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Review of decoupling techniques in MIMO systems

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Abstract: "Mutual coupling" refers to the interaction between antennas in a multiple-input multiple-output (MIMO) system. In a MIMO setup, multiple antennas are used for both transmission and reception of signals. However, the antennas can influence each other due to their proximity, which is called mutual coupling. This phenomenon can affect the performance of the MIMO system by altering signal transmission and reception characteristics. The review likely explores how this interaction impacts the overall performance and how it can be managed or mitigated to optimize the system's efficiency. In the intricate web of antenna optimization, mutual coupling emerges as a crucial player, impacting system performance in multifaceted ways. While some relief can be found through post-processing techniques—specifically by calibrating the received voltage to mitigate these coupling effects—it's important to note the limitations. Despite these adjustments, the Signal-to-Interference-plus-Noise Ratio (SINR) remains stubbornly unaffected by post-processing maneuvers. To truly unlock the pinnacle of performance, the focus must shift to the initial design stages of the array antenna. Here lies the key to achieving optimal system efficacy. While existing literature is rife with a multitude of techniques aimed at mitigating mutual coupling, there's a catch: the majority of these methods are tailored for the more common two-port antennas, leaving a gap in solutions for the complex demands of massive MIMO antennas found at base stations. However, amid this landscape, hope twinkles on the horizon. This paper stands as a beacon of promise, poised to unravel a series of innovative mutual coupling reduction techniques specially curated for the colossal arrays housed within base station setups. As it delves deeper into these cutting-edge strategies, it holds the potential to bridge the gap between theory and practical implementation, ushering in a new era of optimized performance in massive MIMO systems.

Keywords: MIMO antennas, mutual coupling, decoupling techniques

I. INTRODUCTION

Delving into the intricate dance of antennas in MIMO systems, this paper takes a panoramic view of mutual coupling's impact. These interactions aren't just a tango between antennas; they affect the very essence of a MIMO setup, tweaking antenna behaviour and nudging system performance. This coupling isn't just a hiccup—it leads to spectral regrowth and performance degradation, but fear not! While digital tweaks can provide some relief, the real magic happens at the antenna level through decoupling techniques. Unveiling a treasure trove of strategies, especially tailored for massive MIMO base stations, this paper uncovers the secrets to sidestep mutual coupling's influence on MIMO systems. In the grand symphony of modern telecommunications—think LTE and WLAN—MIMO techniques take center stage [1]. Picture this: the massive MIMO system, hailed as the cornerstone of 5G communication [2]-[4]. But here's the catch: in our quest for sleek and space-efficient mobile terminals and base stations, compact MIMO antennas are a must. And therein lies the twist. With these antennas cozying up to each other, electromagnetic matchmaking—aka mutual coupling—becomes an unavoidable part of the show. Mutual coupling in MIMO antennas happens because of how signals interact in the air, flow along surfaces, and travel as waves across those surfaces. These interactions can mess with the signal quality, making it harder to separate what you want from what you don't in a bunch of signals. This interference can mess with things like how well an array can adapt to changes and mess up the estimates of various signal aspects, like frequency, channel strength, and direction. It's a bit like having different instruments playing together but not quite in tune. This tuning issue causes problems in different areas, like making some signals weaker or causing them to spread out where they shouldn't, even making extra noise that could bother neighboring systems. People have tried fixing this digitally, tweaking how the signals are handled after they're received, but that only helps a bit. It's like trying to fix a performance issue by adjusting the volume after the music's already playing—it doesn't solve the core problem. Instead, the better bet seems to be dealing with it right at the antenna level, using techniques that separate antennas from meddling with each other. By doing this, the overall impact of mutual coupling on how well these systems work together can be lessened, which is pretty crucial in making these systems perform at their best[5-18]. Here authors shows that mutual coupling's influence meets its match through the wizardry of stochastic optimizations. Picture this: an antenna ensemble, each member whispering to its neighbors in an intricate dance of signals. Here's where the magic happens. Imagine enhancing the diversity gain of a multi-port antenna using the elegant moves of partial swarm optimization algorithms. It's akin to fine-tuning the harmony of an ensemble, where each antenna finds its sweet spot, amplifying their collective power while minimizing the meddling whispers between them. That's the symphony of stochastic optimizations, transforming mutual coupling into a well-choreographed performance [19]. the MIMO capacity was improved by optimizing the MIMO antenna using the genetic algorithm [20], hybrid Taguchigenetic algorithm [21], or the galaxy-based search algorithm [22]. Compared with these stochastic approaches, there is even richer literature on deterministic techniques for mutual coupling reductions. For examples, decoupling networks[23]–[26], neutralization lines [27]–[32], ground plane modifications [33]–[38], frequency-selective surface (FSS) or metasurface walls [39]–[42], metasurface corrugations or electromagnetic bandgap (EBG) structures [43], [44], and characteristic modes [45]–[48]. It should be noted that, even though the mutual coupling tends to degrade the performance of MIMO systems, it can be utilized for array calibrations [52], [53]. Review papers on mutual coupling exist in the literature [54], [55]. [54] focuses literature survey on the relationship between impedance matrix, radiation patterns, and beam coupling factors (i.e., correlations) in the presence of mutual coupling, Paper [55] seems to focus on exploring methods that model and address mutual coupling after the signals have been processed. It delves into techniques used in post-processing to understand and minimize the impact of mutual coupling on MIMO systems. In contrast, the paper under discussion aims to conduct a systematic review, offering insights into the effects of mutual coupling on MIMO systems and highlighting prevalent techniques to mitigate this issue. Mutual coupling, which alters antenna behavior within an array, directly influences the performance of MIMO systems. This influence can impact various performance metrics such as capacity, error rates, and spectral characteristics. While some improvements can be made by correcting mutual coupling in the digital domain after signal reception, this method has limitations. Although it can partially enhance system performance, it's unable to improve the Signal-to-Interference-plus-Noise Ratio (SINR) in post-processing. The paper argues for a shift in focus toward mitigating mutual coupling at the antenna design stage. Decoupling techniques applied directly at the antenna level can significantly enhance overall MIMO system performance. This approach simplifies the system design compared to relying solely on digital domain techniques. The paper likely discusses various decoupling methods tailored for MIMO systems, particularly addressing massive MIMO base station antennas.

II. MUTUAL COUPLING REDUCTION

In this section, we discuss mutual coupling reduction (decoupling) techniques for MIMO antennas, with a special focus on decoupling techniques for massive MIMO antennas for base stations. There are many decoupling techniques to reduce the mutual coupling in the literature. For examples, decoupling networks [23]–[26], neutralization lines [27]–[32], ground plane modifications [33]–[38], frequency-selective surface (FSS) or metasurface walls [39]–[42], metasurface corrugations or electromagnetic bandgap (EBG) structures [43], [44], and characteristic modes [45]–[48]. In the labyrinth of decoupling techniques for taming mutual coupling, a variety of strategies dance across the pages of research. There are intricate networks—like decoupling networks and neutralization lines—that aim to balance signal paths and cancel out interfering whispers. Yet, these often favor narrower bandwidths or are better suited for fewer antennas. Neutralization lines, akin to specialized networks, aim to cancel coupling by introducing contrasting signal paths that counteract each other. Some innovative designs, like the circular disc and dual strips, attempt to create multiple paths for cancellation across different frequencies. However, they might not waltz well with LTE handset arrays due to frequency constraints. Ground plane modifications, another player in this symphony, carve out slots between antennas to stifle coupling, but they can inadvertently amplify rear emissions, playing a dual role. Metasurface walls, though effective in reducing coupling, clash with the aesthetics of low-profile antennas and might even alter radiation patterns. Finding harmony between effectiveness and visual appeal remains a challenge. Speaking of challenges, the lower frequency bands pose a thorny maze. Handset MIMO antennas struggle to isolate below 1 GHz, as the chassis becomes both ground plane and shared radiator. Some crafty solutions involve strategically positioning antennas—electric and magnetic fields—along the chassis edges, orchestrating high isolation. Practical constraints often impose limitations, restricting the free movement of antenna elements to achieve these ideal setups. The dance between practicality and perfection continues, urging researchers to navigate the delicate balance between efficacy and real-world feasibility in this fascinating symphony of antenna design. In the intricate world of antenna design, where every element and structure has a role to play, the challenge of finding untapped potential continues. Take, for instance, the metallic bezel of a mobile phone—an often overlooked component that holds promise in addressing the limitations of band-limited antenna elements. Here lies an opportunity to leverage this bezel, unlocking a feasible characteristic mode that doesn't ruffle the chassis with unwanted excitement. This approach, rooted in characteristic mode theory, proves more adept in analyzing and addressing the intricacies of handset MIMO antennas. While the majority of research and development has focused on handset MIMO antennas sporting a handful of ports, there's a noticeable gap when it comes to addressing mutual coupling in massive MIMO antennas designed for base stations. This scarcity of exploration sparks curiosity, leading us to the next chapter—a glimpse into recent strides taken in developing decoupling techniques specifically tailored for massive MIMO antennas. Here lies a realm ripe for discovery and innovation, where the challenges and intricacies shift on a grander scale. Massive MIMO emerges as a powerful extension of traditional MIMO technology, unveiling a new dimension by harnessing the directional prowess of an array boasting a multitude of elements. Positioned as a linchpin in the 5G communication ecosystem, Massive MIMO takes center stage predominantly within the realms of base stations. Within this domain lies a distinct focus—an exploration into the realm of recent advancements in reducing mutual coupling within the colossal antennas perched atop these stations. However, it's worth noting that the realm of decoupling techniques within the domain of Massive MIMO antennas remains relatively uncharted territory. The landscape here is challenging and largely unexplored, with a dearth of literature and limited development over the years in mitigating mutual coupling specifically tailored for Massive MIMO setups. Understanding and taming the coupling between antenna elements stand as a critical factor, often adhering to an industry thumb rule that dictates these interconnections should register levels lower than -30 dB within a Massive MIMO base station antenna system. The scarcity of established methodologies and research in this sphere highlights the complexity and significance of the task at hand, beckoning for pioneering efforts to navigate this unexplored terrain.

III. CONCLUSION

In this comprehensive review paper, the intricate dance of mutual coupling and its profound impact on MIMO antennas takes centre stage. Through meticulous exploration, it becomes evident that this coupling phenomenon orchestrates notable transformations in the self- and mutual-impedances within the array antenna. As the tale unfolds, it becomes apparent that mutual coupling's influence extends far beyond mere interactions between antennas; it subtly manipulates the very essence of these antennas' characteristics. The coupling alters not only the individual antennas' self-impedances but also intricately interweaves their mutual impedances within the array. This subtle yet significant shift reverberates across the antenna's behaviour, creating a ripple effect that intricately shapes and alters its fundamental characteristics. Through this detailed exposition, the paper unravels the complex interplay between mutual coupling and antenna characteristics, offering a profound understanding of how these interactions sculpt the behavior and performance of MIMO antennas. Each revelation within these pages paints a vivid picture of how the coupling nuances alter the fundamental properties of these antennas, steering the conversation towards a deeper comprehension of their intricate design and functionality. Amidst the intricate interplay of antennas, the presence of mutual coupling wields its transformative power, subtly shaping the radiation patterns. Picture this: in the realm of two-port antennas, mutual coupling plays the role of a mischievous conductor, coaxing the antenna elements into emitting signals in opposing directions, sculpting patterns that dance in an almost paradoxical harmony. In this symphony of signals, correlations, too, find themselves swayed by the influence of mutual coupling, presenting two contrasting interpretations. On one hand, a comparison between correlations with and without the touch of mutual coupling reveals a lower correlation when the coupling's effects are considered. This lends weight to the notion that mutual coupling tends to dampen these correlations. Yet, as the tale unfurls further, another revelation emerges—a twist in the narrative. When the spotlight shines on antenna separation, a different tune arises. With the acknowledgment of mutual coupling's effect, correlations seem to ebb as the antennas draw closer. This presents a paradoxical paradox: while some argue that mutual coupling diminishes correlations, others claim its potency amplifies these correlations, especially as antennas cozy up in proximity. In this enigmatic tango between mutual coupling and correlations, the melody shifts and sways, leaving room for dual interpretations and sparking an intriguing debate within the realm of antenna theory.

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