# Guest Editorial: Special Cluster on Recent Advances in Applications Involving Mutual Coupling

## I. INTRODUCTION

MUTUAL coupling between antennas and their surrounding environment has been a recognized phenomenon since the inception of antennas [1]. When an antenna element within an array operates as a transmitter, its radiated field induces electromagnetic currents in nearby elements, leading to reradiation. This coupled field can distort radiation patterns and change the terminating impedance. Both effects are typically considered as undesirable, although they may also be exploited to achieve higher performance in some cases. During receiving operations, the received signals comprise both the desired incoming signals and unwanted coupled fields from adjacent antennas and surrounding objects [2].

The topic of mutual coupling has received extensive attention over the years, with comprehensive coverage available in books and review articles [1], [2], [3], [4]. Mutual coupling was considered in the initial studies on linear antennas but was neglected until the work in the 1930s by Carter [5]. In the following years, the extent to which mutual coupling was included in the design was determined by the available computer power because most arrays and coupling problems were for antennas that were usually wider than a quarter wavelength apart when approximate techniques were most successful. These techniques were employed during the 1940s. For large planar or conformal arrays, the periodic unit cell approach gave good predictions although it was not until the 1960s when computers became readily available that these methods were employed with some success in design. In the 1960s, a chapter by A. A. Oliner in the classic book *Microwave Scanning Antennas* edited by R. C. Hansen [6] contained a good exposition of the methods used at the time. Coupling in finite arrays became possible in the 1970s often using earlier methods such as Greens function and induced current methods although with computers increasing in memory capacity and power reliable results could be obtained for relatively simple elements such as waveguide apertures or linear dipoles. The arrival of computer packages, such as NEC in the 1970s [7], HFSS [8] in the 1980s, and CST Microwave Studio [9] and FEKO [10] in the 1990s dramatically changed the landscape of possibilities for including mutual coupling for general radiating structures. In the 2000s, further improvements in computation techniques and processing allowed very large arrays of even closely packed elements with mixed media to be fully analyzed to obtain all the characteristics required by antenna designers. Traditional methods for quantifying the impact of mutual coupling include scattering parameters, mutual impedances, and near-field distributions. Common approaches to mitigating mutual coupling include physical isolation, calibration methods, mutual impedance techniques, decoupling networks, and parasitic decoupling structures [1]. Specifically, techniques, such as electromagnetic bandgap (EBG) structures [11], [12], multilayer substrates [12], complementary split-ring resonators [13], [14], defected ground structures [15], and the relatively recent concept of antenna decoupling surfaces [16], have been explored. Other than hardware implementation, mutual coupling characterization and compensation can also be handled through array signal processing [17].

In the context of the evolving landscape of 6G communications and the Internet of Things (IoT), where the demand for portable electronic devices with wireless communication capabilities is on the rise, the design of low-profile antenna arrays with electrically small interelement spacing has become paramount. Suppression of mutual coupling between antenna elements, especially with interelement separations less than half a wavelength or even down to zero edge-to-edge distance, or even physically connected antennas, presents a significant challenge. For arrays with wideband operation capabilities, the interelement separation often falls well below half a wavelength at lower frequencies. Consequently, for closely spaced antenna elements, there is ample room for improvement in decoupling solutions or designs exploiting mutual coupling.

Building upon Wheeler's current sheet concept [18], mutual coupling has also been deliberately exploited by intentionally overlapping or connecting antenna elements [19], thereby achieving strong coupling—a realization of the current sheet concept, resulting in tightly coupled arrays (TCAs) [20]. While Wheeler's concept was first published in 1965, it took almost half a century to realize TCAs [21].

The objective of this Special Cluster is to compile recent advancements related to the development of mutual coupling between antennas. This encompasses mutual coupling characterization, decoupling methods, and innovative approaches that leverage mutual coupling for antenna array designs. These findings could lead us to create devices that make more efficient use of the electromagnetic spectrum and space while enhancing wireless communication capabilities or radar performance.

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TABLE I
CLASSIFICATION OF THE LETTERS IN THE SPECIAL CLUSTER

| | **Area** | **Emphasis** |
|---|---|---|
| **[A1]** | Fundamental Research and Discovery | Array Patterns Synthesis |
| **[A2]** | | Mutual Coupling Analysis |
| **[A3]** | | Upstanding Dipoles for Base Station Antennas |
| **[A4]** | Emerging Research Themes | Dielectric Decoupling Stub |
| **[A5]** | | Connected Linear Array |
| **[A6]** | | Temperature Management |
| **[A7]** | | Radiation Patterns Decoupling Methods |
| **[A8]** | Innovative Decoupling Structures | Dielectric Resonator (DR) antennas for Multiple-Input–Multiple-Output (MIMO) |
| **[A9]** | | Patch Antennas for MIMO |
| **[A10]** | | |
| **[A11]** | | |
| **[A12]** | Adaptive Arrays | Handling Calibration Errors |
| **[A13]** | | Handling Calibration Errors |
| **[A14]** | Application-Centric Studies | Square Kilometer Arrays (SKAs) |
| **[A15]** | | Square Kilometer Arrays (SKAs) |
| **[A16]** | | Simultaneous Transmit and Receive (STAR)Antenna Systems |
| **[A17]** | | |
| **[A18]** | | Unmanned Ariel Vehicle (UAV) |
| **[A19]** | | MIMO Communication |
| **[A20]** | | Lens Antenna |

## II. CONTRIBUTIONS

This Special Cluster comprises 20 peer-reviewed articles contributed by 75 authors from diverse institutes and industries worldwide, as summarized in Table I. These articles encompass a wide range of topics, addressing various research questions and can be broadly categorized into the following five key areas:

1) fundamental research and discovery;
2) emerging research themes;
3) innovative decoupling structures;
4) adaptive arrays;
5) application-centric studies.

### A. Fundamental Research and Discovery

The articles in this group focus on novel approaches to address mutual coupling in antenna arrays.

*Array Pattern Synthesis:* When an array is composed of single-mode antennas, the radiation pattern of the array can be determined using the isolated antenna radiation pattern, the array factor, and the array impedance matrix. However, Cavillot et al. [A1] observed that these parameters are insufficient for accurately determining the radiation pattern of multimode antennas. To address this limitation, a new quantity called the extended array admittance is defined and applied in conjunction with isolated antenna radiation patterns and the array factor.

*Mutual Coupling Analysis:* Traditionally, the unwanted effects of mutual coupling have been studied and quantified using $S$-parameters, impedance matrices, or near-field distribution analysis. These methods offer valuable insights into coupling behavior and near-field power transfer. However, they do not provide information about nonpropagating reactive electric energy density in the near-field region, which is a crucial aspect not captured by the aforementioned techniques. It is worth highlighting that non-TEM fields and nonpropagating reactive energy density can exhibit significant variations, even among antenna arrays with similar $S$-parameters. Sarkar and Antar [A2] demonstrate how the effects of reactive electric energy density can be identified using EM Lagrangian density and complex helicity.

*Upstanding Dipoles for Base Station Antennas:* In the context of base-station applications, most aperture-shared dual-band arrays have traditionally been designed using planar dipole elements. However, Li et al. [A3] introduce the concept of utilizing upstand dipole elements, marking a departure from the conventional approach. Through extensive full-wave simulations and measurements, this study reveals that the coupling and interference between low and high-band elements are significantly reduced with this design, resulting in a broader bandwidth.

### B. Evolving Research Topics

The articles in this section explore advancing technologies for mutual coupling suppression and harnessing mutual coupling for array design.

*Decoupling Dielectric Stub (DDS):* Similar to the concept of an array decoupling structure (ADS), where a decoupling structure is placed above the array, Mei et al. [22] further enhance this idea with the introduction of a decoupling dielectric stub. Zhang et al. [A4] develop this idea for massive MIMO and this innovation results in an extended operating bandwidth and a more compact vertical profile.

*Connected Linear Array:* Xu et al. [A5] present a directly connected linear array. Unlike evolving TCAs that operate across the entire frequency band, this array introduces a band notch between 3.3 and 3.6 GHz using an additional slot mode, aligning it with the FCC standard proposed in 2002. When compared to other TCAs reported in the literature, this proposed array also offers superior gain.

*Temperature Management:* Celik et al. [A6] introduce a unique solution that addresses both mutual coupling and high-temperature issues arising from power amplifiers. The approach employs a dual-functional complementary split-ring resonator (CSRR) isolation wall to simultaneously reduce mutual coupling and dissipate heat.

*Radiation Patterns Decoupling Method:* Wu et al. [A7] apply the recently developed radiation pattern decoupling (RPD) method [23] to patch antennas. Through an analysis of the $\mathrm{TM}_{01}$ and $\mathrm{TM}_{11}$ modes, the radiation patterns are effectively decoupled by finely tuning the vias and slots to minimize superimposed fields. This design is showcased for a $1 \times 2$ RPD patch antenna with zero edge-to-edge distance, with excellent agreement observed between theoretical predictions and measurement results.

### C. Novel Decoupling Structures

The articles referred to in this section revolve around innovative structures designed to suppress mutual coupling. Elahi et al. [A8] conduct a comprehensive examination on the reduction of mutual coupling and the enhancement of bandwidth using a Z-shaped strip integrated into a dielectric resonator antenna. Wan et al. [A9] introduce an inductor-capacitor (LC) decoupling structure tailored for co-polarized, high-isolation two-port patch antennas, primarily for MIMO applications. This

LC decoupling structure comprises chip capacitors and strategically positioned metallic vias, which are periodically placed at the center of the patch antenna. Odabasi et al. [A10] offer an extensive analysis of a newly proposed U-shaped polarization converter intended for mutual coupling suppression in patch antennas. It has potential for MIMO antenna applications due to its compact size, high isolation, and identical broadside radiation properties. Gangwar et al. [A11] propose a cross-substrate technique to enhance the isolation and lower the envelope correlation coefficient of a four-patch array for MIMO vehicle communication.

### *D. Adaptive Arrays*

The articles in this section focus on contributions related to modeling and compensating mutual coupling in adaptive arrays, particularly in the context of direction finding and power steering.

Elbir et al. [A12] introduce a novel approach, treating beam-splitting and mutual coupling as array imperfections. The letter proposes a subspace-based method using multiple signal classification with calibrated for beam-split and mutual coupling algorithm, aimed at compensating for both beam-splitting and mutual coupling for accurate direction-of-arrival estimation.

Ding et al. [A13] present an interval-based optimal synthesis for antenna array beamformers. This approach encompasses power pattern synthesis while considering imperfections arising from calibration errors and mutual coupling.

### *E. Application-Oriented Studies*

The articles in this section are focused on application-centric studies within the realm of antenna arrays and mutual coupling.

*Square-Kilometer Array (SKA):* Bolli et al. [A14] conduct an extensive assessment to gauge the numerical accuracy of antenna pattern modeling for the SKA-low radio telescope elements (SKALA4.1). In SKA-low, the antennas are electromagnetically in close proximity, and mutual coupling effects are significant. This evaluation is performed by initially comparing the simulated electric field from two commercial electromagnetic solvers, FEKO and Galileo. These solvers utilize a moment-method-based approach with a multilayer fast multipleaccelerator, enabling a comparative analysis to be conducted. Modeling a single element requires approximately 10 000 degrees of freedom, and when extending to model 256 elements, the challenge involves dealing with millions of unknowns. The study rigorously scrutinizes the computed field, encompassing both amplitude and phase, between the two solvers. It also quantifies the errors in beamforming arising from this computation. Throughout this critical analysis, the primary objective of this work, which is to assess the reliability of computational electromagnetics (CEM) solvers for modeling SKA elements, has been achieved. The finding is crucial as the design of future SKA generations is expected to rely on CEM tools. Meanwhile, Paonessa et al. [A15] present experimental investigations into radiation pattern deterioration resulting from mutual coupling among SKA low-frequency elements, using a UAV-based methodology, corroborating the findings of the earlier study utilizing the moment-method solver FEKO.

*Simultaneous Transmit and Receive (STAR) Antenna Systems:* Prasad et al. [A16] propose a novel design strategy to address a host of challenges associated with co-radiator antennas for STAR operations, including insufficient isolation, unwieldy size, intricate feeding mechanisms, complex design, and inadequate bandwidth. Xie et al. [A17] introduce a co-aperture dual CP (CADCP) antenna engineered to provide high isolation for STAR sensing systems. This design incorporates a pair of strategically positioned U-shaped slots (USS) with a 90° phase shift within the ground plane to effectively mitigate mutual coupling between the transmit (Tx) and receive (Rx) antennas. The innovative antenna design offers a compact footprint, excellent Tx-Rx isolation, and consistent Tx and Rx patterns.

*UAV, MIMO, and Lens Antenna:* Salucci et al. [A18] explore an unconventional approach by implementing a soft surface, utilizing the same PCB for a pair of co-located bow-tie blade antennas on a drone. This approach diverges from the conventional horizontal layout with an electrically large ground plane. ousaf et al. [A19] introduce a novel hidden antenna solution tailored for a quad-element Inverted-F Antenna optimized for MIMO applications. Finally, Biswas [A20] presents the implementation of a dual-polarized and wideband antenna feed matrix intended for use as a feed source in a multibeam lens antenna, effectively reducing mutual coupling effects.

## III. DISCUSSION

When planning any Special Cluster on a particular topic, there is always a risk that the selection of papers submitted is not fully representative of the current issues being tackled by the community. We received a total of 36 submissions, of which 20 appear in this issue. The rejected papers had numerous deficiencies, mainly regarding novelty or relevance to the topic of mutual coupling. All papers that were novel in some respects were encouraged to improve aspects of their submission to ensure we included as many new directions as possible.

It was anticipated that papers would be submitted on some other topics, and work may be currently in progress in these areas and will be reported in due course. Some of the anticipated topics included some extensions to the current work on TCAs, traveling wave antennas, computational techniques for large arrays to reduce processing time, coupling between co-sited antennas, and leveraging mutual coupling to enhance antenna performance. The latter has been done through TCAs, dummy parasitic elements [1, pp. 349–354] or for gaining additional information as in radio astronomy.

## IV. CONCLUSION

The topic of mutual coupling has been an active area of research for over 80 years. This Special Cluster is intended to contribute to the literature in this area and give a snapshot of topics in the area of interest in the second decade of the 21 century. The articles are representative of the topics involving mutual coupling for antennas with increasing complexity for a wide range of applications from MIMO to radio astronomy.

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## APPENDIX
## RELATED ARTICLES

[A1] J. Cavillot, D. Tihon, H. B. Van, and C. Craeye, “Embedded patterns and extended array admittance matrix,” *IEEE Antennas Wireless Propag. Lett.*, early access, Jun. 13, 2023.

[A2] D. Sarkar and Y. M. M. Antar, “Antenna mutual coupling in near-field: Insights using EM Lagrangian density and complex helicity,” *IEEE Antennas Wireless Propag. Lett.*, to be published.

[A3] R. Li, Y. Zhang, B. Xiao, and Y. Cui, “An aperture-shared dual-band antenna array based on upstanding dipoles,” *IEEE Antennas Wireless Propag. Lett.*, to be published.

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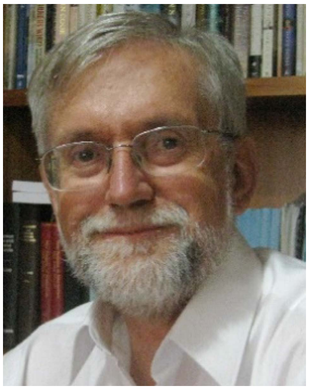

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Prof. Bird is a Fellow of the Australian Academy of Technological Sciences and Engineering, an IET Fellow, a Fellow of the Royal Society of NSW, an Honorary Fellow of the Institution of Engineers, Australia, and a member of Sigma Xi.

Dr Bird has been awarded three CSIRO Medals, the IEEE Third Millennium Medal, and a Centenary Medal for service to Australian society in telecommunications. He has received five best paper awards. He was named 2003 Professional Engineer of the Year by the Sydney Division of Engineers Australia. In 2012, he was awarded the M.A. Sargeant Medal from Engineers Australia for achievement in the field of electrical engineering. He received the James R. James Lifetime Achievement Award of the IET in 2016 for outstanding contributions to the field of Antennas and Propagation. He was a Distinguished Lecturer for the IEEE Antennas and Propagation Society from 1997 to 1999. In 2010, he completed six years as Editor-in-Chief of IEEE Transactions on Antennas and Propagation. He was President of the IEEE Antennas and Propagation Society in 2013.