An end-fire low profile patch antenna to work on WiMAX frequencies used for harvesting power supply

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ABSTRACT

In this paper, an end-fire microstrip patch antenna (MPA) is proposed of 3 GHz as a center frequency, designed, simulated, and measured to work on WiMAX frequencies within standard of 802.16e (WiMAX). A high gain ranged between (12.117-13.324) dB, high front to back ratio (F/B) of (35.770) at the center frequency, a wide band of 1.701 GHz, low profile, and semi-ideal voltage standing wave ratio (VSWR) of 1.053 is achieved. The simulation is done using computer simulation technology (CST-MW). The proposed design is based on two Fire-retardant substrates (FR-4) of relative permittivity (ε) 4.3+j0.025 and 1.53 mm thickness for each one, which is considered a high loss material. The measurement results show good agreement with the simulated results. In addition, the design can be used for harvesting power supply from mobile towers. Finally, the proposed design is compared with two other designs in terms of power conversion efficiency and overall size.

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1. INTRODUCTION

The microstrip patch antenna (MPA) suffered from two well-known disadvantages, which are low gain and narrow bandwidth, although in many applications, a wide range and high gain MPA is required. MPA has very good specifications, such as low cost, easy to fabricate, and small surface area [1]-[4]. That is the reason behind many researchers are working to design their antennas considering the MPA technique and using different materials as well as different methods and designs to gain optimum parameters, which are required for their applications. New technologies such as using screen printing of conductive paint and using sticky copper film [5]-[7] as well as finding new designs that can affect the gain and the bandwidth of the MPA [8]. The complicated relationships between different parameters of MPA make the control on MPA parameters very sophisticated and it is very hard to get high gain and wideband at the same time [9]. A high gain antenna and good matching impedance are important goals for many applications. A multi-layer antenna is used to get an 11.5 dB Gain of an MPA for wireless application [10], and X band applications [11] and [12]. The significant end-fire specification is the direction of the propagation, which is laying in X or Y direction rather than Z direction, and that will be a great advantage to increase the gain of the design. The end-fire antenna has a great advantage, such as high directivity, low side-lobe, and high front-to-back ratio (F/R). Scientists have used many designs to get the end-fire specifications, such as Yagi antenna and antipodal antenna, which are the most well-known designs for the end-fire antenna. Moreover, due to the simplicity of using the microstrip technique, most researchers try to use the MPA technique to achieve this
goal. One of the most widely used designs for getting an end-fire antenna is the use of an antenna array [13]-[16]. Others used bow-tie design to achieve end-fire antenna [17]. Zhang and Huang in [18] and Gajibo et al. [19], a design of a tree antenna with a dish reflector is used for end-fire antenna while a design derived from Yagi Uda antenna is proposed in [20]. other authors used reflectors to increase the F/B ratio and gain [21] and [22]. In this work, an end-fire antenna is used as a frequency receiver to collect the power transmitted from mobile towers. The proposed design overcomes polarization-independent cross-dipole design in [23] in terms of overall size and conversion efficiency and dual polarized metasurface design proposed in [24] in term of overall size.

2. ANTENNA DESIGN

From theoretical analyses of conventional MPA, the design is proposed. The theoretical equations are so limited due to limited number of variables. Moreover, they are based on two familiar designs, which are square patch and circular patch antenna. Therefor, for any arbitrary shape design, a simulator should be used. There are many reasons to use simulator program such as extra number of variables, method of solution, which depends on finite element method (FEM), the flexibility of presenting the output results, and the great agreement with measurement results. CST-MW allows optimizing the design to get the best results by sweeping some effective parameters through theoretical equations, these changes can make the design more reliable before implementation. The design dimensions are shown in Figure 1 and Figure 2 shows the antenna design.

![Figure 1. Dimensions of MPA in mm](image)

![Figure 2. These figures are, (a) MPA face, (b) MPA ground layer](image)
The MPA is based on double stacked layers of FR-4 as a substrate, which is high lossy material of epsilon (4.43+j 0.025). These double layers will increase the bandwidth of the resonance frequency. The total volume of the proposed antenna is (70 х50 х 3.132) mm³ as L x W x H and the length of four fork shape is approximately equal to λ/4 where λ is the free space wavelength of 3 GHz. Table 1 illustrated the parameters of the proposed design.

| Parameter                      | Value       | Unit     |
|--------------------------------|-------------|----------|
| Center frequency               | 3           | GHz      |
| Conductive material            | Copper      |          |
| Conductive thickness           | 0.035       | mm       |
| 1st layer of the substrate     | FR-4        |          |
| 2nd layer of the substrate     | FR-4        |          |
| Substrate thickness            | 1.53        | mm       |
| Distance between substrates    | zero        | mm       |
| Single substrate thickness     | 1.53        | mm       |
| Substrate permittivity (ε)     | 4.3 + j 0.025 |        |
| Connector                      | SMA         | 50 Ω     |

### Table 2. Parameters of the frequency responses in the range (0-10) GHz

| Parameter                      | Value       | Unit     |
|--------------------------------|-------------|----------|
| Center frequency               | 3.01        | GHz      |
| Bandwidth                      | 1.719       | GHz      |
| Bandwidth frequency starts from| 2.387       | GHz      |
| Bandwidth frequency ends to    | 4.106       | GHz      |
| Substrate length               | 70          | mm       |
| Substrate width                | 50          | mm       |
| $S_{11}$ at center frequency   | -30.979     | dB       |
| Directivity at the center frequency | 12.3    | dBi      |
| Gain at the center frequency   | 12.2        | dB       |
| Average gain at the bandwidth  | 12.13       | dB       |
| VSWR                           | 1.058       |          |
| Single side lobe               | -14.2       | dB       |
| Average F/B                    | 31.368      | dB       |
| Linear radiation efficiency    | 0.965       |          |
| Main lobe direction            | 141         | deg.     |
| Average front to back ratio    | 37.868      | dB       |
| Total thickness of the antenna | 3.13        | mm       |

### 3. RESULTS AND ANALYSIS

#### 3.1. Simulation results

In this work, a computer simulation technology (CST-MW) is used to simulate the proposed design. The design started from four fork shapes of 25 mm long, which is equal to λ/4. Then, by considering the effecting of the square shapes, their surface areas, and their distribution on the FR-4 layer, the design is proposed. Finally, the shape of the antenna’s design is finalized by optimizing the desired parameters. A wideband frequency with a center of 3 GHz is achieved.

The simulation results show that the design is an end-fire antenna which indicates that the gain of MPA can reach a high value depending on the design’s shape itself even though a high lossy material is used such as FR-4, and this is one of the main challenges in this design. Wideband which is equal to 0.566 of center frequency achieved using a double-stacked layer of a lossy FR-4 layer [25]. This wideband covers the bands 1, 2, 3, 4, and 5 of 802.16e (WiMAX) [26]. Moreover, the F/B is equal to 35.77 dB at the center frequency which indicates a very good result without using any kind of reflector.

The simulation results achieve the parameters which are designed for harvesting power supply from WiMAX frequencies bands 1, 2, 3, 4, and 5. Moreover, the design can be used as a point-to-point WiMAX transmitter-receiver. Furthermore, the total thickness of the proposed antenna indicates that the design is low profile. The frequency response through the range (0-10) GHz and other parameters of the proposed design are listed in Table 2. In Figure 3, it can be seen that the End-fire far-field direction of the proposed antenna increases the gain of MPA in the direction of X. The E-field and H-field are shown in Figure 4 and the F/B ratio is shown in Figure 5.
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(Anwer Sabah Mekki)
Table 3. Fabricated parameters of the proposed design

| Parameter                        | Fabricated values | Unit |
|----------------------------------|-------------------|------|
| Center frequency                 | 2.97              | GHz  |
| Bandwidth                        | 1.45              | GHz  |
| Bandwidth frequency starts from  | 2.65              | GHz  |
| Bandwidth frequency ends to      | 4.1               | GHz  |
| Substrate length                 | 70                | mm   |
| Substrate width                   | 50                | mm   |
| $S_{11}$ at center frequency     | -28.9             | dB   |
| Gain at the center frequency     | 11.1              | dB   |
| Average gain                     | 11.6              | dB   |

Figure 7. Simulated vs measured $S_{11}$ of the proposed antenna

4. HARVESTING CIRCUIT

The antenna is designed for harvesting power supply from WiMAX frequencies scattered in the air. By using the specifications of the end-fire antenna, the efficiency of harvesting can be increased. Many methods used to harvest the energy from radio frequency (RF) signal [27]-[30], and the schematic diagram is shown in Figure 8.

Figure 8. The Schematic diagram of harvesting power supply from RF energy

Many rectifier designs were implemented and used in this field [31], each one has its specifications and topology. In this paper, the Greinacher charge pump was used as shown in Figure 9, where $R_L=90\,\text{k} \Omega$ and $C_L=10\,\text{pF}$. The software used for harvesting is NI circuit design suite (multisim).

Figure 9. Greinacher charge pump
The efficiency which is the most important parameter can be calculated from (1), where $P_{dc}$ is the output power and $P_{in}$ is the input power, is being as:

$$\eta = \frac{P_{dc}}{P_{in}}$$

From simulation the input power is 0.5 W and the average output power is 0.41 W within the bandwidth. This means that the efficiency is equal to 0.82. Table 4 listed a comparison between this work and two other works. From Table 4, for the same center frequency, it can be seen that the proposed design overcomes the polarization-independent cross-dipole design proposed in [23] in terms of overall size as well as conversion efficiency. Moreover, the proposed antenna has a smaller overall size than the dual polarized metasurface design proposed in [24]. It is important to note that the proposed design covers a wider range of frequency than the two works as shown in Table 4.

| Reference | Dielectric Constant | Frequency | Size | Conversion Efficiency |
|-----------|---------------------|-----------|------|-----------------------|
| [23]      | 2.2                 | 3 GHz     | 140 x 140 x 4.37 | 74 % |
| [24]      | 2.2                 | 3 GHz     | 70 x 70 x 3.175  | 90 % |
| This work | 4.3                 | 3.01 GHz  | 70 x 50 x 3.13   | 82 % |

The contribution of this paper is the use of an End-fire antenna design for harvesting power supply from RF. This will lead to convert electromagnetic wave into electric wave with high efficiency using small size of antenna due to the use of patch antenna technique without using any type of reflector layer. Moreover, it is important to note that the proposed design covers a wider range of frequencies than the two references in the comparison.

5. CONCLUSION
The End-fire antenna is an appropriate and active design for power harvesting applications, especially for good directivity which allows the antenna to harvest more power than other antenna designs. The proposed design is fabricated and measured. The measurement results show good agreements with the simulated results in terms of matching impedance, gain, center frequency, and bandwidth. Moreover, the proposed design has reduced the overall size by 87.2% and increased the conversion efficiency by 8% as compared with the polarization-independent cross-dipole design. Furthermore, the proposed design has reduced the overall size by 29.58% while decreasing the conversion efficiency by 8% as compared with the dual polarized metasurface design.

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