Electronically Steered MIMO Patch Antenna with Conformal Feeding for 5G Applications

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October 21, 2021 / Published online: 21 January 2022
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Abstract
Multiple input multiple output antenna is the key technology which enables the design of 5G networks. In order to achieve desired beam forming and side lobe reduction capabilities, antennas used in MIMO technology are required to feed with signals having different phase and amplitude. It is possible to achieve variable phase shift and variable attenuation using phase shifter and amplitude limiters. However, when these devices are used between source and antenna, they make the system non-planner and non-conformal. This research presents a 16 element, multiple user MIMO Patch antenna with conformal and planner power divider network to achieve electronically steered beam along with the desired side lobe level reduction. Wilkinson power divider is used to achieve conformal and planner power divider for MIMO antenna. Desired beam forming capabilities are achieved by controlling the phase of input signal to antennas by controlling the length of microstrip line, and desired side lobe reduction capabilities are achieved by controlling the amplitude of input signal to antenna by controlling the width of microstrip line used in Wilkinson power divider. This provides an overall planner and conformal structure. In this research same antenna is used to generate two major beams by controlling the phase and amplitude of input signal. The designed structure is simulated and analyzed using HFSS. Simulated results for the designed MIMO antenna are verified by analyzing the fabricating structure using vector network analyzer and horn antenna. The novelty in this research is to design power divider, phase shifter and amplitude limiter in single unit.

Keywords Multiple input and multiple output antenna (MIMO) · Wilkinson power divider (WPD) · Patch antenna · Microstrip line

1 Introduction

The evolution of wireless technology is continuously influencing the every sphere of life. Initially wireless technology was emerged to communicate between two devices separated by large distance. However the scope of wireless technology is improving continuously.
with the improvement in data rate and Channel capacity. Based on data rate and Channel capacity world had witnessed four generations of wireless technology. Now world had entered into fifth generation of wireless technology where date rate up to 20 GBPS, Channel bandwidth of 500 MHz and latency time less than one millisecond is achievable. This could make possible due to use of millimeter waves in 5G technology [1–7]. Using 5G technology it is possible to connect and control various real time devices [8–11]. This is attracting the interest of many academicians and industrialist in research and development of 5G technology. The key requirement to implement 5G technology are antennas having, very high gain, electronically beam steering capabilities, able to operate in millimeter wave dimensions and having conformal structure. These requirements can be achieved through a great extent by using multiple input and multiple output technology (MIMO). In MIMO system multiple antennas are used in transmitter and receiver. As many antennas are used in MIMO technology so gain is significantly improved. Further by changing the phase of input signals direction of major lobe can be steered electronically. The additional advantage of MIMO system is to have high energy efficiency and low latency time [12–14]. In MIMO system we use orthogonal frequency division multiplexing in which multiple symbols are transmitted at the same time for relatively longer period of time. The transmitted symbol occupies very narrow bandwidth as compared to available spectrum which results in a very high channel capacity. Digital signal processing techniques can be used to reconstruct the original signal from received symbols. Receiving the received symbol for a longer time makes possible for the receiver to recover the transmitted symbol even with the noise interference. MIMO systems can be classified as single user MIMO or multiple user MIMO. In single user MIMO all the transmitted symbols by the transmitter are received by only single user while in multiple user MIMO transmitted symbols by the transmitter are received by many users. Single user MIMO has the advantages to improve the data rate within available spectrum while multiple user MIMO has the advantage of improving the channel capacity [15–17]. Various radiating elements like monopole, dipole, yagi-uda, Horn or Dish can be used as radiating elements in MIMO system However due to planar and conformal design and further due to ease of performance enhancement techniques, antennas designed using microstrip technology are most favored for MIMO system [18–29]. Several antenna designs are proposed in literature for MIMO system [30–33]. All these designs are suffering from one serious problem of using non planer and non-conformal feeding structure [34–36]. Misran et al. [37] in their research proposed a conformal feeding network using WPD along with separate phase shifters and attenuator to achieve beam steering capabilities. They were able to achieve side lobe reduction by 20 dB by feeding antenna elements according to Tchebychef polynomial coefficients. Mahdi Haghzadeh et al. [38] proposed a BST/Polymer based Left hand transmission line phase shifter for beam steering. This phase shifter needs additional DC bias circuit to control the phase of phase shifter. They reported maximum gain of 30 dB for 1 × 4 antenna array. Mao et al. [39] proposed a massive MIMO antenna of 2 × 2 subarray. Each subarray consist of 4 × 4 Patch antenna. Each element is fed by a conformal power divider circuit and separate phase shifter in order to achieve beam steering. They demonstrated a beam steering angel of ±26° and gain of 18 dBi. Wang et al. [40] proposed a conformal MIMO antenna and used Taylor distribution in order to reduce side lobe level. They demonstrated the reduction of first side lobe by 16 dB from main beam. Mustafar et al. [41] proposed a beam steered MIMO antenna using pins as switches. By properly adjusting the location of pins the main beam of antenna can be obtained at nine locations.

This research proposed a conformal electronically steered MIMO Patch antenna along with conformal feeding for 5 G applications. Antenna structure is designed by 16 element
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Probe fed patch antenna powered by Wilkinson power divider. Two main beams are obtained at different locations by adjusting the phase difference of excitation signal fed to different antenna elements. One main beam is obtained by adjusting the phase difference between excitation signals by $+45^\circ$ and another main beam is obtained by adjusting the phase difference between excitation signal by $-45^\circ$. Required phase difference of $+45^\circ$ and $-45^\circ$ between excitation signal is achieved by adjusting the length of microstrip line in WPD. Required amplitude level of excitation signals as per Tchebychef polynomial coefficients is achieved by adjusting the width of microstrip line in WPD. The proposed MIMO antenna can be potentially used in Radar base stations.

2 MIMO Conformal Antenna Design

Various prototypes are required to be designed for MIMO conformal antenna. The first part includes the design of radiating element. Second part includes designing the array of radiating elements. Array elements are required to be fed in particular fashion in terms of amplitude and phase. So third part includes the design of power dividing circuit for the antenna array. This section elaborates the complete design process adopted in this work.

2.1 Design of Radiating Element

In this research probe fed patch antenna is selected as radiating element for MIMO antenna design. Probe fed patch antenna is selected owing to its enormous advantages like planer and conformal structure, ease of fabrication, low cost, various technologies available to enhance the performance parameters of antenna and further due to its easiness of feeding while using antenna array. A coaxial connecter is connected between ground and patch to feed the patch antenna. The first step in designing patch antenna is to choose the dielectric constant and dimensions of substrate. The dielectric constant of patch antenna varies from 2.2 to 12. For large bandwidth and higher efficiency requirements patch antenna with thick substrate and low dielectric constant are preferred. However they suffer from high dielectric loss. Miniaturization of patch antenna can be obtained using thin substrate having high dielectric constant. However they possess low efficiency and smaller bandwidth. The patchon substrate is the radiating element which is concerned with radiations. Operative frequency of patch is decided by the length of patch antenna, Dielectric constant of substrate, and height of substrate. The width of patch antenna dictates the efficiency of antenna. The optimized length and width of patch antenna as proposed in [19–30] is given by

\[
w = \frac{C}{2f \sqrt{\frac{\varepsilon_{\text{eff}} + 1}{2}}}
\]

Here \( C \) is the velocity of light and \( \varepsilon_{\text{eff}} \) is the effective permittivity of the substrate which is given by expression

\[
\varepsilon_{\text{eff}} = \frac{\varepsilon + 1}{2} + \frac{\varepsilon - 1}{2} \sqrt{1 + 12 \frac{h}{w}}
\]

Here \( \varepsilon \) is the dielectric constant of substrate and \( h \) is the thickness of the substrate.

The patch length is given by the expression

\[
w = \frac{C}{2f \sqrt{\frac{\varepsilon_{\text{eff}} + 1}{2}}}
\]
In this design parameters of Patch antenna are (Table 1).

### 2.2 Design of Patch Array

Superior characteristics in terms of directive gain, side lobe reduction and beam steering capabilities can be achieved using array of antennas. Antenna elements can be feed in series manner or in corporate manner. In series feed manner each antenna element is feed by its preceding element however in corporate feed antenna elements are feed by many transmission lines. It is possible to control the phase and amplitude of exciting signal in corporate feed antenna precisely as compared to series feed antennas. So improved beam forming and side lobe reduction can be achieved by using corporate feed antenna. Various synthesis Methods are proposed in literature to design antenna array [19–30].

The radiation pattern of antenna array can be calculated by multiplying the radiation pattern of single element and antenna array factor.

For N element antenna array in one dimension array factor is given by

\[
AF(\theta) = \sum_{n=1}^{N} I_n e^{i\alpha} e^{(ikd\cos\theta)}
\]

Here antenna elements are separated by distance d. \(I_n\) is the magnitude of feeding current to various elements. \(\alpha\) Is the progressive phase shift between antenna elements. The point of observation makes angle \(\theta\) with array axis and \(k\) is phase shift constant.

Enhanced beam steering and side lobe reduction can be achieved by arranging antenna elements in two dimensional arrays. When antenna elements are arranged in two dimensional structure then array factor is given by

\[
AF(\theta, \phi) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} I_{mn} e^{i\alpha_{mn}} e^{(ik \bar{r}_{mn})}
\]

\(I_{mn}\) is the magnitude of feeding current of \(mn\)th element.
\(\bar{r}_{mn}\) is the location of \(mn\)th element.

\[
\bar{r}_{mn} = x_{mn}\hat{x} + y_{mn}\hat{y} + z_{mn}\hat{z}
\]

| Table 1  | Patch antenna parameters |
|----------|--------------------------|
| **Patch material** | **Perfect electric conductor** |
| Patch length | 12.45 mm |
| Patch width | 16 mm |
| Patch thickness | 0.05 mm |
| Material of substrate | Rogers RT/duroid 5880 (tm) |
| Dielectric constant of substrate | 2.2 |
| Substrate height | 0.794 mm |
| Operative frequency | 7.55 GHz |
\[ \hat{r} = \sin \theta \cos \phi \hat{x} + \sin \theta \sin \phi \hat{y} + \cos \theta \hat{z} \]

\( \alpha_{\text{e}} \) is the excitation phase difference between elements.

Tapering of antenna arrays is used to achieve the desired side lobe rejection level. Tapering of antenna arrays is achieved by controlling the magnitude of excitation currents to antenna elements.

A 4\( \times \)4 array of patch antenna elements arranged as shown in Fig. 1 is used to design electronically steered MIMO antenna. Separation between elements is kept as \( \lambda/2 \). Excitation phase difference between elements is kept at 45° and \(-45°\) to obtain two major lobes positions. Elements are fed as per Tchebychev polynomial to obtain side lobe reduction.

### 2.3 Power Dividing Circuit

Power dividing circuit is needed to feed antenna elements with required phase and amplitude of current. It is the phase and excitation amplitude of current to the antenna elements which is responsible for desired beam forming and side lobe reduction. Wilkinson power divider is extensively used as a power divider in monolithic microwave devices [42–45]. Structure of Wilkinson power divider is as shown in Fig. 2.

Each section of Wilkinson power divider is designed using microstrip line. Section A of WPD is connected with source of microwave signal. Section A is a microstrip line having characteristics impedance of 50 \( \Omega \). Section B and Section C is a microstrip line having characteristics impedance of 70 \( \Omega \). Section D is a lumped resistance of 100 \( \Omega \). Length of microstrip

![Fig. 1 Patch antenna array](image-url)
line E and F is adjusted to obtain the required excitation phase difference between signals so as to feed patch elements.

The phase shift introduced by microstrip line depends on the length and effective permeability of substrate.

The optimized expression for phase shift introduced by microstrip line is given as

$$\Delta \varphi = \sqrt{\frac{2\pi f L_M}{C_o}}$$  \hspace{1cm} (6)

Here $f$ is the operative frequency, $L_M$ is length of microstrip line and $C_o$ is velocity of light.

Required amplitude coefficient of excitation current to patch antenna is obtained by adjusting the Voltage Standing Wave Ratio (VSWR) between WPD and Patch element.

The expression of VSWR between WPD and Patch element is given by

$$\text{VSWR} = \frac{I_{\text{reflected}}}{I_{\text{input}}} = \frac{Z_{\text{Patch}} - Z_C}{Z_{\text{Patch}} + Z_C}$$  \hspace{1cm} (7)

Here $Z_{\text{Patch}}$ is the input impedance of patch antenna and $Z_C$ is the characteristics impedance of line feeding the antenna. From the expression it is evident that If characteristics impedance of Patch antenna is same as that of microstrip line then maximum power will be delivered from microstrip line to patch antenna. Mismatching of impedance of microstrip line with patch antenna is used to obtain the required amplitude coefficient of excitation current to patch antenna.

Characteristics impedance of microstrip line depends on the width ($w$) of microstrip line, height ($h$) and relative permeability $\varepsilon_r$ of substrate [46–50].

The optimized expressions of Characteristics impedance of transmission line is given as

For $\frac{w}{h} \leq 1$

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ \left( 1 + 12 \left( \frac{h}{w} \right) \right)^{-\frac{1}{2}} + 0.004 \left( 1 - \left( \frac{w}{h} \right) \right)^2 \right]$$  \hspace{1cm} (8)
In this work two WPD are designed to feed signals to MIMO antenna elements. One is used to achieve a phase shift of 0° and 45° at output ports w.r.t. input port and another is used to achieve a phase shift of 90° and 135° at output ports w.r.t. input port. The width of microstrip line is varied to obtain desired Tchebychef polynomial coefficient of excitation current.

\[ Z_C = \frac{60}{\sqrt{\varepsilon_{re}}} \ln \left( 8 \frac{h}{w} + 0.25 \frac{w}{h} \right) \]  

(9)

For \( \frac{W}{h} \geq 1 \)

\[ \varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \left( \frac{h}{w} \right) \right] \]  

(10)

\[ Z_C = \frac{120\pi}{\sqrt{\varepsilon_{re}}} \times \left[ \frac{w}{h} + 1.39 + \frac{2}{3} \ln \left( \frac{w}{h} + 1.44 \right) \right] \]  

(11)

In this work two WPD are designed to feed signals to MIMO antenna elements. One is used to achieve a phase shift of 0° and 45° at output ports w.r.t. input port and another is used to achieve a phase shift of 90° and 135° at output ports w.r.t. input port. The width of microstrip line is varied to obtain desired Tchebychev polynomial coefficient of excitation current.

### 3 Results and Discussion

Several prototypes of MIMO antenna are designed and analyzed using HFSS. Fabricated prototypes of MIMO antenna using Rogers RT/duroid substrate are analyzed using VNA. Fabricated MIMO antenna along with WPD and VNA are shown in Fig. 3. In this work 8

![Fig. 3 Fabricated MIMO antenna along with WPD and VNA](image-url)
Wilkinson Power Dividers are used to feed 16 antenna elements. The schematic diagram of connections among VNA, WPD and MIMO antenna are shown in Fig. 4.

The designed patch antenna resonates at 7.5 GHz. The simulated and measured results of return loss $S_{11}$ are plotted in Fig. 5. Simulated and measured return loss at 7.5 GHz is read to be $-16$ dB and $-21$ dB respectively.

Simulated maximum directive gain in boresight direction of patch antenna is 7.1 dB as shown in Figs. 6 and 7. Measured gain using Horn antenna and VNA is 6.8 dB.

The Magnitude of transmission parameter $S_{12}$ of designed Wilkinson power divider is plotted in Fig. 8.

The Magnitude of transmission parameters of Wilkinson power divider obtained by varying the width of microstrip line in output ports are plotted in Fig. 9.

At operative frequency of 7.55 GHz magnitude of achieved transmission parameter $S_{12}$ is $-3.0$ dB. This indicates that power is equally divided among the output ports.

From the Fig. 9 it is evident that an attenuation of $-3.37$ dB is achieved at port (2) while an attenuation of $-3.64$ dB is achieved at port (3) as per the requirements of Tchebychef polynomial to reduce side lobe level. Now the length of microstrip line in output ports of WPD is varied in order to achieve the desired phase shift at output ports w.r.t input port.

A phase shift of nearly 0° and 45° w.r.t. input port is achieved at output ports of one of WPD as shown in Fig. 10. A phase shift of nearly 90° and 135° w.r.t. input port is achieved at output ports of another of WPD. The designed Wilkinson power dividers are used to feed patch antenna arrays as per the specifications given in Fig. 1.
When the phase difference between adjacent elements of MIMO antenna is 45° one major beam having gain of 18 dB is obtained at theta equal to 10° and Phi equal to 180°.

The side lobe level less than 13 dB of main beam is achieved using designed antenna. The simulated results are plotted in Figs. 11 and 12.
Fig. 7 Radiation pattern of directive gain of patch antenna

Fig. 8 $S_{12}$ Parameter of WPD
Fig. 9  Magnitude of $S_{12}$, $S_{13}$ parameters of WPD designed to feed MIMO Antenna

Fig. 10  Phase of $S_{12}$ and $S_{13}$ parameters for WPD

Fig. 11. 3-D Polar representation of radiation pattern of MIMO antenna having 45° phase difference between adjacent elements
When the phase difference between adjacent elements is $-45^\circ$ another major beam having gain of 18 dB is obtained at theta equal to $10^\circ$ and Phi equal to $270^\circ$. The side lobe level less than 13 dB of main beam is achieved using designed antenna. The simulated results are plotted in Figs. 13 and 14.

The gain of fabricated structure is also measured using VNA and Horn antenna. The achieved gain of major lobe for fabricated structure is 16.8 dB.
4 Conclusion

An multiuser Electronically steered MIMO antenna using planar and conformal power partition circuit is designed and fabricated. The achieved radiation pattern of designed antenna consists of one major beams having gain of 18 dB and located at theta equal to 10° and Phi equal to 180°. When phase of input signal to antennas are changed another major beam having gain of 18 dB and located at theta equal to 10° and Phi equal to 270° is obtained. The side lobe level less than 13 dB of main beam is achieved using designed antenna.

Declarations

Conflict of interest  The authors declare that they have no conflict of interest.

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**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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