**Parasitic Metamaterial Loaded Inverted L Multiband Antenna for WLAN, WiMAX, 5G and LTE bands**

**Dr. S. Prasad Jones Christydass1\*, Dr. S. Suresh Kumar2**

1,2Associate Professor, Department of ECE, QIS College of Engineering and Technology, Ongole Andhra Pradesh, India

\*1prasadjones.ece@gmail.com, 2sureshkumar.67014@gmail.com

This chapter presents a dual-band Inverted L Parasitic SRR Loaded antenna featuring an upturned L-shaped monopole enhanced with a hexagonal Split Ring Resonator (HSRR). The antenna is tailored for applications in 5G and WLAN/WiMAX contexts. Constructed on a 20 mm x 40 mm x 1.6 mm FR4 substrate, the antenna integrates two precisely optimized rotational symmetric components. Notably, the introduction of the hexagonal split ring resonator serves to notably mitigate mutual coupling between these elements.

The upturned L-shaped monopole component is attuned to the 5 GHz band, while the hexagonal SRR focuses on the same frequency range. This antenna design covers a comprehensive spectrum, encompassing frequencies from 2.65 GHz to 4.36 GHz and from 4.87 GHz to 5.86 GHz. In specific detail, the 2.65 GHz to 4.36 GHz range encapsulates the 5G band spanning 3.3 GHz to 4.2 GHz, alongside accommodating WLAN usage, and LTE bands B42 and B43. Meanwhile, the higher range of 4.87 GHz to 5.86 GHz caters to the demands of WLAN and WiMAX applications.

To validate the antenna's performance, crucial metrics such as return loss, radiation pattern, and gain were measured and systematically compared against simulated outcomes. Impressively, a strong concordance exists between the two sets of data, affirming the precision of the antenna's anticipated behaviors.

An additional advantage of this proposed antenna configuration lies in its compactness. This attribute facilitates seamless integration with internal circuits within mobile devices. This potential for harmonious assimilation underscores the antenna's suitability for inclusion in the next generation of mobile technology.

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**Keywords:** 5G, Monopole, SRR, Metamaterial

# INTRODUCTION

The realm of wireless mobile communication stands as a catalyst, swiftly reshaping human existence through a series of generations, from the inception of 1G to the current zenith of the 4G standard. This trajectory has ushered in a diverse array of services to end-users. The relentless pursuit of elevated speed and expanded bandwidth has steered researchers toward crafting the 5G standards. These standards herald ultra-low latency and exceptional speed, anchoring the edifice of reliable communication.

The architecture of the 5G standard is underpinned by a tripartite spectrum classification: below 2 GHz, 2 GHz to 6 GHz, and above 6 GHz. The initial rollout is poised to leverage the 2 to 6 GHz band [1]. Within this landscape, MIMO (Multiple Input Multiple Output) antennas take center stage, harnessed within 5G communication devices for their prowess in delivering lofty data rates. The approach incorporates multiple antennas at both transmission and reception ends, imparting a linear increase in capacity. However, the proximity of these elements in systems breeds a conundrum: robust mutual coupling that encroaches upon antenna performance [2].

Mitigating this coupling quandary has birthed a plethora of techniques. Strategies like slotted ground planes and neutralization lines have been employed [3,4], albeit inviting intricate designs. Ingenious solutions such as Stub shapes — the T-shaped, L-shaped, and F-shaped incarnations [5,6] — have fortified isolation between elements. Decoupling structures like parasitic elements [7] have surged to the fore, ushering in enhanced isolation. The fusion of neutralization lines with decoupling resonator networks [8] also advances isolation. Metamaterials, boasting the unique trait of negative refractive indices, have been harnessed [9-12] to counter coupling, often through superstrates comprising composite metamaterial structures alongside neutralization lines.

Given the spatial confines, innovative decoupling methods have surfaced, spanning neutral lines [13], parasitic-laden strips [14], slotted ground planes [15], and polarized isolated antennas [16-18]. Yet, a clamor persists for an efficacious technique that bolsters isolation without convoluting antenna design.

Recent strides have seen antennas, with multiple elements, embedded in sub-6 GHz 5G wireless applications. These antennas flaunt minimal envelope correlation coefficients and enviable element isolation. Metamaterials, distinguished by their counterintuitive negative permittivity and permeability, have found their niche in multiband and wideband antenna design. Notably, however, the concurrent attainment of multi-wideband performance and superior isolation has remained elusive.

In this paper, we proffer a antenna tailored for sub-6 GHz 5G and WLAN applications. At its core lies a symmetrical hexagonal SRR-enhanced upturned L-shaped antenna. The incorporation of the hexagonal SRR notably boosts isolation between the antenna elements while fostering impeccable impedance matching. The subsequent sections delve into the design strategy (Section 2), a parametric analysis of critical attributes (Section 3), results and their discourse (Section 4), culminating in a conclusion (Section 5).

**II. Design of Proposed antenna:**

The evolution of the proposed antenna unfolds across two distinct stages, each contributing to its refined design and performance. The inaugural stage features a solitary element monopole, constituting a foundational step. Subsequently, in the second stage, this single element undergoes a symmetrical rotation, resulting in the culmination of a proposed configuration. The visual representation of this evolution is succinctly captured in Figure 1, offering a comprehensive illustration of the antenna's journey. A comprehensive overview of its pertinent parameters is conveniently encapsulated within Table I, succinctly detailing the essential attributes that define the antenna's architecture.

A fundamental aspect within the context of the monopole design lies in the calculation of its resonant length, a pivotal factor dictating its operational characteristics. This vital dimension can be accurately derived through the utilization of a specific equation, which precisely establishes the relationship between the antenna's resonant properties and its dimensions.

L=C/4f (1)

The equation incorporates the speed of light (C), valued at 3x10^8 m/s, while 'f' symbolizes the frequency of resonance. The entirety of the antenna structure is meticulously devised and constructed upon a substrate with a dielectric constant of 4.4. This substrate's dimensions are conveniently conveyed as W x L x H mm3. The deliberate choice of adopting an upturned L-shaped monopole is driven by the objective of maintaining a compact form factor, paramount in size-conscious applications.

The monopole's resonance characteristics are adeptly governed through the manipulation of specific parameters, denoted as X1, X2, and XG. This orchestrated control manifests in the monopole's resonant range, spanning from 3.51 GHz to 4.85 GHz, covering a bandwidth of 1338 MHz. This resonant configuration yields a return loss of -23.09 dB, indicative of its operational efficacy.

Subsequent to this, the introduction of a hexagonal Split Ring Resonator (SRR) onto the monopole significantly augments its capabilities. This augmentation entails the realization of dual-bandwidth resonance at frequencies of 3.75 GHz and 5.2 GHz. The operational domains of these bands span from 3.5 GHz to 4.01 GHz and from 5.08 GHz to 5.33 GHz, respectively. The return loss profiles correspondingly measure approximately -11.83 dB and 23.66 dB, signifying the antenna's improved performance.

Visual insight into the evolutionary trajectory of the proposed structure is concisely depicted in Figure 2, encapsulating the pivotal stages that shape its design. Furthermore, a comparative analysis of return loss across these different stages is presented graphically in Figure 3, succinctly capturing the progression and improvements in the antenna's performance.



Figure 1. Inverted L Parasitic SRR Loaded antenna

**A. Metamaterial effect on the proposed structure:**

Through the employment of eigenmode analysis, the dimensions of the Hexagonal Split Ring Resonator (SRR) are strategically fine-tuned, resulting in a close alignment of its resonance with that of the upturned L-shaped monopole. Notably, in the absence of the hexagonal SRR, the upturned L-shaped monopole's inherent resonant frequency rests at 4.04 GHz. This design is tailored to harmonize with sub-6 GHz 5G applications, encompassing the spectrum within the range of 3.3 GHz to 5 GHz

Table 1. Inverted L Parasitic SRR Loaded antenna Parameter (in mm)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| W | L | Xg | X1 | X2 | a | b |
| 20 | 40 | 12 | 6.2 | 10 | 2.25 | 1.7 |
| S | W1 | W2 | Y | T | H | Xg1 |
| 0.3 | 2.5 | 1 | 0.5 | 0.035 | 1.6 | 12 |

 

Stage 1 Stage 2

Figure 2. Evolution of Inverted L Parasitic SRR Loaded antenna antenna

Upon the integration of the hexagonal SRR, a transformative resonance phenomenon transpires within the hexagonal SRR-loaded upturned L-shaped monopole antenna. This metamorphosis results in dual-band resonance, with resonant frequencies manifesting at 3.75 GHz and 5.2 GHz. The lower resonance is a consequence of the interaction between the SRR and the upturned L-shaped monopole, wherein their modes coalesce with the unloaded resonance. Conversely, the higher resonance arises due to a reduction in the electrical length of the upturned L-shaped monopole in the presence of the hexagonal SRR.



Figure 3 Return loss Comparison Stage 1 vs Stage 2

Figure 4 encapsulates a compelling comparison: the return loss (s11) profiles of the hexagonal SRR-loaded and unloaded upturned L-shaped monopole antennas. This visual representation provides an insightful depiction of the alterations induced by the integration of the hexagonal SRR, delineating the transformation in resonance characteristics.

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Figure 4 Return loss Comparison loaded and unloaded upturned L monopole



Figure 5 Proposed antenna S parameter

**B. Parametric analysis:**

In order to ascertain the optimal configuration, an exhaustive evaluation of crucial parameters has been undertaken. This process encompasses an in-depth analysis of key factors including the ground length, split width of the hexagonal Split Ring Resonator (SRR), and the spacing between the upturned L-shaped monopole and the hexagonal SRR. This comprehensive parametric analysis is conducted utilizing the advanced capabilities of CST software.

Through this meticulous investigation, the intent is to discern the parametric values that yield the most favorable outcomes. By systematically varying and examining these essential parameters, we aim to uncover the precise combination that results in an antenna system boasting superior performance. This iterative approach not only guides us toward optimizing the antenna's efficiency but also elucidates the intricate interplay between the specified parameters, helping to unlock the antenna's full potential.



Figure 6 Variation in return loss with respect to ground length lg

The range of variation for the ground length (Lg) spans from 11.8 mm to 12.2 mm, incrementally adjusting in steps of 0.2 mm. The outcomes of these simulations are visually represented in Figure 6. The discernible trend from these results underscores that an optimal ground length of 12 mm emerges as the configuration that excels in both bandwidth extension and impedance matching. This parameter selection stands as a pivotal achievement, harnessing the antenna's potential to its fullest extent.

Subsequently, an exploration of the split width (S) ensues, encompassing a range of 0.2 mm to 0.4 mm, with increments of 0.1 mm. The revelations depicted in Figure 7 portray a notable relationship: as the split width expands, a corresponding shift occurs within the 5 GHz band. This conspicuous shift underscores the hexagonal SRR's integral role in governing the behavior of the 5 GHz band. This interdependence underlines the SRR's active contribution in this critical frequency range. Further inquiry delves into the spacing between the upturned L-shaped monopole and the hexagonal SRR, symbolized as 'Y.' This parameter varies progressively in steps of 0.3 mm, spanning from 0.2 mm to 0.8 mm. The insights gleaned from Figure 8 conspicuously affirm that a spacing value of 0.5 mm presents a desirable equilibrium. This arrangement is characterized by a compelling combination of impedance bandwidth and matching across both frequency bands.



Figure 7 Variation in return loss with respect to split width s

In summary, the orchestrated manipulation of these critical parameters has culminated in the refinement of the antenna's design, attaining a configuration that demonstrates robust performance in terms of bandwidth, matching, and functionality across the target frequency bands.



Figure 8 Variation in return loss with respect to distance y

**C. Retrieved S parameter of HSRR using NRW method**

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PEC

PMC

Port 1

PEC

Port 2

Figure 9 S-Parameter retrieval waveguide setup

The procedure for acquiring s-parameters using the waveguide method is illustrated in Figure 9. In conformity with this depiction, electric and magnetic boundary conditions are meticulously established. Within this setup, the Hexagonal Split Ring Resonator (HSRR) is stimulated via the designated input port. Computation of the s11 and s21 parameters is facilitated at the output port, the outcomes of which are visually represented in Figure 10. An insightful observation emanates from these results: the proposed HSRR configuration unveils a distinct passband materializing at 5.28 GHz. This noteworthy range of functionality spans from 4.97 GHz to 5.68 GHz, encapsulating a frequency spectrum where the HSRR effectively exhibits its resonant behavior.

Figure 11 provides a comprehensive representation elucidating the negative permeability characteristics inherent to the Hexagonal Split Ring Resonator (HSRR). This distinctive property is ascertained through the utilization of the Non-Resonant Wire (NRW) method, a technique renowned for its effectiveness in extracting key material parameters. Within this visual depiction, the negative permeability trait of the HSRR is meticulously showcased, offering valuable insights into its unique electromagnetic behavior.

 v1 = s21+s11 (2)

v2 = s21-s11 (3)

s11 = re(s21) + j(im(s21)) (4)

s21 = re(s11) + j(im(s11)) (5)

 (6)

 (7)

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Figure 10 Magnitude of Transmission and Reflection coefficient

Utilizing MATLAB, the code is diligently constructed, facilitating a thorough analysis of the Hexagonal Split Ring Resonator's (HSRR) behavior. As depicted in the figure, a salient observation emerges: the proposed HSRR materializes a negative permeability state precisely at 5.02 GHz. This compelling finding decisively affirms that the 5 GHz band exhibited by the proposed antenna owes its existence to the presence and influence of the HSRR component.

The resonant frequency governing the HSRR's behavior is amenable to calculation through specific equations, as elucidated by prior research [19]. To unlock these insights, the inductance and capacitance of the HSRR are diligently derived using Equation 8 and Equation 9. The culmination of this process culminates in Equation 10, effectively yielding the resonant frequency intrinsic to the HSRR. This mathematical framework unveils the intricate mechanisms underpinning the resonant characteristics of the HSRR, further enhancing our comprehension of its electromagnetic attributes.

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Figure 11 Permeability Characteristics

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8)

 (9)

where

 (10)

The equation at hand is characterized by its reliance on a set of pivotal variables: 'w,' which signifies the width of the HSRR ring; 'l,' denoting the average length of the HSRR ring; 'S,' representing the dielectric spacing; and 'K,' symbolizing a comprehensive elliptic integral of the first kind. Leveraging these integral factors, a meticulous process of calculation is initiated, leading to the unveiling of significant properties. Specifically, this analytical journey yields an inductance value quantified at 1.96x10^-14 Henry and an associated capacitance value measured at 5.18x10^-6 Farad.

Further exploration is conducted through the application of Equation 10, a critical juncture that merges theoretical insight with practical outcomes. The culmination of this systematic investigation lies in the determination of the resonant frequency intrinsically linked to the HSRR. This resonant frequency is conclusively identified at 5.01 GHz, a value that carries considerable implications for the HSRR's functionality within the antenna structure.

It's worth noting that the resonance frequency is not only substantiated through meticulous mathematical analysis but also corroborated through empirical investigations, such as the quasi-static analysis and permeability evaluations. These corroborations affirm the uniformity of the resonance frequency, resonating between the theoretical calculations and the experimental retrievals. This striking harmony underscores the precision of the theoretical framework and solidifies the understanding of the HSRR's resonant behavior within the broader context of the antenna's operation.

**III. Result and Discussion**

The simulation of the reflection coefficient, s11, is skillfully carried out through the implementation of CST software, while its practical measurement is conducted utilizing the advanced Agilent Technologies N5230A network analyzer. Notably, a marginal dissimilarity between the measured and simulated outcomes is discernible, a variance attributed to factors such as the insertion loss of SMA connectors and the inherent intricacies of fabrication. This inherent divergence underscores the subtle nuances between theoretical expectations and practical realizations, yet serves as a testament to the comprehensive accuracy achieved in both simulation and measurement procedures.

The antenna configuration, under scrutiny, spans an impressive frequency spectrum ranging from 2.65 GHz to 4.36 GHz and extends from 4.87 GHz to 5.86 GHz. This multifaceted bandwidth allocation is significant in its implications, as it effectively embraces diverse applications. The lower band, from 2.65 GHz to 4.36 GHz, encompasses the 5G band (specifically from 3.3 GHz to 4.2 GHz), provides support for WLAN applications, accommodates LTE bands B42 and B43, thereby demonstrating its compatibility with a plethora of contemporary wireless communication standards. The upper band, ranging from 4.87 GHz to 5.86 GHz, caters to the specialized demands of WLAN and WiMAX applications.

However, it's important to acknowledge that subtle disparities between the measured and simulated outcomes exist, primarily attributed to the aforementioned factors. The depiction of this comparative analysis, aptly capturing these nuances, is eloquently presented in Figure 12, offering a visual testament to the alignment between theoretical simulations and empirical measurements, while also highlighting the inherent variances that are inherent to real-world conditions.

Illustrated in Figure 13, a vivid depiction of the surface current distribution across the Inverted L Parasitic SRR Loaded antenna antenna emerges, offering insightful revelations into its electromagnetic behavior. The conspicuously divergent characteristics within the lower and upper frequency bands are particularly noteworthy. Within the lower frequency band, a discernible prominence of surface current is observed predominantly concentrated upon the upturned L-shaped monopole. This correlation is notable, as the maximum surface current activity occurs within the contours of this monopole structure. This compelling observation solidifies the inference that the monopole predominantly governs the antenna's resonance in this specific frequency range, leaving an indelible imprint upon the lower band performance.



Figure 12 Simulated Vs Measured S11

Conversely, as the frequency spectrum escalates to the upper band, a striking shift in the distribution of surface current becomes evident. The focal point of this alteration centers around the hexagonal Split Ring Resonator (SRR). Specifically, at the 5 GHz mark, the surface current attains its zenith within the hexagonal SRR structure. This precise alignment substantiates the pivotal role played by the hexagonal SRR in influencing and directing the electromagnetic characteristics within the upper frequency band. This coherent interplay of surface currents serves as a poignant reminder of the intricate interdependencies underlying the antenna's dual-band operation, effectively delineating the distinct contributions of each element to the overall performance.



Port excited at 3.39GHz



Port excited at 5.05GHz

**Figure 13 Surface current distribution**

Within the entirety of its operational spectrum, the Inverted L Parasitic SRR Loaded antenna showcases a commendable gain consistently exceeding 2 dBi. Notably, the zenith of this gain performance registers at an impressive 4.17 dBi, a highlight readily discernible through an examination of Figure 14. This graphical representation elucidates the antenna's prowess in maintaining a robust gain profile, thereby reinforcing its efficacy across the designated frequency ranges.

In an endeavor to validate and substantiate the antenna's simulated performance, a comprehensive comparison is drawn between the simulated radiation pattern and its empirically measured counterpart. This insightful comparison is masterfully illustrated in Figure 15, providing a compelling visual narrative that bridges the theoretical and practical dimensions of the antenna's behavior. Specifically, the radiation pattern unveils distinctive traits: an omnidirectional radiation pattern in the horizontal (H) plane, coupled with an intricate eight-shaped pattern in the vertical (E) plane. These dual-plane patterns persist consistently across both resonating frequencies, underscoring the antenna's versatile capability to cater to multiple orientations.

The culmination of this rigorous design process is vividly captured in Figure 16, which artfully showcases the tangible embodiment of the fabricated antenna. This visual representation serves as a tangible testament to the successful translation of theoretical concepts and simulations into a tangible, functional artifact, thereby encapsulating the comprehensive journey from conception to realization.



**Figure 14 Gain plot**



e-plane at 3.39GHz

 

e-plane at 5.05GHz



h-plane at 3.39GHz

 

h-plane at 5.05GHz

**Figure 15 Radiation pattern**



**Figure 16 Fabricated Antenna**

**IV. Conclusion**

This paper introduces a dual-band Inverted L Parasitic SRR Loaded antenna catering to 5G and WLAN/WiMAX usage. It encompasses two rotational symmetric upturned L-shaped monopole antennas fine-tuned for 5G operation. To enhance performance, a dual-ring hexagonal SRR is introduced proximate to each monopole, leading to improved isolation and dual-band capabilities. This integration of a 5GHz SRR reduces mutual coupling significantly, maintaining it well below -18.25 dB.

The antenna's design assigns distinct roles: the upturned L-shaped monopole manages the 5G band, while the hexagonal SRR tackles the same range. This innovative arrangement spans two frequency ranges: 2.65 GHz to 4.36 GHz and 4.87 GHz to 5.86 GHz. The lower range, 2.65 GHz to 4.36 GHz, subsumes the 5G band from 3.3 GHz to 4.2 GHz, along with accommodating WLAN use, LTE bands B42 and B43. The higher range, 4.87 GHz to 5.86 GHz, is tailored for WLAN and WiMAX applications.

The antenna's performance metrics are noteworthy. It sustains a gain surpassing 2 dBi, ensuring reliable signal strength. Additionally, the ECC remains consistently below 0.068 throughout the entire operational band, highlighting its stability and effectiveness.

One of the antenna's notable advantages is its compact size, making it highly amenable for integration into forthcoming mobile devices. The seamless blending of this antenna into the architecture of such devices underscores its potential to be a key enabler for advanced communication capabilities. By harmoniously balancing size, performance, and adaptability, the proposed antenna emerges as a promising candidate for the evolving landscape of wireless technology.

**Summary of Chapter**

This paper introduces a novel dual-band antenna configuration designed for applications in both 5G and WLAN/WiMAX systems. The antenna employs a distinctive upturned L-shaped monopole in combination with a hexagonal Split Ring Resonator (HSRR) to achieve its dual-band performance. The carefully optimized elements of this antenna are symmetrically arranged and fabricated on a compact FR4 substrate measuring 20 mm x 40 mm x 1.6 mm.

The incorporation of the hexagonal split ring resonator brings about a noteworthy reduction in mutual coupling between the two antenna elements. The specific roles of the constituent parts are clearly defined: the upturned L-shaped monopole governs the 5 GHz band, while the hexagonal SRR takes charge of the 5G frequency range. Consequently, the antenna's operational range spans from 2.65 GHz to 4.36 GHz and extends further from 4.87 GHz to 5.86 GHz.

In terms of frequency allocations, the interval spanning 2.65 GHz to 4.36 GHz effectively covers the 5G band's 3.3 GHz to 4.2 GHz range, along with accommodating WLAN applications and the LTE bands B42 and B43. On the other hand, the frequency range of 4.87 GHz to 5.86 GHz caters to the requirements of WLAN and WiMAX applications.

To validate the performance of the proposed antenna, various parameters such as return loss, radiation pattern, and gain were measured and compared against simulated results. The agreement between the two sets of data is notably strong, affirming the accuracy of the proposed design. Moreover, due to its compact dimensions, this antenna configuration lends itself to seamless integration within mobile devices alongside their internal circuitry.

Reference

1. Saxena, S., Kanaujia, B. K., Dwari, S., Kumar, S., & Tiwari, R. (2018), “ MIMO antenna with built-in circular shaped isolator for sub-6 GHz 5G applications” Electronics Letter,54, 478- 480,208.
2. Y. Ban, C. Li, C. Sim, G. Wu and K. Wong, "4G/5G Multiple Antennas for Future Multi-Mode Smartphone Applications," in *IEEE Access*, vol. 4, pp. 2981-2988, 2016,
3. . S. Zhang, Z. Ying, J. Xiong and S. He, "Ultrawideband MIMO/Diversity Antennas With a Tree-Like Structure to Enhance Wideband Isolation," in *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 1279-1282, 2009,
4. S. Zhang, B. K. Lau, Y. Tan, Z. Ying and S. He, "Mutual Coupling Reduction of Two PIFAs With a T-Shape Slot Impedance Transformer for MIMO Mobile Terminals," in *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 3, pp. 1521-1531, March 2012.
5. R. Chandel, A. K. Gautam and K. Rambabu, "Tapered Fed Compact UWB MIMO-Diversity Antenna With Dual Band-Notched Characteristics," in *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 4, pp. 1677-1684, April 2018
6. A. Iqbal, O. A. Saraereh, A. W. Ahmad and S. Bashir, "Mutual Coupling Reduction Using F-Shaped Stubs in UWB-MIMO Antenna," in *IEEE Access*, vol. 6, pp. 2755-2759, 2018,.
7. L. Kang, H. Li, X. Wang and X. Shi, "Compact Offset Microstrip-Fed MIMO Antenna for Band-Notched UWB Applications," in *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 1754-1757, 2015.
8. S. Zhang and G. F. Pedersen, "Mutual Coupling Reduction for UWB MIMO Antennas With a Wideband Neutralization Line," in *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 166-169, 2016.
9. F. Liu, J. Guo, L. Zhao, G. Huang, Y. Li and Y. Yin, "Dual-Band Metasurface-Based Decoupling Method for Two Closely Packed Dual-Band Antennas," in *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 1, pp. 552-557, Jan. 2020.
10. X. Zhao, F. Liu, Y. Liu, L. Zhao and Y. Liu, "Compact Meta-Surface Antenna Array Decoupling (MAAD) Design for Tightly Coupled Antennas," *2019 International Workshop on Antenna Technology (iWAT)*, Miami, FL, USA, 2019, pp. 73-76.
11. Luo, Shengyuan, Yingsong Li, Yinfeng Xia, and Liang Zhang. "A Low Mutual Coupling Antenna Array with Gain Enhancement Using Metamaterial Loading and Neutralization Line Structure." Applied Computational Electromagnetics Society Journal 34, no. 3, 2019.
12. Yu, Kai, Yingsong Li, and Xiaoguang Liu. "Mutual coupling reduction of a MIMO antenna array using 3-D novel meta-material structures." Applied Computational Electromagnetics Society Journal 33, no. 7,pp 758-763, 2018.
13. J. Guo, L. Cui, C. Li and B. Sun, "Side-Edge Frame Printed Eight-Port Dual-Band Antenna Array for 5G Smartphone Applications," in *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 7412-7417, Dec. 2018,
14. Z. Li, Z. Du, M. Takahashi, K. Saito and K. Ito, "Reducing Mutual Coupling of MIMO Antennas With Parasitic Elements for Mobile Terminals," in *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 473-481, Feb. 2012.
15. A. Ghalib and M. S. Sharawi, "TCM Analysis of Defected Ground Structures for MIMO Antenna Designs in Mobile Terminals," in IEEE Access, vol. 5, pp. 19680-19692, 2017..
16. M. Li et al., "Eight-Port Orthogonally Dual-Polarized Antenna Array for 5G Smartphone Applications," in IEEE Transactions on Antennas and Propagation, vol. 64, no. 9, pp. 3820-3830, Sept. 2016.
17. Zhao, A, Ren, Z. Multiple‐input and multiple‐output antenna system with self‐isolated antenna element for fifth‐generation mobile terminals.  Microwave and oprtical letter2019;61:20-27.
18. X. Zhang, Y. Li, W. Wang and W. Shen, "Ultra-Wideband 8-Port MIMO Antenna Array for 5G Metal-Frame Smartphones," in IEEE Access, vol. 7, pp. 72273-72282, 2019.
19. F. Bilotti, A. Toscano, L. Vegni, K. Aydin, K. B. Alici and E. Ozbay, "Equivalent-Circuit Models for the Design of Metamaterials Based on Artificial Magnetic Inclusions," in IEEE Transactions on Microwave Theory and Techniques, vol. 55, no. 12, pp. 2865-2873, Dec. 2007.
20. H. Jiang, L. Si, W. Hu and X. Lv, "A Symmetrical Dual-Beam Bowtie Antenna With Gain Enhancement Using Metamaterial for 5G MIMO Applications," in IEEE Photonics Journal, vol. 11, no. 1, pp. 1-9, Feb. 2019, Art no. 4600409.