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Conclusion and Scope for Future Research

The theme of the thesis is to improve the capacity and spectral efficiency of the wireless communication channel link by increasing the number of antenna elements and bandwidth. To facilitate this aim, some different types of novel higher-order MIMO antenna designs are proposed in chapter-wise works, which have different wireless applications with certain advantages that will be useful for modern user's devices. This chapter reflects a colossal amount of work that has been done on higher-order MIMO antennas in the dissertation. Therefore, the contributions, key findings, and concluding remarks on the present thesis are summarized in this chapter. This chapter also discusses a future scope where future MIMO designs can take this work forward.

6.1 Summary and Concluding Statements

Chapter 1 of this thesis started with enabling key of capacity in the wireless channel link and motivated to enhance the channel capacity and spectral efficiency by utilizing the MIMO system. The enhancement of the number of antenna elements in MIMO configuration, how it's responsible for improving the capacity of the channel link, and the effect of mutual coupling between antenna elements is explored. This chapter also introduces the basic concept of the printed planar monopole antenna, which is one of the suitable antenna structures used in portable user's devices. Moreover, the conventional and diversity performances parameters having mathematical expressions are presented to know the correct behaviour of the MIMO antenna in practical scenarios. The state-of-the-art review of different MIMO antennas based on 2-element, 4-element, and 8-element, along with their pros and cons, were presented, and coupling reduction techniques are also reviewed to reduce the correlation between antenna elements. Based on the literature review, some problems were identified, and to rectify these findings, that is the objective work towards this thesis. Finally, the future scope and structure of the thesis were presented at the end of this chapter.

In Chapter 2, a compact two-element MIMO antenna with improved impedance matching and isolation is presented for 5G NR sub-6 GHz spectrum. The proposed antenna consists of two identical modified rhombus-shaped radiating elements are placed in the same orientation fed through a tapered microstrip line on a compact substrate area of $0.24\lambda_0\times0.42\lambda_0$ (where λ_0 at 3.6 GHz) with a shared ground plane. A remodeled T-shaped ground stub is placed between antenna elements to improve impedance bandwidth and isolation. A split U-shaped stub is connected to the centre of each radiating element to achieve the desired resonant frequency of 3.6 GHz. Further, the simulation study is carried out to see the effect of housing and the extended ground plane on a two-element

MIMO antenna. Furthermore, an realization of 12-element MIMO antenna is proposed by utilizing six sets of the two-element MIMO antenna along with smartphone's PCB.

The proposed antenna achieved a -10 dB impedance bandwidth ($S_{ij} \in i=j$) of 530 MHz (3.34-3.87 GHz) with a minimum isolation value ($S_{ij} \in i \neq j$) of 20 dB (simulated) and 15dB (measured) between antenna ports. The value of ECC < 0.012, DG > 9.999, the ratio of MEG ≅ 1, TARC < 0.5, and CCL < 0.5 bps/Hz are observed throughout the band. The essential parameters (radiation characteristics, diversity performances, compact size, and ease of fabrication) of the designed two-element MIMO antenna are satisfactory. The housing effect on the two-element MIMO antenna is also analyzed with an extended ground plane, and found that the results are close to the free space condition of two-element MIMO antenna. The configuration of the 12-element MIMO antenna is also achieved satisfactory results, and the found satisfactory results confirm that it will be useful for 5G wireless user's devices. Further, the number of antenna elements and operational bandwidth is increased in the investigation of next Chapter 3, which will provide higher channel capacity and data rate without compromising any aspect compared to this chapter.

In Chapter 3, a low-profile wideband quad-element MIMO antenna with high isolation is presented for the localization system. Each element of the MIMO antenna covers a wideband occupying a small area of 15×15 mm^2. The orthogonal symmetric arrangement of a single antenna forms a highly compact quad-element MIMO antenna having shared ground, and its occupied volume is $0.84\lambda_g \times 0.84\lambda_g \times 0.019\lambda_g$ (λ_g at 3.95 GHz) with a minimum ($0.155\lambda_g$) edge to edge distance between elements. Further, a low-profile quad-element MIMO antennas are arranged orthogonally at the four corners of a centrally located quad-element MIMO antenna forms a 20-element planar MIMO antenna. Additionally, the proposed is integrated at the top face of a cubic block creates a 3D-MIMO system.

The proposed antenna obtained a -10 dB ($S_{ij} \in i=j$) impedance bandwidth of 77.52% (3.95-8.95 GHz) and a minimum isolation ($S_{ij} \in i\neq j$) value of 17 dB. The obtained results (isolation, gain, efficiency, pattern, ECC, TARC, and CCL) in the wideband are satisfactory. The measured and simulated results of the quad-element MIMO antenna are found in good agreement that confirms the proposed antenna is appropriate for extending a higher-order MIMO system. As a result, a 20-element 3D-MIMO antenna system is proposed by utilizing a quad-element MIMO antenna. The obtained results are also close to the quad-element MIMO antenna, confirming that it will be appropriate for WPAN, indoor localization systems, and 3D system-in-package application-based compact devices. The design proposed in Chapter 4 will ensure more channel capacity and data rate than this chapter without compromising any aspect, which is further possible by increasing the number of antenna elements and operational bandwidth.

In chapter 4, a compact ultra-wideband eight-element MIMO antenna with high gain is proposed for modern vehicular applications. The eight-element MIMO antenna consists of four sets of two-element MIMO antenna, which are placed in orthogonal symmetric fashion on an octagon-shaped substrate cross-section area of 0.4374 λ_0^2 (where λ_0 is the highest operating wavelength at the lowest frequency of 3.03 GHz). The two-element MIMO antenna consists of two identical radiating elements placed in the same orientation at the top of the same substrate board, which are fed through the tapered microstrip line. A combination of the stub-loaded shared ground plane is designed at the bottom side of the same board for better impedance matching and low correlation between the same orientation antenna elements. Similarly, dual I-shaped ground stubs are placed between a pair of corner elements. Further, an eight-element MIMO antenna with the extended ground is vertically symmetrically rotated 90^0 around the central axis, configuring a 32-element 3D-MIMO antenna for wireless vehicular communications. Furthermore, the 3D-MIMO antenna is placed on the vehicle's roof-top and inside the radome to see the antenna's capability in the 3D system-in-package.

The proposed eight-element MIMO antenna achieved a -10 dB measured impedance bandwidth ($S_{ij} \in i{=}j$) of 12.3 GHz (3.03-15.33 GHz) with a minimum isolation ($S_{ij} \in i{\neq}j$) value of 15.5 dB between a pair of antenna elements throughout the operating band. The obtained value of ECC and TARC are less than 0.185 and 0.41 throughout the operating band, respectively. The simulated and measured results (characteristics and diversity) of the proposed eight-element MIMO antenna are satisfactory, confirming it is a competent candidate to configure a 32-element vehicular 3D-MIMO antenna for modern IoV communication (5G Sub-6 GHz/WLAN/V2X/V2V/V2I/V2S). The proposed 32-element 3D-MIMO antenna obtained simulated S-parameters results of $S_{ij} \in i{=}j < -10$ dB (3.03-16 GHz) and $S_{ij} \in i{\neq}j < -15.5$ dB, which is almost close to the eight-element MIMO antenna. The effects on that 3D-MIMO antenna with the radome and metallic roof are also studied, obtained satisfactory results show that it may be more appropriate for modern automotive vehicles. Further, two different higher-order MIMO antennas with different operational bandwidths are integrated on a common aperture, as presented in Chapter 5, ensuring highly improved performances.

In chapter 5, an extremely low-profile/compact MIMO system is proposed by utilizing the dual antenna for 5G sub-6 GHz and mm-wave application. The antennas are integrated on a centrally located square-shaped slot-loaded octagon-shaped substrate board. The identical dual antenna elements having the same orientation are orthogonally placed on an octagon-shaped substrate from the outer side, creating an 8-element MIMO antenna for the 5G sub-6 GHz application. From the inner side of the same substrate board, a 1×4 array-based antenna is orthogonally placed in front of the remaining side of the octagon, forming a 4-element MIMO antenna for the 5G mm-wave application. The stubs are connected to the shared ground plane to reduce the coupling between a pair of antenna elements. Due to the 0.508 mm low-profile, the antenna is integrated within the back cover of smartphones; thereby, inside device volume will reduce.

Finally, an appropriate higher-order 5G-MIMO system is investigated for the smartphone's back cover by integrating the 5G sub-6 GHz ($S_{ij} \in i{=}j$, *1* to *8*) and mm-wave ($S_{ij} \in i{=}j$, *9* to *12*) antennas. It achieves the whole -6 dB 5G NR spectrum band of n79 (4.0-5.6 GHz) and n257/n258 (24.25-29.5 GHz) with a high isolation ($S_{ij} \in i{\neq}j$) value of 12 dB and 22 dB, respectively. Moreover, the value of gain, efficiency, and ECC are satisfactory in the dual wideband. The prototype's measured results (characteristics and diversity) are found significantly matched with simulated results. As a result, the proposed antenna is integrated within the dielectric back-cover of smartphones to reduce the device's inner volume. The antennas with back cover also achieved satisfactory performances, which is almost close to the free space MIMO antenna's performances. Therefore, the proposed ultra-low-profile MIMO antenna system may be a highly potential 5G smartphone applicant.

6.2 Scope for Future Research Work

This thesis emphasizes the design and development of practical application-oriented higher-order MIMO antennas with satisfactory performances that have fixed their performances like frequency, pattern, and polarization corresponding to specified antenna elements, which is one of the limitations of the planar/non-planar MIMO antenna. Also, have a specified limit for conventional parameters (impedance bandwidth, isolation, gain, efficiency, polarization) of the antenna element that never exceeds the limit. Moreover, the integration of the non-planar MIMO antenna in the transceiver system is another challenge, and maintaining the same performance in package-in-system with other electronic components is another limitation. Therefore, some techniques may be utilized in future research to enhance the conventional parameters and eliminate the antenna's limitations.

The metamaterial-inspired structures may be utilized to enhance these conventional parameters. The meta-surface-based absorbers/polarizers may be applicable as a decoupling topology in the MIMO configuration. Also, the meta-surface structures may be utilized to improve the antenna's gain. Moreover, the frequency selective surface may also be utilized to change the polarization of the antenna in a particular hemisphere and is also used in RCS (radar cross-section) reduction. Apart from that, some scopes for future work still exist, that is:

The extension of the present thesis works towards reconfigurable MIMO antenna, where antenna element's conventional parameters as frequency, pattern, and polarization are switched using active components in the form of frequency reconfigurable MIMO, pattern reconfigurable MIMO, polarization reconfigurable MIMO, and hybrid reconfigurable MIMO antenna. These techniques may be helpful in various applications and reduce the need of different application-oriented antennas in the user's equipment.

Further to achieve an enhancement in capacity, the number of antenna elements needs to be increased at the transmitter side (base station side) as well as at the receiver side (user's devices), which is the main enabling key for MIMO systems. Consequently, the higher-order MIMO antenna proposed in the thesis can be extended toward a massive MIMO antenna along with enabling beamforming and beam steering techniques. It may be utilized in the base stations (BSs).

This thesis works further may be extended towards filtering MIMO antenna, which can be applicable for microwave and mm-wave applications.