Mutual Coupling: Concept, Challenges and Research Areas

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Abstract— Mutual coupling in antenna arrays is an emerging area of research that has drawn the attention of many researchers. Starting with the definition of mutual coupling, the paper discusses the need for these systems to be implemented in different application domains, and the research challenges to define a suitable formalism that is more than applicable in the wireless domain. The paper concludes with mutual coupling playing a major role in the design and development of future antenna systems, a state of art with regard to the main research on mutual coupling reduction.

Keywords: ASM-MBF, RMIM, DOA

I. INTRODUCTION

In many areas, the world of wireless cellular communications is explosively increasing. It can't be imagined its scale. Global activities are an indication of its significance in this thriving industry. The deployment of telecommunications systems antenna arrays has been proposed in recent years for the purpose of solving inadequate canal bandwidth problems, thus satisfying the ever growing demand on a wide range of communication channels. Various studies have demonstrated that, if a range is used appropriately in a Telecommunication System, it helps improve the performance of multiple mobile devices by enhancing channel power and spectrum efficiency, extending coverage, customizing beam shapes, tilting multiple beams to track multiple mobile equipment. It also reduces multi-way fading, co-channel interference, complexity, network costs and the probability of failure. The antenna array system degrades its efficiency and is the topic of discussion. Mutual coupling takes place. The paper is organized as follows- the concept of mutual coupling is discussed in section 2. Section 3 discusses the challenges in elimination of mutual coupling. Section 4 addresses various techniques for reducing reciprocal coupling in antenna arrays.

II. MUTUAL COUPLING CONCEPT

The mutual coupling between the antenna elements in an array is the electromagnetic interaction. The current developed in each array antenna element depends on its own excitement and on the contributions made by the antenna elements adjacent to it. Mutual coupling is inversely proportional to the spacing between the different antenna elements in an array. Mutual coupling in an array causes:

Modifications of the array radiation pattern Changes the input impedance of the antenna elements you may use mutual impedance, S parameters, a matrix or an embedded element pattern to describe the mutual coupling. The first paper "An open-source code for the calculation of the effects of mutual coupling in arrays of wires and for the ASM-MBF method'' by C. Craeye et al. introduces a method known as "array scanning method-maro basis function (ASM-MBF)'' to illustrate the fast numerical calculation and analysis of wire antenna arrays. For finite and infinite arrays, Matlab-language open-source codes are described and used in appropriate examples. This study offers a user-friendly tool for understanding the phenomenon of mutual coupling in antenna arrays. In the second paper "Mutual coupling compensation for direction-of-arrival estimations using the receiving-mutual-impedance method'' by H. S. Lui and H. T. Hui, the authors introduce a new idea in mutual coupling analysis by proposing a so-called receiving mutual impedance method (RMIM). This method, proposed specifically for antenna arrays receiving, provides a correct method for the analysis of the mutual coupling effect in antenna arrays receiving. A new concept of mutual impedance is introduced which explains and demonstrates its significance and effect on the analysis of the mutual connection. In an estimation problem of direction-of-arrival (DOA), the reception mutual impedance that differs fundamentally from traditionally defined mutual impedance is used to produce precise DOA estimate results. Readers interested in this paper are strongly encouraged to learn more.

The third paper, entitled "Bandwidth enhancement of antenna arrays utilizing mutual coupling between antenna elements" by M. Wang and W. Wu et al. introduces an interesting idea in mutual coupling analysis by relating the enhancement of an array's bandwidth to a proper manipulation of its input S parameters. The authors present a formula relating the VSWR bandwidth with the so-called frequency derivatives of the reflection coefficients, which in turn can be expressed in terms of the frequency derivatives of the S parameters. They further point out that a mutual cancellation of some of the S parameters can increase the bandwidth of an antenna array.

In the fourth paper, "Decoupling of multi-frequency dipole antenna arrays for microwave imaging applications," the authors E. Saenz and K. Guven et al. make use of a metasurface superstrate to reduce mutual coupling of a printed dipoles array. The metasurface consists of three layers of printed metallic strips aiming to spread the radiated field over a larger aperture, thus enhancing the final gain of the dipole array laid on top of it. It is found that this metasurface structure can reduce the mutual coupling by 3 dB to 20 dB, increase the boresight radiation, and reduce the endfire radiation.

In the fifth paper, "Compact printed arrays with embedded coupling mitigation for energy-efficient wireless sensor networking," C. G. Kakoyiannis and P. Constantinou use photonic bandgap (PBG) structures to reduce mutual coupling between compact printed antenna arrays used for the construction of wireless sensor networks. Their study shows that an efficient reduction of mutual coupling effect by 15–20 dB can be achieved by a proper design of the PBG structure. Furthermore, they show that impedance bandwidth can be maintained even with a substantial decrease in element separation.

The remaining four papers all deal with the antenna mutual coupling effect in MIMO systems. In the sixth paper of "Optimization of training signal transmission for estimating MIMO channel under antenna mutual coupling conditions," X. Liu and M. E. Bialkowski investigate the effect of antenna mutual coupling on the performance of training-based channel estimation for MIMO systems. Two training-based channel estimation methods are intensively studied: the scaled least square (SLS) method and the minimum mean square error (MMSE) method. They find that the accuracy of MIMO channel estimation is governed by the sum of eigenvalues of the channel correlation matrix which, in turn, is affected by the mutual coupling in the transmitting and receiving antennas. A water-filling-based procedure is proposed to optimize the training signal transmission to minimize the MIMO channel estimation errors.

In the seventh paper of "Effect of antenna mutual coupling on MIMO channel estimation and capacity," X. Liu and M. E. Bialkowski further consider the antenna mutual coupling effect on MIMO channel capacity with imperfect channel estimations, that is, the case of lacking perfect channel state information (CSI). Their study investigates the effect of different antenna element separations on channel estimations and the resulting MIMO channel capacities.

The eighth paper, entitled "The effect of mutual coupling on an HAP diversity system uses compact antenna arrays" by T. Hult and A. Mohammed, investigates the effect of antenna mutual coupling on MIMO system performance in a special diversity system. This system is the high altitude platform (HAP) diversity system proposed in Europe. In this HAP system, signal repeaters equipped with multiple antennas are deployed in the stratosphere layer to relay signals within a given local area, forming an effective MIMO communication system. The effect of mutual coupling which is present in the MIMO compact antenna arrays on the system capacity is rigorously studied, leading to determination of the optimal angle separations between transmitters and receivers that maximize the total mutual information of the HAP system. In this paper, a novel communication system is considered employing multiple antenna channels.

In the final ninth paper which entitled "Mutual coupling effects on pattern diversity antennas for MIMO femtocells," the authors Y. Gao and S. Wang et al. characterize the effect of mutual coupling on the performance of a diversity antenna system operating in MIMO femtocells. This is accomplished through experimental investigations. A suitable patch antenna is designed with two excitation ports to achieve pattern diversity. The dependence of the channel capacity on mutual coupling between the excitation ports is determined by measurements. This is an application study with practical measurement values provided.

III. Challenges in Reducing Mutual Coupling

The open-circuit voltage method does not exactly match the real situation in an antenna array, for example a receiving array, in which all the antenna elements are excited by an external source outside the array. In this case, the current distribution on a particular antenna is not driven by an embedded current source connected at its terminals but by the external source. Hence the use of the definition in (2) will cause an error when applied to a receiving antenna array. This error is likely to become large (i) when the antennas' electrical sizes are large, (ii) when the antenna separations are small, or (iii) when the external excitation source causes a different current distribution on an antenna element from that caused by the embedded current source on that antenna.

In the s-parameter method, the receiving or transmitting antenna array is modelled as an N-port network and the mutual coupling between antenna elements is modelled using scattering parameters. Once the s-parameters are all determined, the decoupled signals can be computed from the coupled measurable terminals signals. However, by using this method, only the transmitting array is modelled correctly with respect to the handling of the mutual coupling effect. For a receiving array, because the definition of s-parameters requires that the antenna elements be driven by an active source connected at the terminals of one of the antennas in the array, it fails to correctly model the array whose antenna elements are all driven by an external source outside the array. The consequence of this method is that the mutual coupling in the receiving array is independent of the external source (the impinging wave) which is incorrect as explained in Section 2.1. Hence the performance of this method (which can be measured by its decoupling power = 20log|coupled signal/uncoupled signal|) is similar to that of the open-circuit voltage method and it suffers from the same problems as that method.

This method was first proposed by Steyskal and Herd in 1990. The terminal voltage (coupled voltage) developed on a particular antenna element is expressed as a sum of two parts. The first part is due to the response of the isolated radiation pattern of that particular element to the incoming signal. The second part is a linear combination of the responses of the isolated radiation patterns of all the other antenna elements in the array to the incoming signal. The mutual coupling between the particular antenna element and the other elements in the array is modelled by a set of combination coefficients, cmn, which, when taken together for all the antenna elements, form a coupling matrix relating the coupled and decoupled voltages. Once the combination coefficients are all known, decoupled voltages can be obtained from the coupled terminal voltages. The problem with this method is the determination of the combination coefficients (the coupling coefficients). One method to determine the coupling coefficients is through the s-parameter measurement. However, this again detaches mutual coupling from the incident signal and this method will be similar to the open-circuit voltage method.

In the calibration method, a coupling matrix is usually formed first. This coupling matrix relates the coupled signals to the uncoupled signals and is similar to the impedance matrix in (1). The important step in this method is to determine this coupling matrix by a carefully designed experimental procedure or by an iterative calculation method based on some known initial conditions. Once the coupling matrix is known, decoupled signals can be obtained from the coupled signals through a transformation using the coupling matrix. The performance of this method critically depends on the accuracy in measuring or calculating the coupling matrix which is usually not an easy task because the number of unknowns to be determined can be very large. A problem faced by this method is the tedious measuring procedure or iterative steps to determine the coupling matrix which are required to be carried out again once there is a change to the antenna array configuration or a change to the external signal environment. 2.6. Decoupling by Antenna Design Mutual coupling in arrays can be reduced or minimized by a proper design of the antenna elements and/or the array configuration. For example, in [18] a two-element planar Yagi antenna array shows a very low mutual coupling (S21 < -22 dB) when the Yagi antennas were aligned in a co-linear form rather than in a parallel form. When the Yagi elements are in the co-linear form, they are almost in the radiation null of the near field pattern of the other element and this result in a low mutual coupling level. In [15], an antenna array was designed to minimize the parasitic current on the antenna elements by changing the load impedances so that the parasitic radiation fields caused by adjacent elements are reduced. This results in the active (coupled) element patterns of the antenna elements similar to that of a single (uncoupled) element pattern, i.e., mutual coupling is substantially reduced. Note that this method, though rather effective and simple (requiring no additional processing procedure), is only applicable to specific types of antenna elements.

An inductive decoupling network was reported in which two small inductor coils are connected to two large imaging coils. The two small inductor coils are for decoupling the mutual coupling between the two large imaging coils. The small inductor coils are placed very close to each other so that their mutual coupling can counteract the mutual coupling of the imaging coils. Capacitive decoupling networks, on the other hand, employ capacitors rather than inductor coils to decouple the mutual coupling effect. This can be seen in the patents. Adjacent coils and non-adjacent coils are connected together through a capacitor network whose capacitor values, when carefully chosen, can decouple the mutual coupling between adjacent coils as well as non-adjacent coils. The capacitive decoupling networks are applicable to surface coils, a capacity decoupling network works at a high-field condition of 14.1 T and a decoupling power of around -20 to -40 dB could be achieved. The method using inductive or capacity decoupling networks requires an accurate determination of the decoupling inductor or capacitor values which is sometimes a formidable task, especially for large phased arrays. Looking from a broader perspective, the inductive or capacitive decoupling network is actually to realize (or approximately realize) the impedance matrix obtained in the open-circuit voltage method (in (1)) or the impedance matrix obtained in the receiving mutual impedance method (in (3)). Hence depending on how the capacitor or inductor values in the decoupling networks are determined, this method is basically similar to either the open-circuit voltage method or the receiving mutual impedance method.

IV. Research Areas to Reduce Mutual Coupling

Meander lines (MLs) in two configurations are presented to reduce the mutual coupling (MC) between two microstrip patch antenna elements. Inserting a slot in the ground plane between the antenna elements is a simple method to reduce the MC, while adding the MLs in the slot of the ground can further reduce the MC. In the first configuration, one ML is inserted in the slot of the ground and a maximum MC reduction of 39 dB throughout the −10 dB bandwidth is achieved. What's more, the radiation patterns are not changed compared with the dual-element microstrip antenna array with a slotted ground. For the second configuration, two MLs are added in the slot of the ground. It is found that a maximum isolation of 53 dB can be obtained. However, the radiation patterns are slightly changed compared with the dual-element microstrip antenna array with a slot in the ground. Meanwhile, the measured peak gain and efficiency of the dual-element microstrip antenna array in the two configurations are given. Along with this paper, several prototypes have been fabricated and measured. The simulated results are in good accordance with the measurements, which are presented to verify that MC reduction can be achieved between microstrip antenna elements by adding the MLs in the slotted ground.

In antenna arrays, mutual coupling is an undesired effect which degrades the array pattern and the performance of array signal-processing algorithms like for Angle-Of-Arrival (AOA) estimation. Various approaches for mutual-coupling compensation that evaluate the coupling in receiving and transmitting modes have been studied. In this paper, a definition of the mutual coupling in receiving mode from the scattering parameters is introduced. A dissimilarity factor is added on the signals after the coupling calibration to simulate amplitude and phase variations at the termination of array elements. The coupling model shows the role of antenna characteristics and distance between the elements. When the antennas are all connected to a matched load and there is no dissimilarity between the antennas, the coupling in the receiving mode assimilates to that in the transmitting mode. To validate this statement, the coupling of an array of two patch antenna elements in these two modes is calculated, which shows an adequate agreement. A simplified technique calibrating the coupling and the dissimilarity is also proposed. The application of these coupling calibration techniques together shows many possibilities to improve antenna arrays processing.

Reducing mutual coupling between elements of an antenna array is one of the main topics in array designs. The use of electromagnetic band-gap (EBG) structures built by microstrip technology is an attractive way to mitigate the mutual coupling problem. This letter describes a novel configuration of uniplanar compact electromagnetic band-gap (UC-EBG) structures to reduce mutual coupling between the radiating elements. The idea is to use the UC-EBG structures placed on top of the antenna layer. The main objective is to reduce both the element separation and the mutual coupling between the patch antennas, which in turn increases antenna directivity. The proposed configuration eliminates drawbacks of similar structures presented in previous works.

A new type of mutual coupling reduction technique is applied to metamaterial substrate integrated waveguide (SIW) slotted antenna array. The circular shaped reference SIW antenna array is constructed from Alumina substrate with dimensions of 40×5×1.5mm3. Embedded in the reference antenna are 38 slots with dimensions of 2×1×1.5mm3. The reference SIW antenna operates over X- to Ku-bands with average isolation between the radiation slots of approximately -10dB. Isolation was increased by inserting metal fence isolators (MFIs) between the radiation slots, which increased the isolation by an average of 13dB. In addition, the antenna's impedance matching bandwidth is improved with no degradation in the radiation patterns. With MFIs the maximum gain achieved improves by ~10%. The technique is simple to implement and proposed for synthetic aperture radar (SAR) and multiple input multiple output (MIMO) applications.

V. Conclusion

The paper presents a short state of the art regarding the development of the mutual coupling-future antenna systems to which many researchers pay more attention. Mutual coupling in various ways will contribute substantially in antenna array design. The paper concludes by discussing different techniques to reduce mutual coupling.

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