Development of a novel optimization algorithm for a microstrip patch antenna array

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ABSTRACT

Microstrip patch antennas are typically used because they have a low profile and cost. The main theme of this study is to present a novel 2×2 microstrip antenna array design using rough set theory. In designing the 2×2 microstrip antenna array, an FR4 dielectric substrate was used to improve the performance. The rough set theory was used to optimize the microstrip antenna parameters. The FR4 dielectric substrate compared better to the microstrip patch antenna array wherein no substrate was used. The antenna with no substrate used had the energy that is radiating underneath which contributed to the sidelobes of the radiation pattern whereas the use of the substrate reduced the energy radiated at the substrate. Furthermore, the gains of the two were also simultaneously evaluated and it showed that the microstrip antenna array with the dielectric substrate had better gain than the one without. This 2×2 microstrip array antenna design may be used for applications such as mobile communications since it is small in size and performs well.

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1. INTRODUCTION

Antennas are electrical devices capable of converting electric power to electromagnetic waves and back [1], [2]. In a wireless system, antennas are usually required to optimize or accentuate the receiving or transmitting energy in some directions and suppress in others [3]. With this, an antenna is considered to be a directional device, aside from being a probing device. It has different parts or forms to comply with a particular need. Antennas are essential in a wireless communication system since signals are either transmitted or received using these [4], [5]. Due to this, antennas have continuously advanced and improved throughout the years. Different types of antennas have been designed and developed for different applications like the monopole antenna, dipole antenna, and yagi-uda antenna [6]. These designs have adapted to different needs as well as improved the performance of each [7].

One of the applications where antennas are widely used is communications [8]. Humans utilize antennas every day through different technologies such as televisions, computers, and especially smartphones [9], [10]. Because of this, various researchers have studied more on antennas focusing on 5G [11], long term evolution (LTE) or 4G [12], universal mobile telecommunications system (UMTS) or 3G [13], global system for mobile communication (GSM) or 2G [14] for improvements of the general performance of each antenna. The overall performance of an antenna is measured through different parameters such as its frequency, radiation pattern, gain, bandwidth, and directivity [15]. These specifications must be met to conclude that the designed antenna can be used for its specific purpose.

For cellular mobile applications, microstrip patch antennas are typically used since they are small in size and can be printed on a circuit board. This type of antenna costs less has a lower profile, and is easier to fabricate. In constructing a microstrip patch antenna, a conductive metal patch that serves as the transmission line is installed at a level above the dielectric material or the substrate in the middle [16]. The dielectric material generates waves when it undergoes reflections during antenna excitation [17]. Low power then radiates at the edges of the metal. The usual shape of a microstrip antenna is a square or a rectangle since these shapes are easier to fabricate and use. Microstrip antennas are known for their small size and low radiation. Additional advantages include easier fabrication and a simple process for integrating integrated circuits. In addition, they exhibit implicit resonant performance and good bandwidth performance. Despite its size, the microstrip patch antenna’s radiation pattern is large in one direction [18]. In addition, the directivity of this antenna is small and to increase the directivity, an array is created using multiple antennas. Other applications of the microstrip patch antennas include aircraft and spacecraft implementations [19].

Mobile communications are dependent on the antennas present in each device for transmitting and receiving signals which contain information. One of the commonly used antennas for this field is the microstrip patch antenna. Because of its use for mobile communications, the microstrip patch antenna has been further developed [20]. In addition, the use of the microstrip patch antenna costs less, has a lower profile, and is easier to fabricate in comparison with other antennas. However, the performance of this antenna is limited because it has a low capacity handling, a narrow bandwidth, and a low gain compared with other antennas available [21]. This research intends to simulate a 2×2 microstrip patch antenna array using MATLAB [22].

This paper provides a novel design that may be used in phones. One reason is mobile communications are continually developing. This research provides a method for designing a 2×2 microstrip patch antenna array using MATLAB. The design is optimized with the use of rough set theory. The results of this research target to show information about how the antenna is made and an in-depth analysis of the overall performance of the design. This research also provides a thorough comparison between using a substrate and not using a substrate in a microstrip patch antenna. This research may be used as a reference for future studies and development in the area of antenna design. Furthermore, this study provides an in-depth comparison between the use of a dielectric material and the absence of it which may be utilized for another research.

The development, design, improvement, and implementation of microstrip antennas have been tackled in numerous studies. One study presents the design of a microstrip antenna array with a W-band [23]. Here, the microstrip antenna array is composed of 8×8 patches which are fed by a microstrip line. The presented design has been tested and the results based on the measurements of its bandwidth and gain show that it performs well. In one study, a wideband linear microstrip antenna was discussed [24]. The proposed antenna is series fed and its performance was measured and showed that the design has a high efficiency. The microstrip array antenna was tested without a feeding network in a study [25].

Various works and studies on microstrip array antennas for 5G applications have been conducted. In one paper, a 2×2 microstrip antenna array for 5G implementation was designed [26]. The proposed design utilized foam for its substrate. The performance of the proposed antenna was better in comparison to existing works. Another study on using microstrip antennas for 5G technology designed a 1×4 microstrip antenna array [27]. The design presented used rogers RT for its substrate and the simulations were done through computer simulation technology (CST) studio. In line with 5G applications using microstrip antennas, one study proposed an ultra-wideband design [28]. This paper focuses on a technique called proximity coupling which enhances the performance of the antenna bandwidth. The result of the performance of the proposed design was better than that of existing designs and this could be utilized for 5G applications. More on 5G applications, a study presented a microstrip antenna with four elements fed using the corporate-series technique [29]. This was then compared to the same antenna but with series-fed and corporate-fed instead of both. The results showed that the use of corporate-series fed networks worked better than the others. In improving the design of a microstrip antenna, the use of circular polarization was presented [30]. This approach addressed the circularly polarized major lobe through the spacing of the elements in the antenna array. In another paper, the bandwidth of a microstrip array antenna was improved. Here, the use of a reactive screen was presented for enhancing the bandwidth of the antenna [31].

A 2×2 patch antenna can be constructed with the FR4 substrate [32], [33]. It can represent an important component of prevalent wireless communication systems [34], [35]. This type of antenna is compact and versatile. Its antenna design can offer many advantages like having a small form factor, ease of fabrication, and an omnidirectional radiation pattern. The FR4 substrate has a dielectric constant that is moderate and cost-effective [36], [37]. It is also reliable in several applications patch sensors, IoT applications, and monopole systems [38]–[40]. This type of system can also be used in wireless LAN technology [41].

The rough set theory is a mathematical tool that is powerful and is used to deal with uncertainty and data imprecision [42]. This theory has found a significant application in microstrip antennas. These antennas are widely used in modern wireless communications and often encounter complexities because of the geometric variations and environmental factors of the system. Rough set theory can be leveraged to improve performance prediction and design optimization of the antenna [43]. The rough set theory can discern the essential attributes in the datasets even in the presence of incomplete information [44]. This theory can empower antenna designers to make the correct decisions to enhance the effectiveness of the microstrip antenna with the use of computer systems [45].

2. METHODS

This section composes of three parts, it focuses on how the proposed method is designed. The first sub-section focuses on the theoretical concept of antenna design. The second sub-section is focused on the process of antenna design. The third subsection discusses antenna testing.

2.1. Theoretical consideration

There are many different types of antennas used for different purposes. Fundamentally, array antennas are compound antennas which means they are constructed by using multiple different antennas working together as one singular antenna. By collectively using the power of several antennas, combining them resulted in a more capable and efficient antenna than by using them separately. The combination of several antennas makes it so that the antenna can achieve a high gain, high directivity, better efficiency, and overall performance. Array antennas are mostly used for radar systems, satellite communications, and long-distance wireless communications. The complex nature of these antennas presents apparent imperfections like high operational and maintenance costs, and a large open space is required to deploy one of these antennas. However, there are antenna arrays that can be implemented onto PCBs. These antennas offer the same benefits as their bigger counterparts albeit at a smaller scale. These antennas are useful for mobile applications since they are low power and small in size, but they can be implemented on bigger arrays which are also used in large aircraft. When designing an antenna array, one must consider the number of elements to be used, the spacing between those elements, the amplitude and phase of the elements, the beam width, and directivity.

2.2. Antenna design

The antenna designed and simulated is a rectangular 2×2 microstrip patch antenna array with FR4 used as the dielectric substrate with dimensions of 60×60 mm, a thickness of 0.000299792458 m, and a relative permittivity of 4.8. Each microstrip element has dimensions of 0.01439 m in length, 0.018737 m wide, a height of 0.0.00029979 m, and row and column spacings of 0.019951 m. The antenna will operate at a resonant frequency of 10 GHz. Figure 1 shows the 2×2 microstrip antenna array simulated in MATLAB and Figure 2 shows the antenna array element layout.

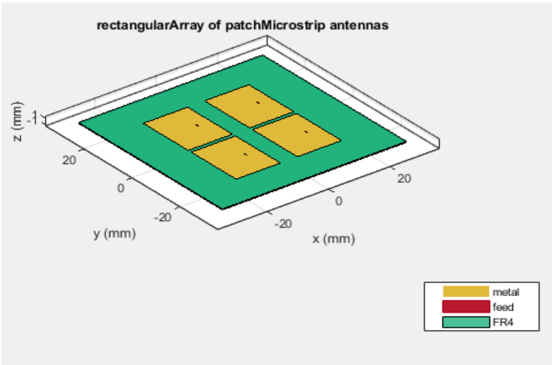

Figure 1. The 2×2 microstrip antenna array simulated in MATLAB

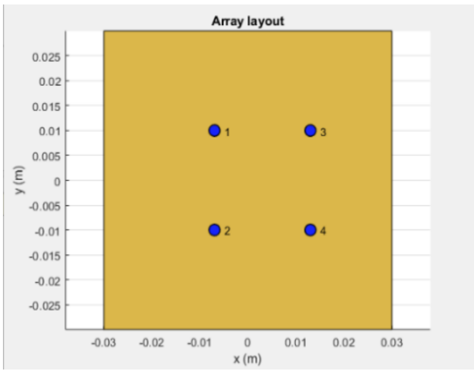

Figure 2. Antenna array element layout

The 2×2 microstrip antenna array was designed and then simulated using MATLAB. The toolbox used was the antenna array toolbox. To optimize the parameters using rough set theory, the rough set data explorer (ROSE) optimization toolbox will be used [46]. The antenna can be optimized on factors such as maximizing gain, minimizing the area of the system, and minimizing bandwidth. For this study, the authors opted not to optimize the antenna because the optimization model takes a long time to make adjustments.

After all, it needs to make use of many iterations which translate to values ≥100 to gain tangible and noticeable results, and also to leave room for future improvements. The antenna analysis includes the plotting of the 3D radiation pattern, H-plane and E-plane plots, the impedance of the antenna, and the scattering parameters. There were two main designs compared in this study, an antenna array without a substrate material used; while the other used FR4. Figure 3 shows the screenshot of the ROSE optimization toolbox.

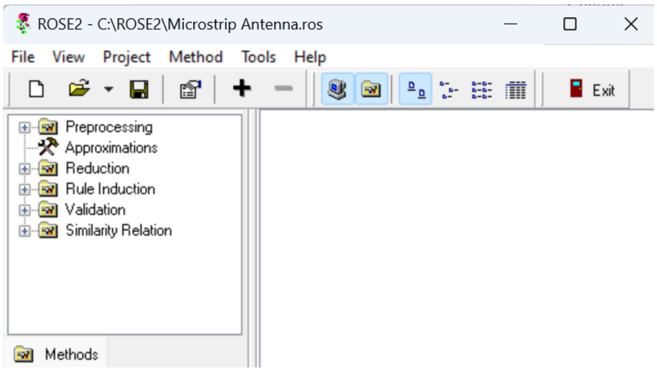

Figure 3. Screenshot of the ROSE optimization toolbox

2.3. Antenna testing

The 2×2 microstrip antenna array will then be tested. The antenna geometry will be defined. After defining the geometry, the simulation domain will be chosen. A 3D pattern will be chosen for the antenna radiation pattern. The azimuth plane and the elevation plane will then be simulated. After the simulation, the 3D radiation pattern with the FR4 will be tested. The next test will be the 3D radiation pattern with the FR4. The S-parameters of the antenna will then be simulated. Figure 4 shows the testing flowchart of the antenna.

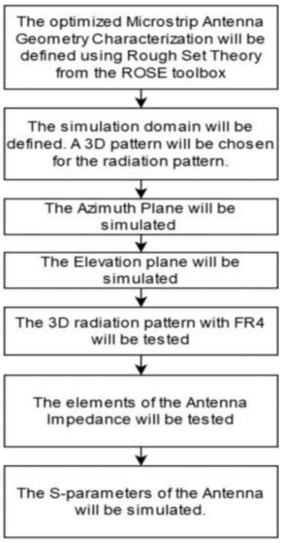

Figure 4. Testing flowchart of the antenna

3. RESULTS AND DISCUSSION

3.1. Data presentation

This section shows the data from the MATLAB Simulation of the optimized antenna outputted in the ROSE optimization toolbox. The first part of the simulation is for the antenna without the substrate. Figure 5 shows the 3D radiation pattern without a substrate. Figure 6 shows the azimuth plane pattern without a substrate. Figure 7 shows the elevation plane pattern without a substrate.

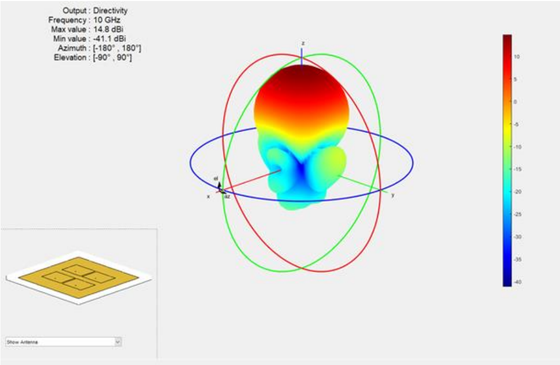

Figure 5. 3D radiation pattern without a substrate

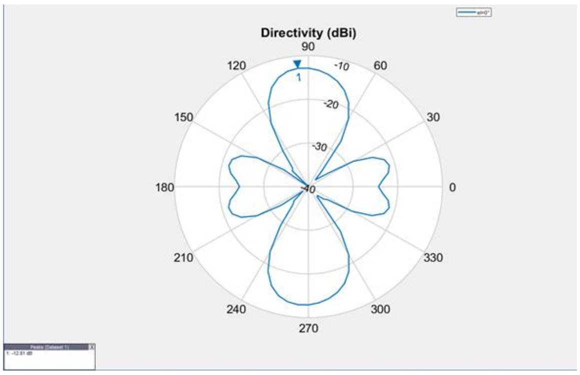

Figure 6. Azimuth plane pattern without a substrate

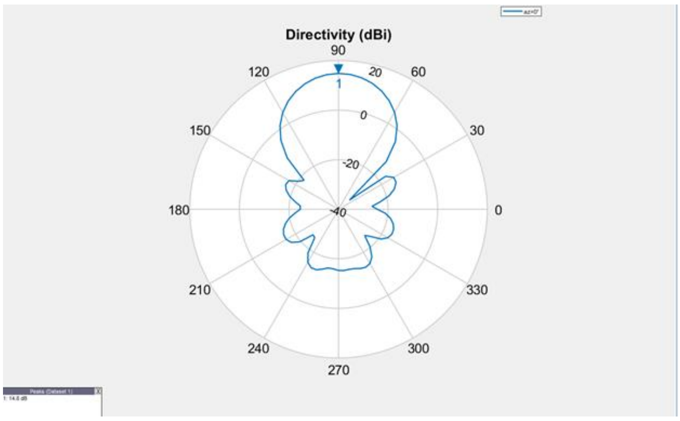

Figure 7. Elevation plane pattern without a substrate

In the second part of the simulation, an FR4 material was added to the system. This is to serve as the dielectric substrate to which the conductive elements of an antenna can be placed. It can also serve as a good electrical isolation of a multilayer PCB which can allow improve antenna structures. Figure 8 shows the 3D radiation pattern with FR4, Figure 9 shows the azimuth plane pattern with FR4, and Figure 10 shows the elevation plane pattern with FR4.

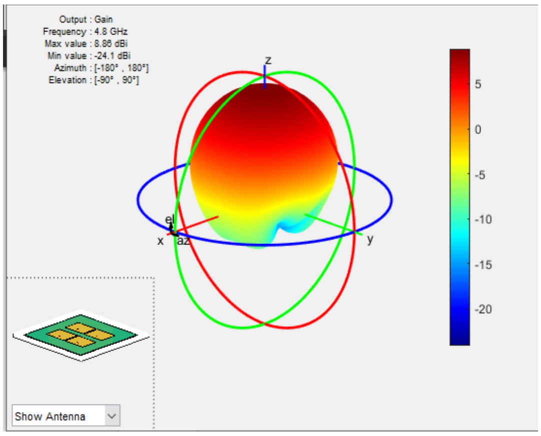

Figure 8. 3D radiation pattern with FR4

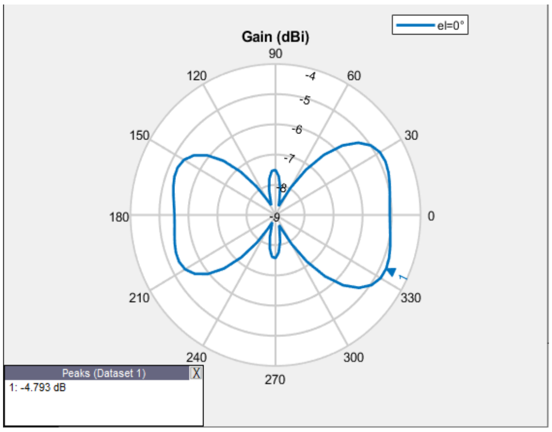

Figure 9. Azimuth plane pattern with FR4

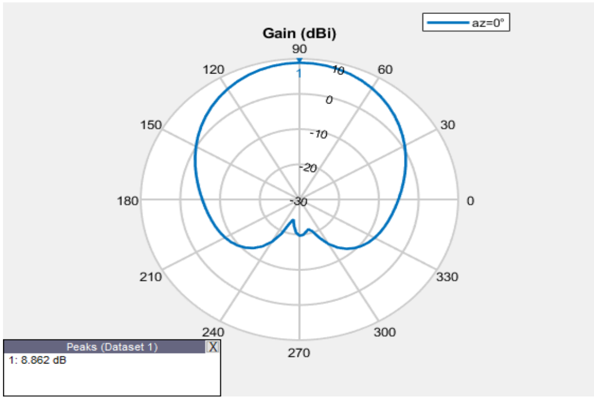

Figure 10. Elevation plane pattern with FR4

The third part of the simulation is to show the impedance of the antenna. The MATLAB antenna toolbox was used in the simulation. Figure 11 shows the antenna impedance of antenna elements 1 and 2, Figure 12 shows the antenna impedance of antenna elements 3 and 4 and Figure 13 shows the S parameters of the antenna.

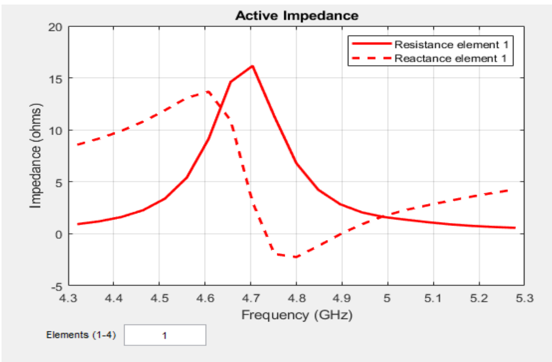

Figure 11. Antenna impedance of antenna elements 1 and 2

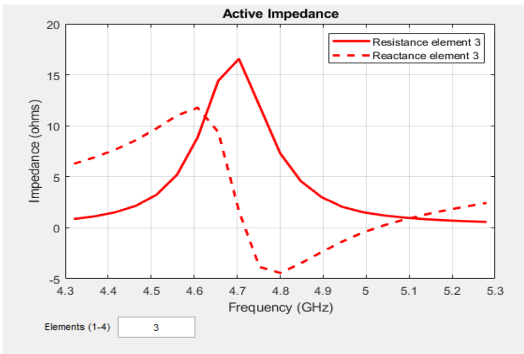

Figure 12. Antenna impedance of antenna elements 3 and 4

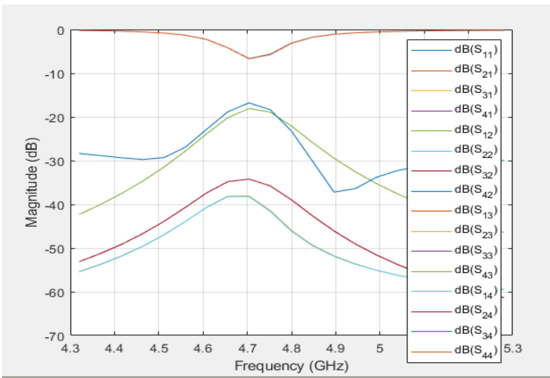

Figure 13. S parameters of the antenna

3.2. Analysis of data

Initially, the antenna was designed without a substrate. However, after the simulations, the researchers found that this is not optimal. As can be seen from Figures 5-7, the radiation pattern from the antenna array without a substrate showed that the antenna was radiating energy underneath it. Furthermore, there were more prominent side lobes which indicate sub-optimal efficiency. To remedy this problem, the authors used FR4 as the dielectric substrate. FR4 was the first choice since it is the most popularly used, low-cost, and durable. Which could make the manufacturing of the antenna array easier.

After introducing FR4 as the substrate, the performance of the antenna notably improved; this can be seen in Figures 8-10. The radiation pattern of the antenna is similar except for the fact that the max gain went down to 8.8 dBi from 14.8 dBi and the side lobes were almost eliminated. Because of this, the antenna is not wasting energy by radiating in unnecessary places. From Figure 10 it can be seen that the beamwidth of the antenna is 10 dBi this went down from approximately 15 dBi when the antenna was designed without a substrate. Figures 11 and 12 show the impedance of the antenna elements which vary depending on the frequency; something to note is that antenna elements 1 and 2 have the same impedances, as do antennas 3 and 4. Lastly, Figure 13 shows the scattering parameters of the antenna. From this graph, the various gains of the system are plotted.

4. CONCLUSION

The main goal of this study is to design and simulate a 2×2 microstrip patch antenna array. This has been successfully done using MATLAB. The design of the antenna was first simulated without a substrate and then with a substrate. The results of the simulation showed that the use of the FR4 substrate improved the general performance of the microstrip patch array antenna compared with the other. The presented design of the antenna with the FR4 substrate had a max gain of 8.8 dBi and a beamwidth of 10 dBi which shows that it is effective in reducing path loss. After careful analysis of the results, it can be concluded that the designed 2×2 microstrip patch antenna array performs well and can be used for other applications. Since this paper merely tackles the simulation of the proposed antenna, it is recommended that a hardware implementation should be visited to get a more accurate picture of how the antenna performs in real-world applications. Furthermore, as previously mentioned the antenna still has room for further improvement because it was not optimized properly due to the limitations that the researchers encountered with time and hardware limitations. Additionally, since adding the FR4 as the substrate gave a pretty noticeable improvement in the radiation pattern of the antenna array; future research could use other dielectric materials as the substrate and compare them to each other. Moreover, many other antennas can be implemented in small PCBs like the log periodic, antipodal, and non-array patch microstrip antennas. A comparison among the antennas and substrate materials types should merit an interesting discussion. An analysis of the comparison would be beneficial since it could show which antenna and substrate material combination would be the most practical.

After going through the process of designing and simulating the 2×2 antenna array the researchers recommend that the simulation be done on a decent high-end workstation PC because the frequency sweep calculation for 21 frequency points ended up taking 2 hours to complete. It is recommended that a PC with at least 32 GB of RAM and a CPU with at least 6 cores is used for the design and simulation of antenna arrays to reduce processing time and reduce any possible errors that might occur. In addition to that, the optimization of the antenna array would also be feasible thanks to the additional processing power from the extra CPU cores since it will drastically reduce the model optimization time and even enable the optimization algorithm to go through more iterations.

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