legacy omnidirectional antenna equipped systems with minimal training overhead.

Index Terms—Beam-steering, reconfigurable antenna, full-wave analysis, signal to noise ratio.

I. INTRODUCTION

WIRELESS communication technology has grown rapidly in recent years. The IEEE 802.11 b/g standards operating in the 2.4 GHz band have been widely accepted and used in numerous wireless products such as routers, cell phones and laptops. However, for such systems to achieve the desired high data rate performance, relatively large Signal to Noise ratios (SNR) is required since some other electronic devices such as Bluetooth and microwave oven also operate in the 2.4 GHz band and present noise.

In this paper, a multifunctional reconfigurable antenna (MRA) is presented to provide improved performance in wireless systems. MRAs have gained a significant interest to achieve dynamically changeable antenna properties in frequency, radiation pattern and polarization, by modifying its architecture [1]–[6]. The performance improvements of multiple-input multiple-output (MIMO) systems equipped with reconfigurable antennas have extensively been studied in the literature [7]–[11]. In [7]–[10], reconfigurable dipole, leaky-wave, and spiral antennas were used as antenna elements in MIMO systems, and capacity improvement of these systems was confirmed. The reconfigurability of these antennas was achieved by integrating switches or varactors directly into the driven antenna. This integration approach is disadvantageous due to the conflicting design requirements of the driven antenna and the switching network (individual switches and control circuitry). In [11], a reconfigurable antenna that can steer its beam into three directions was proposed, where the switching network is separated from the driven antenna, but they are both located on the same layer. The reconfigurable antenna of this work, which is capable of steering its beam into nine directions, relies on a parasitic layer technique, where the driven antenna and the switching network are placed on different layers, thereby completely separated. This approach enables individually optimizing the designs of the driven antenna and the switching network, thereby providing enhanced reconfigurability. The presented MRA steers its beam into nine different directions corresponding to nine modes of operation by configuring the surface geometry of the parasitic layer, where $3 \times 3$ electrically small square-shaped metallic pixels (parasitic pixel surface) are connected by PIN diode switches with ON/OFF status. The nine beam steering directions are \(\{\theta \in \{-30^\circ, 0^\circ, 30^\circ\}; \phi \in \{0^\circ, 45^\circ, 90^\circ, 135^\circ\}\}\) operating in 802.11 b/g band. The PIN diode switches integrated in the proposed MRA are on the parasitic pixel surface of the parasitic layer, which is separated from the driven antenna layer. With the beam steering capability, leakage (interference) both from and to the node of interest can be minimized in unintended directions while the SNR can be maximized in the desired direction. Full-wave analyses by HFSS [12] and multiobjective genetic algorithm optimization [13]–[16] were jointly employed to determine the interconnecting PIN diode switches’ status (i.e., ON/OFF) corresponding to the targeted nine modes of operation.

The advantages of the MRA as compared to the antenna presented in [17] can be summarized as follows: 1) the beam steering capability is enhanced. The presented MRA can perform beam steering in nine directions in the semispheric space \(\{\theta \in \{-30^\circ, 0^\circ, 30^\circ\}; \phi \in \{0^\circ, 45^\circ, 90^\circ, 135^\circ\}\}\) instead of only five directions \(\{\theta \in \{-30^\circ, 0^\circ, 30^\circ\}; \phi \in \{0^\circ, 90^\circ\}\}\) in [17].
A. MRA Design and Component Models

Structure of the MRA: The top view photograph of the MRA is shown in Fig. 1(a). This MRA employs aperture-coupled feed mechanism for RF feeding similar to the MRA presented in [17]. The main two components of the MRA architecture are, namely, the driven patch antenna and parasitic layer as shown in Fig. 2. The driven patch (19.3 × 19.3 mm²) is designed to operate at in the frequency band of 2.4–2.5 GHz and is fed by a 50-Ohm microstrip line through an aperture (21.4 × 1.4 mm²) etched on the center of the common ground plane. The feed layer (90 × 90 × 0.508 mm³) and patch layer (90 × 90 × 3.048 mm³) are built respectively by using the substrate Rogers 4003C (ε_r = 3.55, tan δ = 0.0021) [18]. The same substrate (98 × 90 × 1.524 mm³) is used to form the parasitic layer above the driven patch. Notice that there is a 7.62 mm gap between the parasitic layer and driven patch antenna, where the gap is filled with the RO4003C. The reconfigurable parasitic surface, which consists of 3 × 3 square-shaped metallic pixels connected by PIN diode switches with ON/OFF status, is formed on the top surface of the parasitic layer with individual pixel size being 15 × 15 mm². Thus the geometry of the parasitic surface can be configured by switching ON/OFF the PIN diode switches. DC bias lines are also formed on the parasitic layer but on the backside of the substrate, where the backside of the whole parasitic layer can be seen in Fig. 1(b). Vias are plated through the parasitic layer so that DC bias lines can be connected to the PIN diode switches on the parasitic surface. Four different kinds of components are used on the parasitic layer as shown in the magnified sections of Figs. 1(a) and 1(b):

1) PIN diode switches are used in between all square-shaped pixels. Metallic pixels are connected/disconnected by switching ON/OFF the PIN diode switches to change the geometry of the parasitic surface, which in turn change the current distribution, and thus antenna characteristics.
2) DC block capacitors are used to properly bias the PIN diode switches as shown in Fig. 1. The SRF of DC block capacitor is around 2.5 GHz to provide low RF impedance in 802.11 b/g band. In this way, the effect of DC block capacitor on RF performance is minimized.
3) Inductors are also placed in between all pixels. In this manner, all the pixels can be DC grounded together to provide ground for DC biasing purpose. The SRF of these inductors was chosen to be the same value as RF chokes to keep the high RF impedance between pixels. Moreover, all the pixels can be DC grounded together to provide a ground for DC biasing purpose. The SRF of these inductors was chosen to be the same value as RF chokes to keep the high RF impedance between pixels.

II. ANTENNA STRUCTURE AND WORKING MECHANISM

A. MRA Design and Component Models

Working Mechanism

The working mechanism of an antenna system, which is composed of one driven antenna and multiple parasitic elements, can be described by the theory of reactively controlled directive arrays developed by R. F. Harrington [22]. It was shown that the main beam direction of the driven antenna can be directed into a desired direction by the proper reactive loading of the parasitic elements. In the presented MRA, the proper reactive loading corresponds to a specific geometry of the parasitic pixel surface, which is obtained by switching ON/OFF the PIN diode switches between adjacent pixels of this surface [23]. The presented MRA is aimed to steer its main beam in nine directions in the semisphere space \( \{ \theta \in \{-30^\circ, 0^\circ, 30^\circ\}; \phi \in \{0^\circ, 45^\circ, 90^\circ, 135^\circ\} \} \). Fig. 5 illustrates the planes in which the beam is steered, and the definitions of the beam-steering angles \( (\theta \text{ and } \phi) \).

C. Optimization Methodology

To find the optimum switch status for each of the 9 beam steering directions, multiobjective genetic algorithm (GA) is utilized [23]. The multiobjective GA is different from...
the single-objective GA in the sense that it has more than one aim which may conflict with each other and should be evaluated simultaneously. There are 3 objectives/aims need to be satisfied, namely: a) one of the beam directions of

\[
\begin{align*}
\text{obj}_1 &= \text{Gain} (f_0, \theta, \phi) \quad \text{Gain} \geq 6 \text{ dB} \\
\text{obj}_2 &= \text{BW} (\omega_{11}, -10 \text{ dB}) \quad \text{BW} \geq 4\% \\
\text{obj}_3 &= \text{AR} (f_0, \theta, \phi) \quad \text{AR} \geq 10 \text{ dB}
\end{align*}
\]
where $f_0$ is the center frequency of the 802.11 b/g band as 2.45 GHz, $\theta$ and $\phi$ describe the desired beam steering direction. $|S_{11}|$ represents the magnitude of reflection coefficient, and $AR$ is the axial ratio for polarization. These three criteria are applied simultaneously in multiobjective genetic algorithm, and in conjunction with full-wave EM analysis to find the optimized switch configurations resulting in each of the 9 beam steering directions. Note that corresponding to beam directions of $\theta \in \{-30^\circ, 0^\circ, 30^\circ\}; \phi \in \{0^\circ, 45^\circ, 90^\circ, 135^\circ\}$, 9 optimization problems are defined. The further details of the multiobjective algorithm are omitted here and can be found in [23].

III. ANTENNA MEASUREMENTS VS. SIMULATIONS

To validate the theoretical analysis and simulated results of the MRA, a prototype was fabricated and measured. The switch configurations for all nine desired modes are shown in Table II, where S1–S12 represent the 12 PIN diode switches used in the design as shown in Fig. 1 (0 indicates that the switch is OFF, 1 indicates that the switch is ON). The MRA prototype was designed to operate in the 802.11 b/g frequency band (2.4–2.5 GHz). The reflection coefficients and radiation patterns in terms of realized gain have been measured for all the modes. Figs. 6(a) and 6(b) show the simulated and measured reflection coefficients for the modes on $\phi = 0^\circ$ plane with $\theta = 0^\circ$, $-30^\circ$ and $30^\circ$. It can be seen that the common bandwidth covers IEEE 802.11 b/g frequency band. Fig. 7 shows good agreement between simulated and measured realized gain patterns for these three modes indicating that the maximum realized gain of the MRA is $\sim 6.5$ dB in each mode. Note that only copolarization components are plotted in the patterns since cross-polarization components are less than $-10$ dB and thus are not shown. Simulated and measured reflection coefficients and realized gain patterns for other modes on the planes $\{\phi \in \{45^\circ, 90^\circ, 135^\circ\}\}$ are shown in Figs. 8, 9, and 10, respectively. It can be seen that there is also good agreement between simulation and measurement for these modes.

IV. SYSTEM LEVEL TESTS AND CHARACTERIZATIONS

In this section, to confirm the advantages of the MRA, the system-level experimental analysis and performance characterization of MRA-based WLAN systems is presented.

A. Experimental Setup

An MRA-based WLAN system is constructed using the Universal Software Radio Peripheral (USRP) software defined radio (SDR) platform [24]. Each USRP contains a Radio Frequency (RF) transceiver and a Field Programmable Gate Array (FPGA). All USRPs are connected to a host PC through a Gigabit Ethernet connection. The baseband signal processing is performed over the host PC. The baseband signals are streamed to/from the USRPs at a rate of 25 M sample/sec. The RF
transceivers are then used for real time signal transmission and reception. All experiments are performed in the IEEE 802.11 b/g band at 2.5 GHz carrier frequency with a 10 MHz signal bandwidth.

As shown in Fig. 11, the system consists of two nodes (node A and node B) communicating to each other. Each node is equipped with one antenna. In this work, one of the two nodes is equipped with an omni-directional antenna, while the other node is equipped with a MRA (node A is equipped with omni-directional antenna, while node B is equipped with MRA). The MRA antenna has a total of nine different radiation patterns \( \{ \theta \in \{-30^\circ, 0^\circ, 30^\circ\}; \phi \in \{0^\circ, 45^\circ, 90^\circ, 135^\circ\} \} \). The pattern selection is performed through a 12-line digital control cable driven from an FPGA on a Zedboard [25]. The timing of all USRPs and the FPGA that drives the antenna switches are aligned with one reference Pulse Per Second (PPS) signal. Another system architecture where both nodes are equipped with omni-directional antennas is used for comparison purposes.

B. Experimental Framework

Fig. 12 shows the transmission frame structure used for performance characterization. The transmission frame consists of two main intervals: 1) training interval, and 2) data transmission interval. The training interval consists of 9 training segments used for MRA pattern training. The MRA radiation pattern is changed at the segment edge such that, each training segment corresponds to one of the 9 MRA radiation patterns. At the end of the training interval, the received signal power for each pattern is calculated, and the pattern that maximizes the received signal power is selected.

During the data transmission interval, useful data transmission takes place. The data transmission interval consists of several data frames that have the same frame structure as in the IEEE 802.11g systems [26]. Each data frame consists of 125 Orthogonal Frequency Division Multiplexing (OFDM) symbols with 64 subcarriers per OFDM symbol.

C. Experimental Environment

The experimental analysis is conducted in the Wireless Systems and Circuits Laboratory (WSCL) within Engineering Hall at the University of California, Irvine. Fig. 13 shows a floor plan for the area where the experiments are performed, and present a typical laboratory environment with measurement workstations, tables, metallic surfaces, etc. The outer walls of the building are either concrete walls or glass walls with steel pillars, while the inner walls are dry walls with steel pillars.

To enrich the experimental analysis, the two communicating nodes are placed at different positions inside and outside the laboratory to create a variety of Line Of Sight (LOS) and non-LOS
environments (the different circle and square dots are the different positions that node B and node A are placed in during the experiments). In addition, different MRA orientations are tested such that the two communicating nodes are facing each other, opposite to each other, or side to side (the black arrows going out from node B represent different directions where the MRA antenna is pointing at during the experiments).

D. Experimental Results

In this analysis, the performance of the MRA-based IEEE 802.11g system is evaluated and compared to that of the legacy omni-directional antenna based system. For comparison purposes, three different performance metrics are used: 1) The effective SNR, 2) the achievable rate, and 3) the average un-coded Bit Error Rate (BER). The SNR is defined as the ratio between the received signal power and the total system noise power. One way to calculate the effective SNR in experimental analysis is by calculating the Error Vector Magnitude (EVM) defined as the distance between the received symbols after equalization and the original transmitted symbols. Using the EVM to SNR conversion method in [27], the SNR is calculated as $\text{SNR} = 1/\text{EVM}^2$, where EVM is the average EVM. The achievable rate is defined as the maximum data rate that the wireless system could achieve at certain SNR. The average achievable rate is calculated in terms of the SNR as:

$$R = \frac{1}{N \cdot M} \sum_{n=1}^{N} \sum_{m=1}^{M} \log_2 \left( 1 + \text{SNR}_{n,m} \right),$$

where $N, M$ are the total number of data frames and OFDM symbols per frame respectively.

First, we characterize the performance gain achieved using MRA in different experimental environments. Fig. 14 shows...
the SNR gain achieved using MRA compared to the omni-directional antenna at different antenna orientations. The results show that the worst SNR gain is achieved when the back of the MRA antenna is facing the other node. In this scenario, a significant part of the signal power is received through the MRA back-loops. Although the opposite orientation has the worst performance, the MRA antenna still achieves better performance than the omni-directional antenna (~1 dB better SNR), mainly due to the signal reflections. On the other hand, the face-to-face orientation shows the best performance, where the MRA could achieve ~10 dB better performance than omni-directional antenna. The reason is that in face-to-face orientation, most of the signal power is received through the main loops of the MRA. The side-to-side orientation is in the middle between other orientations.

In typical scenarios, the system will be exposed to all different orientations over time. Accordingly, calculating the average performance gives an indication of how MRA performs compared to omni-directional antenna on the average sense. In the following analysis, the performance is averaged over several experiments with different orientations and node positions.

Unlike omni-directional antenna systems, MRA-based systems require pattern training, which negatively impacts the overall system capacity. Therefore, for fair comparison, the MRA training overhead should be considered. In this analysis, the achievable rate of both MRA-based and omni-directional antenna based systems is evaluated. The MRA training overhead is set to ~0.5% (i.e., MRA training interval/data transmission interval = 0.005). Fig. 16 shows the achievable rate at different transmit power values when MRA training
overhead is considered. The results show that, even after training overhead is considered, MRA-based systems could achieve ~2 bits/sec/Hz more data rate compared to legacy omni-directional antenna systems.

The overall performance is also characterized for different modulation schemes. Fig. 17 shows the average BER for both MRA-based and omni-directional antenna based systems. The results show that using MRA achieves ~5 – 6 dB SNR gain compared to omni-directional antenna based systems, which confirms the results shown in Fig. 15.

V. Conclusion

This paper presented a full model of a multifunctional reconfigurable antenna (MRA) with the main goal of enhancing the spectral efficiency of existing and future wireless networks. The presented MRA is capable of steering its main beam in nine directions \( \{ \theta \in \{-30^\circ, 90^\circ\}; \phi \in \{0^\circ, 45^\circ, 90^\circ, 135^\circ\} \} \) by reconfiguring the geometry of the parasitic pixel surface. This surface consists of a grid of 3 x 3 electrically small square-shaped metallic pixels, and the geometry of this surface is altered by switching ON/OFF the interconnecting PIN diode switches placed between adjacent metallic pixels. To validate the theoretical analyses and simulations, a prototype of MRA operating in the IEEE 802.11 b/g frequency band has been fabricated and measured. The good agreement between measured and simulated results confirmed the accuracy of the theoretical results. The average realized gain values of the MRA prototype are ~6.5 dB in all modes of operation over the 2.4–2.5 GHz frequency band. The MRA was also implemented in a practical system setting, where the system level experimental performance of an MRA equipped WLAN platform was tested and characterized in typical indoor environments. The results showed that the MRA equipped WLAN systems could achieve an average of 6 dB Signal to Noise Ratio (SNR) gain compared to legacy omni-directional antenna equipped systems with minimal training overhead.

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REFERENCES


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Dr. Eltawil has been on the technical program committees and steering committees for numerous workshops, symposia and conferences in the area of VLSI, and communication system design. He received several distinguished awards, including the NSF CAREER award in 2010 supporting his research in low power wireless systems.