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Advancements in MIMO Antennas for Enhanced Performance in 5G Smartphones Communication

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Abstract

In this review paper provides a comprehensive overview of recent advancements in multiple input multiple output (MIMO) antenna designs for 5G smartphones. There are various antenna configurations that are discussed along with benefit and limitations. The paper also examines key challenges such as antenna mutual coupling, isolation and the size constraints inherent in smartphones. Furthermore, the impact of MIMO antenna design on 5G smartphone performance characteristics such as gain, radiation efficiency and spatial multiplexing capability is also analyzed. Finally, future research directions and potential innovations in MIMO antenna technology for 5G smartphones are identified to address emerging requirements and opportunities in next-generation wireless communication systems. The comprehensive comparison of different MIMO antenna performance is also given.

Keywords: 5G, isolation, MIMO, multiband, mutual coupling, smartphones.

INTRODUCTION

The proliferation of 5G technology has ushered in a new era of wireless communication, capacity, promising unprecedented and connectivity for smartphone devices (Odida, et al, 2024). As 5G networks continue to evolve and expand there is a growing demand for advanced antenna systems capable of harnessing the full potential of this transformative technology (Quinn, et al, 2020). Among the main reason of 5G performance enhancement is the implementation of multiple-input multiple-output (MIMO) antennas, which leverage diversity and also multiplexing of signals to improve its coverage, data rates and reliability (Zhang, et al, 2020). In the context of 5G smartphones multiple input multiple output (MIMO) antennas play an important part for high-speed data transmission, enhancing network capacity and ensuring seamless connectivity in diverse operating environments (Chih-Lin, et al, 2016). This translates to faster loading times for websites and apps, smoother streaming of high-resolution video, and quicker file downloads. Additionally, advanced MIMO can improve signal strength and reception in crowded areas, offering a more reliable and consistent connection overall. These practical improvements showcase the tangible benefits of advanced MIMO technology for everyday smartphone usage. The integration of MIMO antennas into smartphone designs presents unique challenges and opportunities due to the constraints imposed by performance requirements and size (Ibrahim, et al, 2023). Comparing MIMO designs for smartphones involves a trade-off between performance and practicality. High antenna count MIMO systems offer superior data rates and signal strength, but require more space within the phone's limited real estate. This can lead to bulkier designs or compromises in antenna placement, potentially affecting signal reception in certain hand positions. Conversely, simpler MIMO designs with fewer antennas are easier to integrate but may offer slightly lower performance. The optimal MIMO design for a smartphone strikes a balance between maximizing user experience and practical limitations, considering factors like form factor, desired data speeds, and thermal management. The review paper aim is to provide an overview of recent advancements in MIMO antenna technologies tailored specifically for 5G smartphones. It will examine various antenna designs consideration, size, configurations, challenges and emerging trends in the field. This review paper offers a systematic data regarding MIMO antenna design strategies for smartphones to attain desired MIMO antenna results. The core purpose of this review paper is to provide comprehension for potential research avenues for future communication systems. The comparison table included in this manuscript can offer guidance for refining the discussed designed techniques to enhance MIMO antenna design techniques.

MIMO Antenna for Smartphones

The designing of a compact MIMO antenna for smartphones become challenging from perspective of both industry and research (Alja'afreh, et al, 2016). If we classify MIMO antennas there are four categories. First one is based on antenna elements numbers. It is desirable to have eight or more number of antenna elements of MIMO for 5G application (Ban, et al, 2016). In (Ban, et al, 2016; Zhao, et al, 2019; Wong, et al, 2017; Chang, et al, 2019; Zhao, et al, 2018; Li, et al, 2016; Cai, et al, 2019; Liu, et al, 2019; Li, et al, 2019; Hu, et al, 2019; Zhang, et al, 2019; Ding, et al, 2018; Li, et al, 2017; eight element MIMO antennas have been designed. MIMO antennas with more than eight antenna elements are reported in (Hu, et al,2019; Wong, et al, 2015; Li, et al, 2017). Second is isolation techniques used in MIMO antenna structure. Isolation is one of major issue in designing of MIMO antenna system. There are many MIMO antenna designed using isolation techniques like neutralization lines (Li, et al, 2019; Hu, et al, 2019; Wong, et al, 2016), self-isolated structures (Zhao, et al, 2019; Wong, et al, 2017; Zhao, et al, 2018), parasitic elements (Hu, et al,2019; Guo, et al, 2018), polarization diversity (Chang, et al, 2019; Li, et al,2016). Third is operating mode either it is wide-band MIMO antennas (Ban, et al,2016; Zhao, et al, 2019; Wong, et al, 2017;Chang, et al, 2019),(Cai, et al, 2019; Liu, et al, 2019, Li, et al,2019), (Wong, et al, 2015, Ren, et al,2019), Multi-Band MIMO antennas (Hu, et al, 2019; Ren, et al,2019; Guo, et al, 2018) as shown in Fig.1.

Fourth category is antenna structure either its edge design or face design. The edge design is when antenna element is designed on edges perpendicular to the main substrate like (Wong, et al, 2016; Wong, et al, 2015; Li, et al, 2017; Li, et al, 2019; Li, et al, 2019; Ban, et al, 2016). Some other proposed designs like inverted L-antennas in (Alja'afreh, et al, 2015; Alja'afreh, et al, 2014), Slot monopoles given in (Wong, et al, 2015; Li, et al, 2017; Zhang, et al, 2019), Inverted F-antennas like (Zhang, et al, 2019; Liu, et al, 2019), dipole structures in (Ren, et al, 2019; Ren, et al,2019) and loop antenna structure (Hu, et al, 2019). However, the loop antenna's structure given in (Ren, et al, 2019; Ren, et al, 2019; Zhao, et al, 2019) have the drawback of large antenna element size. It is hard to practically implement larger size antenna element in a smartphone. Loop antennas have the advantage of being insensitive to the degradation while in user's hand and have very small specific absorption rate (SAR) (Ibraheem, et al, 2014; Pyattaev, et al, 2018; Al Ja'afreh, et al, 2016; Xu, et al, 2016; Alshamaileh, et al, 2019). Other design techniques reported in (Nadeem, et al, 2018; Dzagbletey, et al, 2018; Sharawi, et al, 2017; Zhang, et al, 2019; Kowalewski, et al, 2020; Nadeem, et al, 2018;

Yang, et al, 2020; Saxena, et al, 2020; Shen, et al, 2019) have complex structure. Dual elements in (Wong, et al, 2017) are good for increasing order but they have high SAR. It is better to use a single element for increasing the order of antenna elements in compact devices like smartphones.

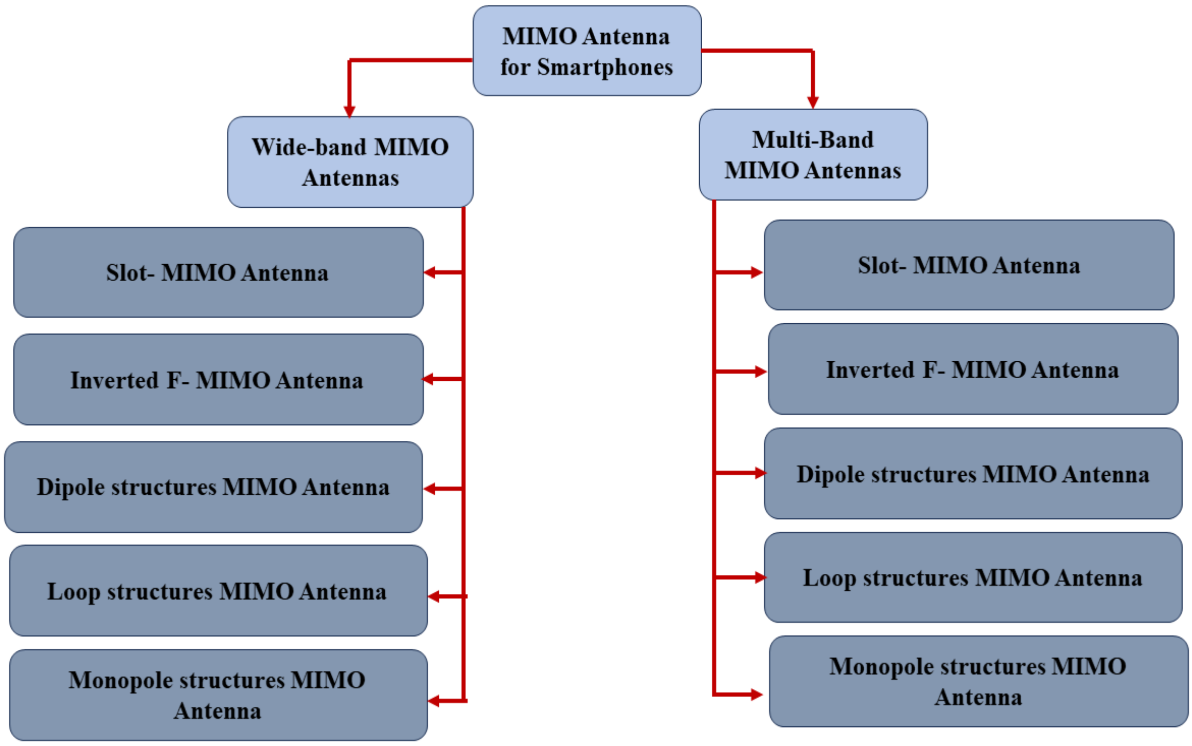
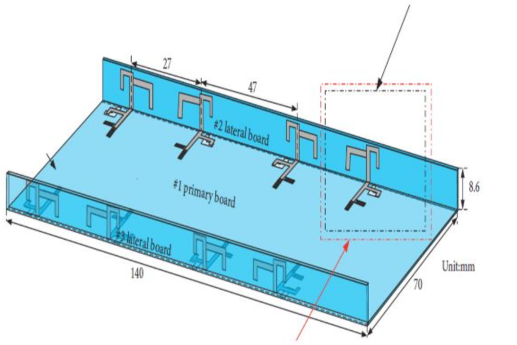


Figure1.
MIMO Antenna Design Categorization.

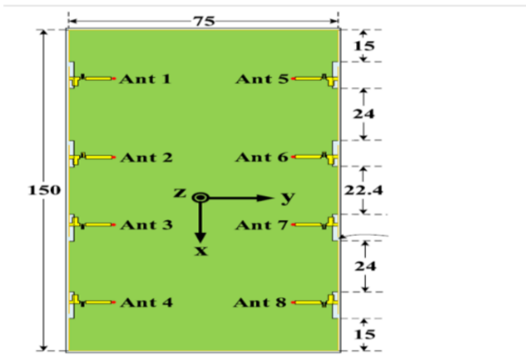
Wideband MIMO antennas

Wideband MIMO antennas have significant ability to operate across a broad frequency spectrum which has advantage to cater to diverse frequency bands in modern smartphones. In this comprehensive overview of wideband MIMO antenna design smartphone is being presented. In (Liao, et al, 2020) a 8x8 the metal frame inverted-F antenna (IFA) is designed. Isolation better than 12 dB and ECC 0.05 is reported. In (Li, et al, 2019) a 3.5 GHz eight-antenna open-slot single band MIMO is reported. The ECC value of 0.05 with isolation of 11dB and efficiency more than 62% is achieved. Fig.2 represents structure of (Guo, et al, 2023) MIMO antenna. In (Cai, et al, 2019) eight elements working in 3.3-3.6 GHz band is proposed is represented in Fig. 3. The MIMO antenna is designed using L shape slots and monopole structure. The isolation of 11dB with efficiency between 50-76% and ECC value less than 0.15 (Deng, et al, 2018).

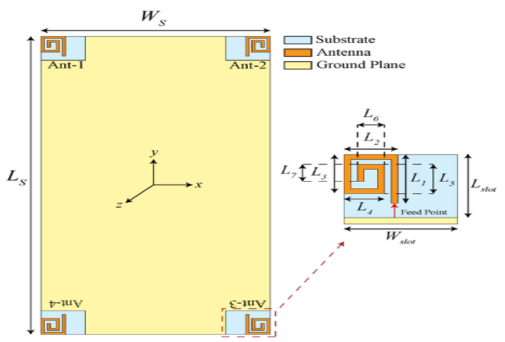
An eight element comprised of ring slots with ring radiators. The efficiency more than 60% with ECC value less than 0.5 and isolation better than 15dB is reported in (Deng, et al, 2018). Fig. 4 represent a four element MIMO antenna for smartphone. In (Chen, et al, 2018) a CPW fed MIMO antenna fed by T ring radiators. Efficiency more than 70% with ECC less than 0.5 and isolation more than 14 dB performance is reported in (Chen, et al, 2018). A twelve element MIMO antenna array in (He, et al, 2023) shown in Fig. 5 is reported. A structure comprised of a rectangular slot with tuning stub. The antenna efficiency is more than 47% while isolation is more than 13dB (Liu, et al, 2020). A four element MIMO antenna structure designed in (Deng, et al, 2019) with efficiency more than 47% and isolation more than 11dB is reported. A self-isolated MIMO antenna comprised of eight elements with isolation more than 15dB and efficiency more than 60% is reported in (Zhao, et al, 2018) . In (Kiani, et al, 2022) an eight-element wideband MIMO antenna operating in 3.2-4.2 GHz is proposed. The MIMO antenna is comprised of slotted structure with polarization diversity, isolation more than 14.5 dB and efficiency above 60%. Despite numerous advantage of wideband MIMO antenna one of significant drawback is the increased complexity and size of wideband as compared to narrow bands. Another disadvantage is that wideband antenna often requires intricating of antenna structures and additional components which may compromise the compact design of smartphones. Another challenge is of size and performance of wideband antenna for smartphones.



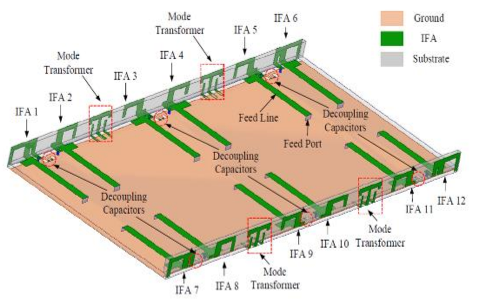
Open-Slot 8x8 Monopole MIMO Antenna (Wei, G., et al, 2020).



Wideband 8-Element MIMO Antenna (Guo, et al, 2023).



Four Element Uni-Planner MIMO Antenna for Smartphones (Cai, et al, 2019).



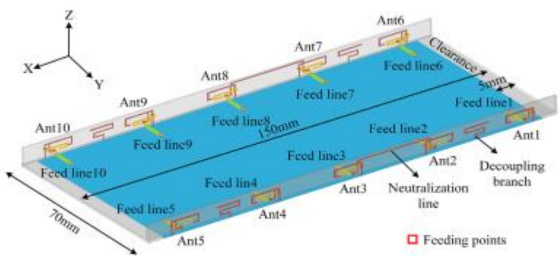
12-Element Inverted-F Wideband MIMO (Rafique, et al, 2022).

Figure 2,3,4,5.

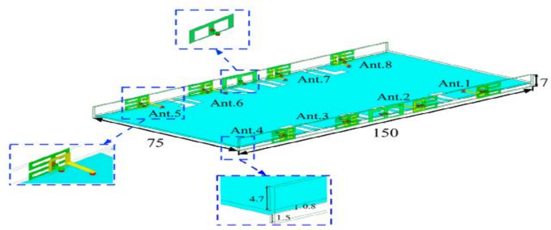
Multiband MIMO antennas

Multiband MIMO antennas have advantage for enhancing the performance and efficiency of smartphones. multiband MIMO antennas have capability to access multiple frequency bands and providing connectivity to different networks at a time. in this section different multiband MIMO antennas have been studied. In (Nandi, et al, 2017). dual-band MIMO comprised of slots operating at 2.5 GHz and 5.6 GHz is proposed. The slot structure helped to achieve isolation more than 20 dB. The ECC is below 0.004. An inverted F-shaped MIMO working in 2.4GHz and 5.4 GHz is proposed (Deng, et al, 2017). Additionally U-shaped slits in ground is utilized to achieve isolation more than 15 dB. A dual-band MIMO working in 3.4-3.6 GHz, 5.2-5.8 GHz given in (Deng, et al, 2019). MIMO comprised of L-shaped, U-shaped and rectangular slots with DGS to improve isolation and efficiency. An eight-element slot-based multi-band MIMO with antenna element size of 15 × 3mm^2 is (Hou, et al, 2023). The MIMO operates in 2-2.6 GHz, 3.4-3.6GHz and 4.8-5 GHz bands has isolation above 11dB and ECC less than 0.1. A dual mode IFA ten element dual band MIMO antenna with isolation more than 12 dB has been presented in (Hu, et al, 2019) shown in Fig. 5. Efficiencies value for lower band (3.3-3.6 GHz) 45-78% and higher band (4.8-5 GHz) is of 47-65% and ECC value of 0.15 which are quite reasonable.

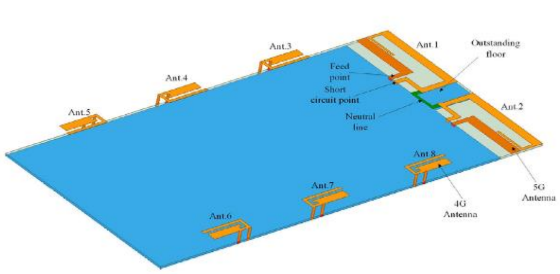
There have been some other multiband MIMO antenna systems literature reported in (Abbasi, et al, 2023; Wong, et al, 2015). (Wang, et al, 2017; Qin, et al, 2016; Li, et al, 2019; Al - Hadi, et al, 2014; Li, et al, 2017; Ban, et al, 2016) which operates in sub 6 GHz bands. In (Kiani, et al, 2024) a dual-band MIMO antenna with a quad-port structure operating in 28 GHz and 38 GHz band. In (Elabd, et al, 2024) a dual-band slot-based MIMO antenna operating in 3.3-3.61 GHz and 4.9-5.1 GHz band. MIMO antenna has efficiency more than 48.5%, isolation above 14dB and ECC below 0.05. The MIMO antenna comprised of a decoupling structure to achieve isolation more than 10dB. Multiband MIMO antennas with many advantages has some limitations as well. Multiband MIMO inherent complexity by integrating multiple frequency bands. Another challenge that comes is to increase number of antenna elements to support multiple bands which can degrade performance like isolation and radiation performances.



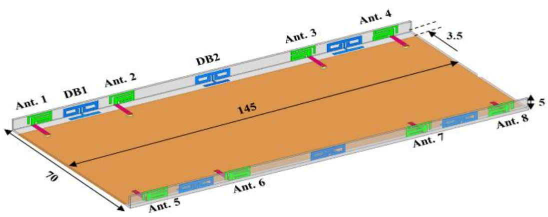
Ten-Element Dual-Band Inverted-F Dual-Band MIMO Antenna (Hu, et al, 2019).



Eight-Element Multiband MIMO Antenna (He, et al, 2023).



Eight-Element Dual-Band MIMO Antenna (Hou, et al, 2023).



Eight-Element Ultra-Thin Multiband MIMO Antennas with Decoupling Structure (Zhang, et al, 2022).

Figure 6,7,8,9.

Table 1.

Performance Comparision Of 5g Mimo Antenna For Smartphones

References	Frequency (GHz)	ECC	Efficiency (%)	Isolation(dB)	Element Numbers	Channel capacity (Bps/Hz)
Guo, et al, 2023	3.28-5.05	<0.01	45-82	>14.5	8	35.2
Rafique, et al, 2022	3.2-3.81	<0.02	-	>10	4	-
Huang, et al, 2022	3.3-3.8	<0.2	>58	>10	12	-
Thakur, et al, 2022	3.4-3.6	<0.1	62-84	>14.8	8	41
Ren, et al, 2022	3.3-3.6	<0.013	>49.4	>20	8	36.1-38
Sun, et al, 2018	3.4-3.6	<0.07	49-73	>17	8	-
Yuan, et al, 2020	3.3-6	<0.05	40-90	>18	8	-
Yuan, et al, 2021	3.3-7.5	<0.06	>78	>10	4	-
Fakharian, et al, 2022	3.0-6	<0.06	>50%	>12.8	8	35-40
Qian, et al, 2023	3.3-5	<0.065	63-86	>11.5	8	-
Abbasi, et al, 2023	3.3-3.6	<0.02	40-64	>15	10	-
He, et al, 2023	3.4-3.6 5.2-5.8	<0.0029	58-72	>15	8	-
Khan, et al, 2023	3.2-3.6 5.0-6.1	<0.11	>68 >78	>20	8	-
Kiani, et al, 2022	3.4-3.6 5.1-5.7	<0.02	58-62 68-74	>12	8	40
Zahid, et al, 2022	3.1-3.78 5.4-6.2	<0.12	50-78 42-70	>10	8	36-41
Chen, et al, 2022	3.4-3.93 4.5-5.3	<0.23	50-78	>10	8	35
Kiani, et al, 2022	3.1-3.6 4.4-6.1	<0.015	50-75	> 18.5	8	40.2
Kiani, et al, 2022	3.34-3.7 4.67-5.08 3.3-3.8,	<0.1	55-62 65-73 55-72	>12	8	35-41

MIMO Antenna Design: Impact On Battery Life, Cost, And Manufacturability

MIMO antenna design choices can significantly impact a smartphone battery life, cost, and manufacturability. Complex designs with multiple antennas or advanced materials like metamaterials tend to consume more power for signal processing, leading to faster battery drain. Additionally, these intricate designs often require specialized manufacturing processes, increasing production costs. Conversely, simpler PCB antennas are more energy-efficient and cheaper to manufacture, but may compromise performance. Finding the right balance between these factors is crucial. Advancements in material science and efficient MIMO antenna architectures hold promise for achieving high performance without sacrificing battery life or manufacturability, making MIMO technology more accessible and practical for future smartphones.

International Spectrum Variability And Its Impact On MIMO Antenna Design

MIMO antenna design choices can significantly impact a smartphone battery life, cost, and manufacturability. Complex designs with multiple antennas or advanced materials like metamaterials tend to consume more power for signal processing, The global rollout of 5G networks presents a challenge for MIMO antenna design due to international variability in spectrum allocation. Different countries allocate specific frequency bands for 5G operation. A MIMO antenna designed for a particular band in one region might not function optimally in another with a different allocation. To address this, smartphone manufacturers often employ multiband antenna designs. These combine antennas like PCB antennas for lower frequencies prevalent globally with custom mmWave antennas for higher frequencies used in specific regions. This multiband approach ensures functionality across various markets while potentially increasing design complexity and production costs.

External Factors And Environmental Conditions Affecting The MIMO Performance And Design Strategies To Mitigate External Factors Affecting MIMO Performance

The performance of MIMO antennas in smartphones isn't solely dependent on the design itself. External factors significantly impact signal strength and reception. User behavior like phone grip can block certain antennas, reducing signal quality. Similarly, device handling near metal objects or in areas with dense signal interference can weaken the connection. Environmental conditions like rain or extreme temperatures can also affect antenna performance. To mitigate these issues, manufacturers are exploring software-based solutions that dynamically adjust antenna configurations based on user grip or signal strength variations. Additionally, advanced materials with better signal transmission properties are being researched to minimize the impact of external factors on MIMO antenna performance.

To combat the negative impacts of external factors on MIMO antenna performance, smartphone designers are exploring several strategies. One approach involves utilizing advanced materials. Liquid Crystal Polymer (LCP) antennas offer good signal transmission and are less susceptible to attenuation when gripped by users, compared to traditional materials. Another strategy focuses on innovative antenna placements. Distributing multiple antennas around the phone's chassis can minimize signal blockage caused by user grip and improve overall reception. Additionally, researchers are exploring metamaterials, which can be strategically placed to enhance beamforming capabilities and mitigate signal degradation in challenging environments. By employing these innovative materials and placements, designers aim to create MIMO antennas that are more resilient to external factors and deliver a consistently strong signal for users.

Integration Challenges Of Incorporating MIMO Antennas With Other Emerging Smartphone Technologies

The integration of MIMO antennas with other cutting-edge smartphone features presents significant challenges. Foldable screens, for instance, introduce moving parts and potential signal disruption. Accommodating both technologies might require flexible antenna designs or strategic antenna placement to avoid interference. Similarly, IoT functionalities that rely on additional radios can compete for space within the phone's chassis, necessitating careful antenna layout to minimize signal conflicts. Additionally, enhanced security features like fingerprint sensors or face recognition systems can be sensitive to electromagnetic interference from MIMO antennas.

Addressing these integration challenges requires close collaboration between antenna designers, engineers working on other or advanced shielding materials that ensure seamless operation of all these technologies within a single smartphone. Smartphone manufacturers are actively tackling MIMO antenna challenges. Apple's iPhone 14 series employs multiband antennas for global functionality, while Samsung's Galaxy S23 Ultra utilizes software to optimize signal reception based on user grip. Xiaomi integrates advanced materials in the Mi 13 Pro for compact, high-performance antennas. These real-world examples showcase the industry's commitment to overcoming limitations and delivering a seamless MIMO experience for users.

- **MIMO Antennas And Other Wireless Communication Technologies**

MIMO antennas are transforming smartphone connectivity by enabling seamless integration and optimization of various wireless technologies. Multiband MIMO antennas combine antennas for both sub-6 GHz and mmWave frequencies, ensuring wider network compatibility and maximizing data speeds. They can also be designed to work with both cellular and Wi-Fi bands, allowing the phone to intelligently switch between networks for optimal connection. Additionally, MIMO's beamforming capability strengthens signals and reduces interference across all these technologies, leading to faster data transfer rates and a more reliable connection for all wireless functions on your smartphone. This synergy between MIMO and other technologies paves the way for future smartphones with exceptional, adaptable connectivity that maximizes data transfer speeds.

- **Economic Implications Of Advanced MIMO On Smartphone Costs**

Advanced MIMO brings a connectivity boost to smartphones, but with a potential bump in price. The intricate design and potentially pricier components of these antennas can inflate production costs. However, manufacturing improvements and efficiency gains from MIMO (like lower power consumption) could balance this out in the long run. Ultimately, the impact on your wallet depends on how manufacturers navigate these cost factors.

- **Scalability Of MIMO Antenna Designs And Supply Chain Impact**

The ease of mass production plays a critical role in how MIMO antenna designs impact the smartphone supply chain. PCB antennas, with their reliance on existing manufacturing processes, are highly scalable and have minimal disruption. PIFA antennas offer a good balance, but intricate designs might require adjustments, causing temporary hiccups. However, dipole and metamaterial antennas, with their complex structures and potentially exotic materials, are difficult to scale, creating bottlenecks and limiting their widespread adoption. To address this, manufacturers are exploring modular designs and standardization efforts to ensure a smooth flow of MIMO-equipped smartphones into the global market.

- **Eco-Friendly MIMO Antennas: Sustainable Materials And Practices**

The telecommunications industry is embracing sustainability, and MIMO antennas are not being left behind. Eco-friendly MIMO antennas are being developed using sustainable materials and practices. This includes utilizing recycled components, biodegradable elements, and energy-efficient designs. Even packaging is being revamped with eco-friendly materials to minimize environmental impact throughout the entire product lifecycle. This focus on sustainability not only benefits the environment but aligns with corporate social responsibility goals.

- **The Rise Of AI And Machine Learning In MIMO Antenna Design**

AI and machine learning are poised to revolutionize MIMO antenna design. AI-powered tools can automate design processes and optimize performance, while machine learning algorithms can analyze vast datasets to identify the best materials and configurations for specific needs. This can lead to faster development cycles, enhanced antenna performance that adapts to user behavior, and even personalized mobile connectivity experiences. As AI and ML mature, they hold the key to unlocking the full potential of MIMO technology for future smartphones.

Future Developments And Strategies For Improvement

The design of MIMO antennas that work across multiple frequency bands is useful for smartphones. However, fitting the antennas into the small space available in a smartphone poses a challenge for antenna designers. To address this, engineers have developed compact antenna designs like inverted-F MIMO antennas, monopole MIMO antennas and loop antennas. These designs can be manufactured easily and can be integrated efficiently. This review paper outlines various compact multiband MIMO antenna designs that are suitable for 5G smartphones.

New MIMO antenna designs, while pushing performance boundaries, can face hurdles in meeting regulatory standards and achieving certification. Complex designs with intricate structures or unusual materials might require extensive testing to ensure they comply with radiation safety regulations across different frequency bands. Additionally, novel manufacturing techniques used for these advanced antennas may necessitate establishing new quality control procedures to guarantee consistent performance and avoid production issues. Overcoming these challenges often involves collaboration between antenna designers, regulatory bodies, and manufacturers to ensure innovative designs meet safety and performance standards for a smooth path to certification. When designing antennas for mobile devices, its important to consider how users hand might affect their performance. At frequencies above 3 GHz, the properties of users skin can impact antenna behavior. Placing a hand directly on top of antenna elements can significantly affected their performance but keeping the hand at distance sometimes improved antenna efficiency by reducing electromagnetic coupling. However, there is limited research on this topic, there is a need for more survey.

CONCLUSION

In this review paper 5G smartphone MIMO antennas are reviewed. In recent years main focus is developing MIMO antennas with good performance parameters, compact size and a greater number of antennas are integrated in MIMO to improve the channel capacity for 5G smartphone antennas. There are many techniques like parasitic elements, polarization diversity, neutralization lines and slots being used to improve the isolation between antenna elements. There is also a lot of work going on to develop MIMO antenna with self-decoupling techniques. Furthermore, the comparison between different antenna design based on performance is also presented. From the comparison we can conclude that MIMO antenna without any decoupling structure can also provide good isolation and radiation performances with reasonable channel capacity for smartphones.

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Consent to Participate: Yes

Consent for publication and Ethical approval: Because this study does not include human or animal data, ethical approval is not required for publication. All authors have given their consent.

REFERENCES

Abbasi, D., Aziz, A., Aljaloud, K., Alqahtani, A. H., Zerguine, A., Al-Garni, A., ... & Hussain, R. (2023). Higher Order MIMO Antenna Design Using Capacitively Coupled Meandered Loop Element for 5G Smartphone Applications. IEEE Transactions on Circuits and Systems II: Express Briefs.

Abbasi, D., Aziz, A., Aljaloud, K., T. Aladadi, Y., Chishti, A. R., I. Alhuwaimel, S., ... & Hussain, R. (2023). A twelve element dual-band MIMO antenna for 5G smartphones. Plos one, 18(12), e0288593.

Abubakar, H. S., Zhao, Z., Munir, M. E., Tareen, W. U. K., Wang, B., Kiani, S. H., & Ali, T. (2024). Enhanced smartphone connectivity: dual-band MIMO antenna with high isolation and low ECC. Physica Scripta.

Al Ja'afreh, S., Huang, Y., & Xing, L. (2016). Low profile and wideband planar inverted-F antenna with polarisation and pattern diversities. IET Microwaves, Antennas & Propagation, 10(2), 152-161.

Al-Hadi, A. A., Ilvonen, J., Valkonen, R., & Viikari, V. (2014). Eight-element antenna array for diversity and MIMO mobile terminal in LTE 3500 MHz band. Microwave and Optical Technology Letters, 56(6), 1323-1327.

Alja'afreh, Saqer S., et al. "A low-profile and wideband PILA-based antenna for handset diversity applications." *IEEE Antennas and Wireless Propagation Letters* 14 (2015): 923-926.

Alshamaileh, M. H., Alja'afreh, S. S., & Almajali, E. (2019). Nona-band, hybrid antenna for metal-rimmed smartphone applications. IET Microwaves, Antennas & Propagation, 13(14), 2439-2448.

Ban, Y. L., Li, C., Wu, G., & Wong, K. L. (2016). 4G/5G multiple antennas for future multi-mode smartphone applications. IEEE access, 4, 2981-2988.

Cai, Q., Li, Y., Zhang, X., & Shen, W. (2019). Wideband MIMO antenna array covering 3.3–7.1 GHz for 5G metal-rimmed smartphone applications. IEEE Access, 7, 142070-142084.

Cai, Q., Li, Y., Zhang, X., & Shen, W. (2019). Wideband MIMO antenna array covering 3.3–7.1 GHz for 5G metal-rimmed smartphone applications. IEEE Access, 7, 142070-142084.

Chang, L., Yu, Y., Wei, K., & Wang, H. (2019). Polarization-orthogonal co-frequency dual antenna pair suitable for 5G MIMO smartphone with metallic bezels. IEEE Transactions on Antennas and Propagation, 67(8), 5212-5220.

Chen, Q., Lin, H., Wang, J., Ge, L., Li, Y., & Pei, T. (2018). Single ring slot-based antennas for metal-rimmed 4G/5G smartphones. IEEE Transactions on Antennas and Propagation, 67(3), 1476-1487.

Chih-Lin, I., Han, S., Xu, Z., Sun, Q., & Pan, Z. (2016). 5G: Rethink mobile communications for 2020+. Philosophical Transactions of the Royal Society A:

Deng, C., Liu, D., & Lv, X. (2019). Tightly arranged four-element MIMO antennas for 5G mobile terminals. IEEE Transactions on Antennas and Propagation, 67(10), 6353-6361.

Dhasarathan, V., Tran, T. K., Kulkarni, J., Garner, B. A., & Li, Y. (2023). Mutual coupling reduction in dual-band MIMO antenna using parasitic dollar-shaped structure for modern wireless communication. IEEE Access, 11, 5617-5628.

Ding, Z., Yao, T., Liu, X., Wang, X., & Liu, Z. (2018, July). An eight-port dual-band antenna array for 5G smartphone applications. In 2018 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC) (pp. 1-2). IEEE.

Dong, G., Huang, J., Lin, S., Chen, Z., & Liu, G. (2022). A compact dual-band MIMO antenna for sub-6 GHz 5G terminals. Journal of Electromagnetic Engineering and Science, 22(5), 599-607.

Dzagbletey, P. A., & Jung, Y. B. (2018). Stacked microstrip linear array for millimeter-wave 5G baseband communication. IEEE Antennas and Wireless Propagation Letters, 17(5), 780-783.

Elabd, R. H., & Al-Gburi, A. J. A. (2024). Low mutual coupling miniaturized dual-band quad-port MIMO antenna array using decoupling structure for 5G smartphones. Discover Applied Sciences, 6(4), 189.

Fakharian, M. M. (2022). A low-profile compact UWB antenna array for sub-6 GHz MIMO applications in 5G metal-frame smartphones. International Journal of RF and Microwave Computer-Aided Engineering, 32(10), e23320.

Guo, J., Cui, L., Li, C., & Sun, B. (2018). Side-edge frame printed eight-port dual-band antenna array for 5G smartphone applications. IEEE Transactions on antennas and propagation, 66(12), 7412-7417.

He, T., Huang, J., Lu, J., Shi, X., & Liu, G. (2023). Eight-Element Dual-Band Multiple-Input Multiple-Output Mobile Phone Antenna for 5G and Wireless Local Area Network Applications. Micromachines, 14(12), 2200.

Hou, J., Peng, Y., Huang, J., Wang, Z., & Denidni, T. A. (2023). MIMO 5G Smartphone Antenna with Tri-Band and Decoupled Elements. Sensors, 23(11), 5186.

Hu, W., Liu, X., Gao, S., Wen, L. H., Qian, L., Feng, T., ... & Liu, Y. (2019). Dual-band ten-element MIMO array based on dual-mode IFAs for 5G terminal applications. IEEE Access, 7, 178476-178485.

Huang, C., & Sui, J. (2022, December). High-Isolated Multi-Element MIMO Antennas for Mobile Terminals. In 2022 IEEE Conference on Antenna Measurements and Applications (CAMA) (pp. 1-2). IEEE.

Ibraheem, A., & Manteghi, M. (2014, July). Performance of electrically coupled loop antenna inside human body at different frequency bands. In 2014 IEEE Antennas and Propagation Society International Symposium (APSURSI) (pp. 975-976). IEEE.

Khan, A., Wakeel, A., Qu, L., & Zahid, Z. (2023). Dual-band 8× 8 MIMO antenna with enhanced isolation and efficiency for 5G smartphone applications. AEU-International Journal of Electronics and Communications, 163, 154600.

Kiani, S. H., Iqbal, A., Wong, S. W., Savci, H. S., Alibakhshikenari, M., & Dalarsson, M. (2022). Multiple elements MIMO antenna system with broadband operation for 5th generation smart phones. IEEE Access, 10, 38446-38457.

Kiani, S. H., Khan, M. A., Rafique, U., Marey, M., Alharbi, A. G., Mostafa, H., ... & Abbas, S. M. (2022). High performance eight-port dual-band MIMO antenna system for 5G devices. Micromachines, 13(6), 959.

Kiani, S. H., Marey, M., SAVCI, H. Ş., Mostafa, H., Rafique, U., & Khan, M. A. (2022). Dual-band multiple-element MIMO antenna system for next-generation smartphones. Applied Sciences, 12(19), 9694.

Kiani, S. H., Munir, M. E., Savci, H. S., Rimli, H., Alabdulkreem, E., Elmannai, H., ... & Alibakhshikenari, M. (2024). Dual-Polarized Wideband 5G N77 Band Slotted MIMO Antenna System for Next-Generation Smartphones. IEEE Access.

Kowalewski, J., Eisenbeis, J., Jauch, A., Mayer, J., Kretschmann, M., & Zwick, T. (2020). A mmW broadband dual-polarized dielectric resonator antenna based on hybrid modes. IEEE Antennas and Wireless Propagation Letters, 19(7), 1068-1072.

Kumar, S., Dixit, A. S., Malekar, R. R., Raut, H. D., & Shevada, L. K. (2020). Fifth generation antennas: A comprehensive review of design and performance enhancement techniques. IEEE Access, 8, 163568-163593.

Li, J., Zhang, X., Wang, Z., Chen, X., Chen, J., Li, Y., & Zhang, A. (2019). Dual-band eight-antenna array design for MIMO applications in 5G mobile terminals. IEEE Access, 7, 71636-71644.

Li, Y., Luo, Y., & Yang, G. (2017). 12-port 5G massive MIMO antenna array in sub-6GHz mobile handset for LTE bands 42/43/46 applications. IEEE access, 6, 344-354.

Liao, C. T., & Huang, P. W. (2020). Multiantennas conjoined with metal frame and integrated into 8× 8 m ultiple-input and m ultiple-output array for fifth generation smartphone applications. International Journal of RF and Microwave Computer-Aided Engineering, 30(12), e22465.

Liu, H. Y., & Huang, C. J. (2019). Wideband MIMO antenna array design for future mobile devices operating in the 5G NR frequency bands n77/n78/n79 and LTE band 46. IEEE Antennas and Wireless Propagation Letters, 19(1), 74-78.

Nadeem, I., & Choi, D. Y. (2018). Study on mutual coupling reduction technique for MIMO antennas. IEEE Access, 7, 563-586.

Nandi, S., & Mohan, A. (2017). A compact dual-band MIMO slot antenna for WLAN applications. IEEE antennas and wireless propagation letters, 16, 2457-2460.

Odida, M. O. (2024). The Evolution of Mobile Communication: A Comprehensive Survey on 5G Technology. J Sen Net Data Comm, 4(1), 01-11.

Parchin, N. O., Al-Yasir, Y. I. A., Ali, A. H., Elfergani, I., Noras, J. M., Rodriguez, J., & Abd-Alhameed, R. A. (2019). Eight-element dual-polarized MIMO slot antenna system for 5G smartphone applications. IEEE access, 7, 15612-15622.

Pyattaev, A., Solomitckii, D., & Ometov, A. (2018). 3D folded loop UAV antenna design. In Wired/Wireless Internet Communications: 16th IFIP WG 6.2 International Conference, WWIC 2018, Boston, MA, USA, June 18–20, 2018, Proceedings (pp. 269-281). Springer International Publishing.

Qian, B., Huang, X., Chen, X., Chang, L., Wei, K., Al-Hadi, A. A., & Kishk, A. A. (2023). Wideband self-decoupled MIMO antenna element based on coupled-loop antenna for 5G smartphones. Journal of Electromagnetic Waves and Applications, 37(1), 110-132.

Qin, Z., Geyi, W., Zhang, M., & Wang, J. (2016). Printed eight-element MIMO system for compact and thin 5G mobile handest. Electronics Letters, 52(6), 416-418.

Quinn, L. (2020). The evolving 5G landscape. Smart cities in application: Healthcare, policy, and innovation, 121-139.

Rafique, U., Khan, S., Ahmed, M. M., Kiani, S. H., Abbas, S. M., Saeed, S. I., ... & Dalarsson, M. (2022). Uni-planar MIMO antenna for sub-6 GHz 5G mobile phone applications. Applied Sciences, 12(8), 3746.

Ren, A., Yang, L., Huang, Z., Yu, H. W., Chen, Q., & Liu, Y. (2022). High-isolation eight-element MIMO array for unbroken metal-rimmed smartphone applications. International Journal of RF and Microwave Computer-Aided Engineering, 32(12), e23404.

Ren, Z., Zhao, A., & Wu, S. (2019). MIMO antenna with compact decoupled antenna pairs for 5G mobile terminals. IEEE Antennas and Wireless Propagation Letters, 18(7), 1367-1371.

Saxena, G., Jain, P., & Awasthi, Y. K. (2020). High diversity gain super-wideband single band-notch MIMO antenna for multiple wireless applications. IET Microwaves, Antennas & Propagation, 14(1), 109-119.

Sharawi, M. S., Podilchak, S. K., Khan, M. U., & Antar, Y. M. (2017). Dual-frequency DRA-based MIMO antenna system for wireless access points. IET Microwaves, Antennas & Propagation, 11(8), 1174-1182.

Shen, X., Liu, Y., Zhao, L., Huang, G. L., Shi, X., & Huang, Q. (2019). A miniaturized microstrip antenna array at 5G millimeter-wave band. IEEE Antennas and Wireless Propagation Letters, 18(8), 1671-1675.

Sun, L., Feng, H., Li, Y., & Zhang, Z. (2018). Compact 5G MIMO mobile phone antennas with tightly arranged orthogonal-mode pairs. IEEE Transactions on Antennas and Propagation, 66(11), 6364-6369.

Thakur, V., Jaglan, N., & Gupta, S. D. (2022). Side edge printed eight-element compact MIMO antenna array for 5G smartphone applications. Journal of Electromagnetic Waves and Applications, 36(12), 1685-1701.

Wang, H., & Yang, G. (2017, October). Compact and low-profile eight-element loop antenna array for the 3.6-ghz MIMO operation in the future smartphone applications. In 2017 Sixth Asia-Pacific Conference on Antennas and Propagation (APCAP) (pp. 1-3). IEEE.
Wei, G., & Feng, Q. (2020). Dual-band MIMO antenna array for compact 5G smartphones. Progress In Electromagnetics Research C, 99, 157-165.
Wong, K. L., & Lu, J. Y. (2015). 3.6-GHz 10-antenna array for MIMO operation in the smartphone. Microwave and Optical Technology Letters, 57(7), 1699-1704.
Wong, K. L., Lu, J. Y., Chen, L. Y., Li, W. Y., & Ban, Y. L. (2016). 8-antenna and 16-antenna arrays using the quad-antenna linear array as a building block for the 3.5-GHz LTE MIMO operation in the smartphone. Microwave and Optical Technology Letters, 58(1), 174-181.
Wong, K. L., Tsai, C. Y., & Lu, J. Y. (2017). Two asymmetrically mirrored gap-coupled loop antennas as a compact building block for eight-antenna MIMO array in the future smartphone. IEEE Transactions on Antennas and Propagation, 65(4), 1765-1778.
Xu, H., Wang, H., Gao, S., Zhou, H., Huang, Y., Xu, Q., & Cheng, Y. (2016). A compact and low-profile loop antenna with six resonant modes for LTE smartphone. IEEE Transactions on Antennas and Propagation, 64(9), 3743-3751.
Yang, Z., Xiao, J., & Ye, Q. (2020). Enhancing MIMO antenna isolation characteristic by manipulating the propagation of surface wave. IEEE Access, 8, 115572-115581.
Zahid, M. N., Gaofeng, Z., Kiani, S. H., Rafique, U., Abbas, S. M., Alibakhshikenari, M., & Dalarsson, M. (2022). H-shaped eight-element dual-band MIMO antenna for sub-6 GHz 5G smartphone applications. IEEE Access, 10, 85619-85629.
Zhang, C., Chen, Z., Shi, X., Yang, Q., Dong, G., Wei, X., & Liu, G. (2022). A dual-band eight-element MIMO antenna array for future ultrathin mobile terminals. Micromachines, 13(8), 1267.
Zhao, A., & Ren, Z. (2018). Size reduction of self-isolated MIMO antenna system for 5G mobile phone applications. IEEE Antennas and Wireless Propagation Letters, 18(1), 152-156.
Zhao, A., & Ren, Z. (2019). Multiple-input and multiple-output antenna system with self-isolated antenna element for fifth-generation mobile terminals. Microwave and Optical Technology Letters, 61(1), 20-27.