

## EFFECT OF MUTUAL COUPLING IN SMART ANTENNA FOR MASSIVE MIMO SYSTEM-A TECHNICAL SURVEY AND DESIGN CONSIDERATIONS

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**Abstract.** *The 5<sup>th</sup> and 6<sup>th</sup> (5G and 6G) generation wireless communications exploit large antenna arrays to serve a large number of users over large distances. In 6G sky communication, large antenna arrays will be used for communications with unmanned aerial vehicles (UAV), satellites and high altitude platforms (HAP) along with terrestrial infrastructures. The manuscript at hand dispenses an organized technical survey of the effects of mutual coupling in massive MIMO (mMIMO) (multiple input multiple output) systems, subsuming the effects on the direction-of-arrival (DoA) of the signals and digital beamforming, which substantiate the performance of the design of smart antenna (SA). The mutual coupling distorts the wave front of the incoming signal, resulting in an erroneous DoA estimation and majorly degrading other performances of the antenna array in an mMIMO system. An assortment of compensation techniques is elucidated since it is unfeasible to completely eliminate the mutual coupling. Further, some investigated results of isotropic antennas and dipole arrays are explicated, screening the mutual coupling effects. For practical antenna array design, compensation for the effect of mutual coupling is necessary, especially for densely populated arrays in an mMIMO system. Investigations on various methods of compensation of mutual coupling in antenna array design are surveyed.*

**Key words:** *Smart antenna, Mutual coupling, Mutual impedance, Massive MIMO, Beamforming*

### 1. INTRODUCTION

The capacity in wireless communication can be enhanced using a MIMO system which uses multiple antennas at both the transmitter and receiver ends [1-3]. At the receiving end, by combining the received signals from all the antennas, the fading effect can be reduced, which increases the signal-to-noise ratio (SNR) and minimizes the error rate. 5G wireless

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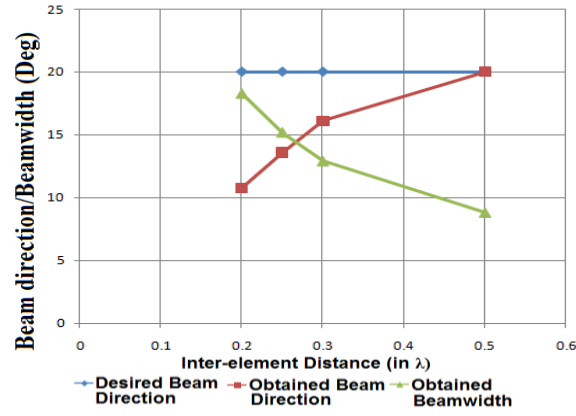
networks and 6G sky connections for the services of multiple users, need massive MIMO (mMIMO) systems where large antenna arrays with directive beams are used [4, 5]. The mMIMO system produces narrow targeted beams with low interference. The escalating technology and widening employment of wireless communications are enriching the present and future years. The very first model of smart antenna i.e. retrodirective antenna, was conferred by a patent in 1959 to L. C. Van Atta [6] for retrodirective beam formation. Smart antenna applications necessitate close analysis of the electromagnetic behaviour of the signals, particularly in regard to mutual coupling [7], [8]. The smart antenna arrays (SAA) [9-11] tilt the beam electronically to any desired user direction while producing a null in the direction of the interferer in a cellular network [12]. The SAA provides enhanced security in the network. The constraints of power utility and frequency reuse can be improved in a cellular network by employing digital beamforming using multiple antenna techniques [13-14]. The massive employment of antenna elements has two main effects: Spatial correlation for the propinquity of the elements as signal sources and mutual coupling due to small inter-element spacing [15-17]. Since the effect of mutual coupling changes impedance and radiation properties of an antenna array, it is necessary to consider the effect of mutual coupling in smart antenna design. After DoA estimation of the incoming signal, the smart antenna system in the base station forms the desired beam towards the user in a cellular network. So, the basics of mutual coupling with related supporting equations and the effect of mutual coupling in DoA estimation and beamforming should be known for the smart antenna design.

In this paper, a technical survey on the impact of mutual coupling in adaptive smart antenna, for 5G and 6G large array applications is reported. The objective of this paper is to survey the methods of analysis of mutual coupling effect in antenna arrays for densely populated arrays for the application to mMIMO systems, including the survey on the compensation methods of mutual coupling effect. The aim of this paper also includes the comparison of analysis and compensation methods for mutual coupling effects in antenna arrays. In section 2 the simulated results for isotropic and dipole antennas are presented to show the effect of mutual coupling on smart antenna parameters. In section 3, the impact of mutual coupling on DoA Estimation is described. In Section 4 research reports on the effect of mutual coupling in adaptive beamforming in smart antennas are reviewed. The research works on different methods of compensation of mutual coupling in smart antenna are surveyed in section 5. In section 6 a discussion on the effect of mutual coupling on antenna arrays used for mMIMO, UAV, and HAP is included. After this technical survey, a brief conclusion is added in section 7 where the importance of this survey and the deficit of research work on the effect of mutual coupling on smart antennas are presented. The topics covered in this technical survey provide useful information for the design of densely populated large antenna arrays.

## 2. MUTUAL COUPLING IN SMART ANTENNA

In an antenna array, part of the energy is coupled with the nearby ones [18] and the radiation characteristics appreciably differ from the stand-alone antenna features. The beam patterns with mutual coupling effects show higher side lobe levels and a broader main lobe, thereby reducing the directivity of the array [19]. In an mMIMO system, the radiation beams of the array system must be very directive with lower side lobe levels. The

effect of mutual coupling [20-21] becomes dominant in a densely populated array. For 5G and 6G wireless communications, the mMIMO systems can use the sub-6GHz band, where dipole antennas can be used as array elements. The design of a dipole array is easier compared to other antenna arrays. The paper [22] investigates the effect of mutual coupling in a smart environment for a linear isotropic array, where inter-element distances are varied to observe the variations of beam direction and half-power beamwidth (HPBW) due to the mutual coupling (Fig. 1). The signal processing algorithm, least mean square (LMS) algorithm, is used for generating adaptive radiation beams and nulls. In this simulation work for a smart antenna of dipole array, the number of antennas  $N=12$ , beam direction (BD)  $=20^\circ$ , null direction (ND)  $=30^\circ$  and  $\mu=0.0001$ .



**Fig. 1** Variation of beam direction and beamwidth (HPBW) for an isotropic array

The simulated results of smart antenna of isotropic elements, for various beam direction (BD) and null direction (ND) by varying the inter-element spacing, are tabulated in Table 1. In Table 1, when the element spacing is less, the BD and ND are far from the desired BD and ND. For low values of element spacing, HPBW is wide, which means due to the mutual coupling effect, the directivity decreases (directivity is inversely proportional to the HPBW). The SLL is very poor due to the mutual coupling effect for low element spacing.

In a dense antenna array (say, inter-element spacing  $d < 0.3\lambda$ ) the mutual coupling is more. For a dipole SA, the impact of mutual coupling in beamforming is investigated. If two transmitting dipole antennas are excited by the voltage sources  $V_{s1}$  and  $V_{s2}$ , the coupled voltages  $V_{12}$  and  $V_{21}$  are [23]

$$V_{12} = Z_{12}I_2 \quad (1)$$

$$V_{21} = Z_{21}I_1 \quad (2)$$

Source internal impedances of antennas 1 and 2 are  $Z_{g1}$  and  $Z_{g2}$ , and  $Z_{11}$  and  $Z_{22}$  are the antenna self-impedances. The  $Z_{12}$  and  $Z_{21}$  are the mutual impedances when antenna 2 and antenna 1 are excited, respectively. Original electrical characteristics are changed due to mutual coupling between the two antennas. Reciprocity theorem is used to determine the current  $I_n$  at n-th antenna, with the equivalent model of Fig. 2.

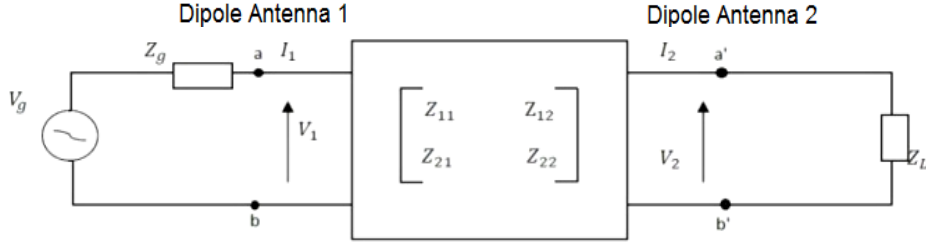
$$V_2 = Z_{21}I_1 + Z_{22}I_2 = -I_2Z_L \quad (3)$$

$$I_2 = -\frac{Z_{21}}{Z_{22}+Z_L}I_1 \quad (4)$$

$$I_n = -\sum_{m=0, m \neq n}^{N-1} \frac{Z_{nm}}{Z_{nn}+Z_g} I_m \quad (5)$$

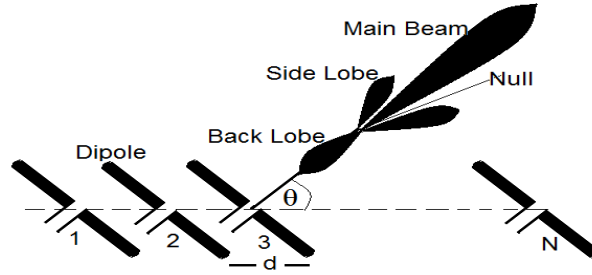
**Table 1** Variation of smart antenna parameters with inter-element spacing

No. of antenna elements	Element Spacing 'd'	Desired BD, ND (Deg)	Obtained BD, ND (Deg)	HPBW (Deg)	SLL <sub>max</sub> (dB)
N=12	0.5λ	20, 30	20, 30	8.8	-11.8
	0.3 λ		16.1, 30	12.9	-5.6
	0.25 λ		13.6, 30	15.2	-4.5
	0.2 λ		10.8, 30	18.3	-3.5
	0.5 λ	-20, -10	-20, -10	9	-12.5
	0.3 λ		-23.6, -10	13.6	-5.7
	0.25 λ		-25.7, -10	16.3	-4.7
	0.2 λ		-28.9, -9.7	20.7	-3.9
	0.5 λ	-10, 0	-10, 0	8.8	-13.2
	0.3 λ		-13.2, 0	13	-6.1
	0.25 λ		-15.3, 0	15.5	-5.1
	0.2 λ		-18.5, 0.2	18.8	-3.8
	0.5λ	20, 30	20, 30	5.3	-12.74
	0.3 λ		19.8, 30	8.8	-12.23
0.25 λ		18.7, 30	10	-8.74	
0.2 λ		16.8, 30	11.7	-6.23	
N=20	0.5 λ	-20, -10	-20, -10	5.5	-13.63
	0.3 λ		-20, -10	9	-13.10
	0.25 λ		-21.4, -10	10.5	-9.45
	0.2 λ		-23, -10	12.5	-6.95
	0.5 λ	-10, 0	-10, 0	5.2	-13.76
	0.3 λ		-10.8, 0	8.6	-12.98
	0.25 λ		-11.4, 0	11.2	-10.1
	0.2 λ		-12.5, 0	11.8	-7.02



**Fig. 2** Equivalent model for two dipole antennas

A linear antenna array of  $N$  number of co-linear dipole antennas is shown in Fig. 3.



**Fig. 3** Array of dipole antennas

For dipole length of ' $l$ ', propagation constant  $\beta$ , the radiation field is [12]

$$E(\theta) = j\eta \frac{I_0 e^{-j\beta r}}{2\pi r} \left[ \frac{\cos(\frac{\beta l}{2} \cos \theta) - \cos(\frac{\beta l}{2})}{\sin \theta} \right] \quad (6)$$

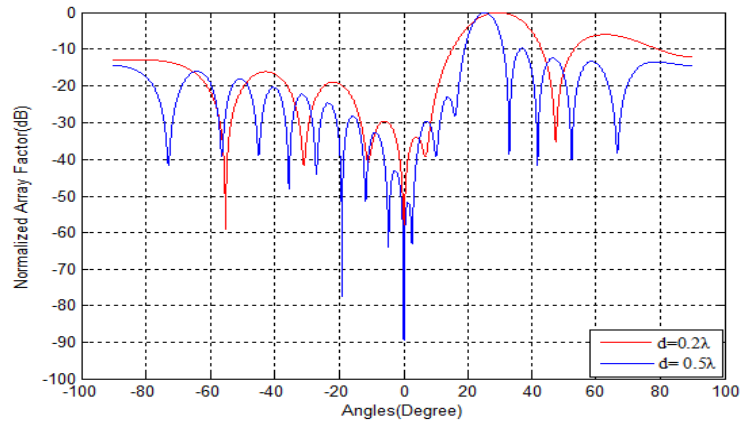
$I_0$  is the excitation current and  $\eta$  is the free-space impedance ( $120\pi\Omega$ ). Total radiated field for  $N$  number of dipoles, with mutual coupling is

$$E_{total}(\theta) = \sum_{n=1}^N I_n E(\theta) e^{j(n-1)(\frac{2\pi d}{\lambda} \cos \theta + \alpha)} \quad (7)$$

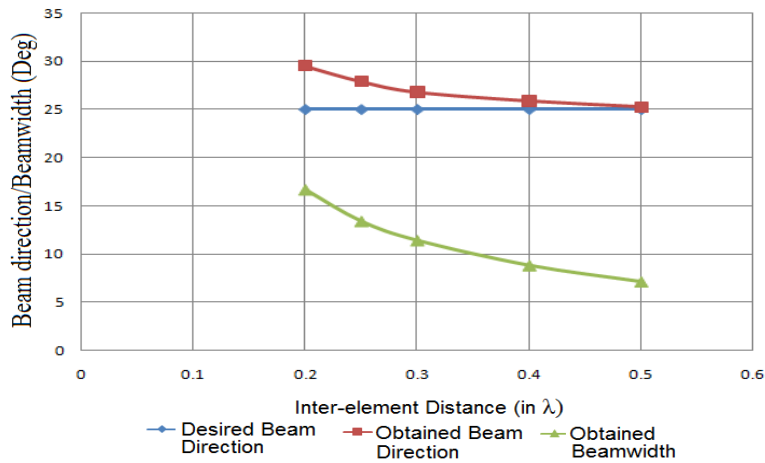
The array factor is

$$AF(\theta) = \sum_{n=1}^N I_n e^{j(n-1)(\frac{2\pi d}{\lambda} \cos \theta + \alpha)} \quad (8)$$

Where  $\alpha$  is the progressive phase shift. The effect of mutual coupling on the radiation beam by varying dipole spacing with  $N=16$ ,  $BD=25$  Deg,  $ND=15$ , and  $\mu=0.0001$  and using the LMS algorithm is simulated and is shown in Fig. 4 (a). In Fig. 4(b), the variations of beam direction and HPBW for the half-wave dipole array are shown.



(a)



(b)

**Fig. 4** (a) Radiation pattern; (b) Variation of beam direction and HPBW

In [20] an optimal beam generation method is extended, evaluating the active element patterns along with the impedance matrix, effective even in severe coupling effects. The MIMO systems [15] in wireless communication are expected to be one of the key technologies in the future using spatial diversity and spatial multiplexing [24] techniques. The problem of computation of mutual coupling for wire antenna arrays was solved by the method of moment (MoM) in numerical electromagnetic code in 1970s [25-28]. Here, the technical survey for the effect of mutual coupling on SA design is described separately in two sections as effect on DoA estimation and effect on adaptive beamforming. A separate section is included on the literature survey for compensation methods of mutual coupling in the design of antenna array.

### 3. EFFECT OF MUTUAL COUPLING IN DIRECTION OF ARRIVAL ESTIMATION

One of the imperative measurements in signal processing is the estimation of the DoA of narrowband signals. The estimation of DoA is an explicit way out for the quality of service degradation owing to the handoff problem. Several approaches can be employed for DoA estimation, like, minimum variance distortionless response algorithm, the multiple signal classification (MUSIC) algorithm, maximum entropy, and the estimation of signal parameters via the rotational invariance (ESPRIT) algorithm. The ESPRIT algorithm presumes all the array elements to have similar radiation patterns, as a result of which mutual coupling impinges on the estimation error directly. Underlining the effects of mutual coupling, particularly in circular antenna arrays, a mutual coupling matrix is given for the received signal  $x(t)$ , giving the equation [29]

$$x(t) = \sum_{k=1}^K a_{MC}(\varphi_k) s_k(t) + n(t) \quad (9)$$

Here,  $a_{MC}(\varphi_k)$  is the array steering vector taking mutual coupling into consideration.  $S(t)$  is a  $K \times 1$  signal vector and  $n(t)$  is the  $N \times 1$  noise vector.

Liao et al. [30] propose subspace-based techniques for DoA evaluation and tracking with the effects of coupling. At times, the high-resolution DoA schemes like ESPRIT may fail due to coupling. Generally, the calibration algorithms assume DoAs as time invariant, but real systems are time varying. In the papers [31-32], the authors describe that among the used DoA estimation approaches, the maximum-likelihood method gives the best asymptotic performance but at the cost of high computational complexity. So, SAGE algorithm which is a modification of expectation maximization is proposed.

In the network theory approach for DoA estimation [11], an array of  $N$  elements is considered as  $N+1$  terminals of a linear, bilateral network that responds to an outside source. A relation between normalized impedance matrix  $Z_0$  (normalized to the load impedance) and open circuit voltages  $V_0$  at the antenna terminals is established as [7]

$$VZ_0 = V_0 \quad (10)$$

Where,  $V$  is the element output voltage.

Using network model approach, signal-to-interference-plus-noise-ratio (SINR) of the SA is estimated as

$$SINR = P_d/P_a \quad (11)$$

$$P_a = \sum_{k=1}^m P_{ik} + P_n \quad (12)$$

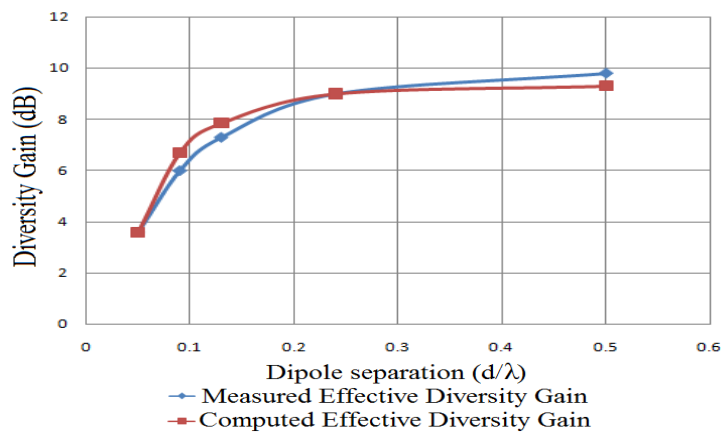
Where,  $P_d$  is the desired output signal power,  $P_{ik}$  is the output interference power and  $P_n$  is the output thermal noise power.

In comparison with the ESPRIT algorithm, the stated method is appropriate for applications in cylindrical array structure. The approach of angles of arrival degrades as the mutual coupling varies with the identical vectors of the array, altering the covariance matrix. DoA estimation for the uniform linear array (ULA) using the MUSIC algorithm supposedly degrades as the mutual coupling by the interactions between receiving antenna elements isn't ignorable and the prior data about the array doesn't hold true. In the subspace approach of the MUSIC algorithm, eigenvectors for the signal space and the noise span are orthogonal to each other [33]. The Root-MUSIC algorithm [34], based on polynomial rooting, reduces the computational complexity of the MUSIC algorithm and is more apt

for fewer array elements with low SNR. The DoAs  $\theta_1, \theta_2, \dots, \theta_k$ , are computed by the conventional algorithms to construct the new transformation matrix using the coupling coefficients [35]. This algorithm response is quite good even in multipath or unknown conditions.

#### 4. EFFECT OF MUTUAL COUPLING IN BEAMFORMING OF ADAPTIVE SMART ANTENNA

In an array antenna, when one antenna is excited and radiates, part of the energy is coupled to the second, inducing a current as a result of which it starts radiating even if it is not excited. Mutual coupling intrudes into the beamforming pattern in an array and needs to be examined thoroughly for the adaptive signal processing step. Quite a few adaptive algorithms [36] have been helpful for beamforming, such as least mean square (LMS), recursive least squares, conjugate gradient method, constant modulus algorithm [21], and so on. The idea is to form maximum gain beam(s) in the desired path, nullifying the intruder's direction. It is always chosen to place a deeper null in the interferer direction, but in a real environment mutual coupling exceedingly undermines it. A lot of studies have concluded that SINR lessens as the interferer comes close to the desired direction. Phase distribution and current magnitude in a dipole array are changed due to mutual coupling, distorting the vectors and giving rise to peaks and nulls in directions from the desired ones. The beam patterns with mutual coupling have higher side lobe levels, broad beamwidths and shallower nulls. In the papers [37, 38], the interaction between the antenna array components is described by a mutual impedance matrix  $[Z]$ . For computation, the methods presented are induced electromotive force, method of moments (MoM) and full-wave electromagnetic numerical computation. Wang *et al.* [39], exploiting mutual coupling between the antenna elements for the printed slot arrays, investigate its effects on the array bandwidth. In the paper [40] diversity gain of a two-port antenna is measured in a reverberation chamber. Variation of measured and computed diversity gains [41] with dipole separation is compared in Fig. 5.



**Fig. 5** Dipole array in MIMO system [41]

A mathematical analysis for the estimation of error with mutual coupling outcome is done in [41]. The methods rely on the sum of eigenvalues of the channel correlation matrix. The increase in spatial correlation lowers the estimation error at the cost of the channel's effective degree of freedom (EDOF) [42]. Studies have shown an improvement in channel capacity due to mutual coupling when antenna spacing at both the transmitting and receiving ends is between  $0.2\lambda$  and  $0.4\lambda$  as a result of an increase in the EDOF. In [43, 44] effects of mutual coupling are highlighted in broad-side and end-fire cases with channel modelling. Experiments point out that the radiation pattern is the same for a half-wave dipole and isotropic source in the azimuthal angle, but mutual coupling changes the size of the back lobe due to variations in phase difference and element spacing, reducing the directivity. By varying the dipole length [45] in the array, maximum directivity increases up to a certain extent with an optimum length of around  $1.2\lambda$ . Beyond it, the side lobe level rises. A smart antenna with an active frequency selective surface for user detection is presented [46], where due to an active element effect of mutual coupling on radiation beam characteristics can be reduced. A most recent article [47] has reported the achievement of low mutual coupling using a metamaterial patch antenna for two-port MIMO, which is suitable for ultra wideband (UWB) applications.

A summary table comparing the surveyed works on mutual coupling in antenna arrays is presented in Table 2.

**Table 2** Summary table for the surveyed works on mutual coupling in antenna array

Research Report	The method of analyzing mutual coupling effect	Antenna type	Applications
Ref [13]	The concept of 'extra port' is introduced in the element-by-element based correction procedure to involve the mutual coupling effects.	Linear dipole array.	5G wireless communication, Wi-Fi, satellite communication.
Ref [16]	The performance of the large-scale adaptive antenna arrays, in the presence of mutual coupling is presented. An expression SINR of in the presence of strong interference signals, considering the mutual coupling between the array elements, is derived.	Dipole antenna array.	Massive MIMO system.
Ref [20]	An optimal beam forming method, in the presence of mutual coupling, is proposed. Using the active element patterns and the impedance matrix, a computationally efficient beam forming algorithm is obtained, which can manage all mutual coupling effects.	Small and medium-size dipole antenna array.	Vehicular communication.
Ref [29]	The full-wave electromagnetic analysis using Integral Equation 3D (IE3D) software is used for the antenna design in the presence of mutual coupling.	Circular and concentric circular patch antenna arrays.	CDMA wireless communication.
Ref [35]	The problem of mutual coupling in DOA estimation is solved by using the time-frequency analysis.	Smart antenna of isotropic elements.	Massive MIMO.
Ref [38]	A Rayleigh fading channel with varying angle-of-arrival spread is considered where maximum SNR beamforming weights are used for array beamforming in the presence of mutual coupling. These weights are further correlated with mutual coupling at the base station array.	Smart antenna.	Digital beamforming in CDMA system.

Ref [39]	Linear antenna arrays with corporate feed and a closed-form expression of the reflection coefficient are derived at the input port of the feeding network to obtain mutual coupling coefficient for bandwidth enhancement.	Slot arrays and a two-element Vivaldi array.	Avionic, UAV, HAP.
Ref [40]	This paper explains how MIMO and diversity antennas with mutual coupling can be analyzed by classical embedded element patterns.		MIMO antennas and diversity antennas.
Ref [41]	Scaled least square (SLS) and minimum mean square error (MMSE) are used to assess the effect of mutual coupling on the performance of training-based MIMO antenna systems.	Wire dipole antenna arrays.	MIMO antenna system.
Ref [42]	The issue of mutual coupling is addressed by applying an exact network theory framework to consider the mutual coupling effect in MIMO systems. This method includes a new power constraint that limits the radiated power in the presence of mutual coupling.	Half-wave dipole array.	MIMO wireless communication.
Ref [43]	A generic matrix coupling model, augmented by a matching network, is used to analyze the effects of mutual coupling to a channel matrix in the channel model.	Uniform linear array of vertical dipole antennas.	Massive MIMO system.
Ref [47]	The effect of mutual coupling are investigated by combining three methods: Cutting the radiating patch with a partial ground plane, shape modification of the patch, and the use of metamaterials.	Metameerial patch antenna array.	MIMO and UWB communications.

##### 5. METHODS OF COMPENSATION OF MUTUAL COUPLING EFFECT IN SMART ANTENNA DESIGN

For the design of a smart antenna of a densely populated array, inter-element spacing may be as small as  $0.2\lambda$ , and in this case it is necessary to consider the mutual coupling in the array design, and for this various methods are available. In [48], a new compensation matrix is proposed to minimize the effect of mutual coupling in antenna arrays. In [49], in receiving thin wire dipole arrays, it is compensated by measurement only. Also adding the compensated excitation weights improves the antenna efficiency [50]. The compensated weight  $W_i$  for each element is calculated by [51]

$$[W] = \{[U] + [S]^{-1}\}^{-1}[S]^{-1} - [W_i^{(0)}] \quad (13)$$

$W_i^{(0)}$  is the zero mutual coupling weight of each array element,  $S$  is the mutual coupling coefficient between the array elements and  $[U]$  the unity matrix. As the decoupling methods depend on the applications of the system, one of the easiest to use is the element pattern method [52] categorized as the isolated element pattern method, which takes the coupling-free voltages, and the other is the coupled element pattern method, which obtains the received coupled voltages through the coupled radiation pattern from the array elements. The coupling between the array elements is given by a set of coefficients  $C_{ms}$ , relating the coupled and decoupled voltages [53]

$$C_{m,n} = \frac{kd}{2\Pi E_0} \int_{-\Pi/kd}^{\Pi/kd} \frac{g_m(u)}{f(u)} e^{-jnkdu} du \quad (14)$$

$E_0$  is the amplitude of the incident plane wave,  $f(u)$  is the isolated element pattern,  $k$  is the wave number,  $d$  is the uniform element spacing,  $g_m(u)$  is the received signal at element  $m$ , and  $u$  is the sine of the angle  $\theta$  from broadside. Thinned smart antenna is proposed to enhance the network performance using large antenna arrays [54]. Bellofiore *et al.*, exemplify the use of eigenspace projections for improved performance of the algorithm, namely the eigensubspace projection algorithm, by adjusting the LMS weights and taking the impedance matrix into account as follows [55]

$$w_{opt} = Z^{-1}w_{opt} \quad (15)$$

Spatially multiplexing of local elements technique [56] delineates the approach of reducing the radio channels to one with no loss of the signal veracity. Mutual coupling effects can be estimated by considering an  $N$ - element antenna array as  $N$ -port network [57] as

$$\sum_{i=1}^N \left( I_{N,i} V_i + \frac{Z_{N,i}}{Z_L} V_i \right) = \sum_{i=1}^N V_{0i} \quad (16)$$

Where,  $N=1, 2, \dots$ ,  $-\frac{Z_t^{N,N}}{Z_L} = 1$  and  $i = 1, 2, \dots, N$ .  $Z_{N,i}$ ,  $V_i$  and  $V_{0i}$  are the matrices.

The above equation calculates decoupled open-circuit voltages  $V_{0i}$  useful for array signal processing. The receiving mutual impedance method surmounts the inadequacy of parameters, judging the elements to be in the receiving mode and is terminated with known impedance [26-27]. The impedance varies as a function of the direction of the incoming signal and demands for an estimated current distribution. In [58], the mutual coupling effect is reduced by using a compensation network, which is realized with two couplers and a passive network based on a 2<sup>nd</sup>-order band-pass filter. Using S-parameters doesn't serve the entire purpose, as it calls for the accurate modeling of the transmitting array only, failing to estimate the mutual coupling effects at the receiving array. An extended S-parameter method (ESPM) encapsulates multiport antennas measuring reflection and mutual coupling coefficient [59-60]

$$B = S^c A \quad (17)$$

Where,  $A$  is the column vector of incident waves and  $B$  of reflected waves at each port.  $S^c$  being the scattering matrix of the  $2n$ -port network. The incident wave  $A_k$  and reflected wave  $B_k$  can be given as

$$A_k = \frac{V_k + I_k}{2} \dots \dots \dots B_k = \frac{V_k - I_k}{2} \quad (18)$$

$V_k$  and  $I_k$  are the port voltage and port current,  $k=1, 2, \dots, n$ . Earlier S-parameter-based method were confined to single antenna measurements, but the ESPM emphasizes accurate measurement of reflection and mutual coupling of multiport antennas. Furthermore, it extends to radiation pattern, radiation efficiency, and actual gain measurements [61]. The technique fits very well in the designing of decoupling and matching circuits for small antennas. A powerful and consistent decoupling method to minimize the coupling effects is a must for the present expansion of antenna array applications [62]. The methods of

compensation of mutual coupling effect in antenna array design, are presented in tabulated form in Table 3.

**Table 3** Comparison of methods of compensation of mutual coupling effect in array design

Sl. No.	Research Report	Mutual coupling compensation method
1.	Ref. [28]	The report presents that the mutual coupling is not increased when mutual impedance between the thin wire dipoles is forced to keep constant. The method of moment is used for computation.
2.	Ref. [48]	A compensation matrix is proposed to make the modal excitation coefficients of each antenna element in an array equal to those obtained without considering the effect of mutual coupling.
3.	Ref. [49]	The characteristic mode analysis (CMA) can be used to develop a method for compensating the mutual coupling effect. Using the knowledge of CMA, a mutual coupling compensation matrix is constructed by obtaining the characteristic matrix and Z-matrix of a metallic antenna array and in this way compensation error can be reduced.
4.	Ref. [52]	The mutual coupling compensation may be considered as a matrix multiplication performed on the received-signal vector. This restores the received signals by the isolated elements in the absence of mutual coupling. This technique is most practical for digital beamforming antennas.
5.	Ref. [53]	The method of compensating mutual coupling, presented here, uses the calculation of the coupling coefficients between the array elements to form a matrix. This matrix is used to compensate for the effects of mutual coupling for a planar antenna array.
6.	Ref. [54]	In thinning of the antenna array, some antenna elements remain 'off' which increases the inter-element spacing and reduces the mutual coupling effect.
7.	Ref. [57]	This report describes the importance of compensation of mutual coupling in array design and also describes the various compensation methods.
8.	Ref. [58]	The mutual coupling effect is reduced by using a compensation network and it is realized with two couplers and a passive network, based on a 2 <sup>nd</sup> -order band-pass filter.
9.	Ref. [59]	The Impedance and mutual coupling characteristics are found after reducing the effect of the coaxial cables by synthesizing the measured S-parameters, and the unbalanced currents on the outside of the coaxial cables are canceled at feed points.
10.	Ref. [60]	The microstrip antenna arrays are fed by co-planar waveguide (CPW) and to minimize the mutual coupling effect, orientations of the patches are optimized.

## 6. THE EFFECT OF MUTUAL COUPLING IN ANTENNA ARRAYS FOR FUTURE WIRELESS TECHNOLOGIES

In this section the discussion on the effect of mutual coupling in millimeter wave mMIMO, UAVs and HAPs are presented. In millimeter wave mMIMO, UAV and HAPs different frequency bands are used, and therefore the effect of mutual coupling differs

between antenna arrays (element spacing depends on wavelength). For MIMO and mMIMO systems, used frequency bands are the 2.4 GHz band, the 3.5 GHz band, the 5 GHz band and for UWB communication, the 3.1-10.6 GHz band [63-65]. For millimeter wave (mmWave) mMIMO systems, the frequency band of 24-100 GHz is used in 5G mmWave deployments [66]. The popular frequency bands for 5G UAV are 900 MHz, 2.4 GHz, and 5.8 GHz, whereas in 6G wireless communication, in addition to these bands, mmWave bands are also proposed [67]. The HAPs all over the world use different frequency bands, like frequency bands 21.4 - 22 GHz, 24.25 - 27.5 GHz, 31 -31.3 GHz, and 38 - 39.5 GHz [68]. In an mMIMO system the number of antennas in the array is large. Therefore, the mutual coupling effect directly affects the performance of mmWave mMIMO systems and should be considered in array design [69]. Mutual coupling effect degrades the matching efficiency and radiation pattern of the mMIMO system. In UAV communication, mostly light weight patch antennas, dipoles, or monopoles are used. At low frequencies, because of the space constraints in the device, the element spacing is low, and the mutual coupling effect should be taken into account in array design. The mutual coupling between the radiating patches can be controlled using varicap diodes [70]. Mutual coupling between the antenna elements modifies the reflection coefficient when monopole antennas are used for UAV communication [71]. In [72] optimal antenna element position in a limited plane is determined to minimize the mutual coupling effect for a sparse array for UAV application. The HAPs generally placed at an altitude of 18 to 20 km from the earth's surface because the wind speed at that level is minimum. Therefore, high-gain antennas are required, and large array antennas are used. A MIMO-HAP diversity system is proposed in [73] which takes into account the effect of mutual coupling in the antenna system. This antenna array system consists of twelve electric dipoles, which are positioned on the twelve edges of a cubical configuration. A MIMO-HAP diversity system is used [74], where a power control method is used to minimize the mutual coupling effect in the array antenna. For low-profile and light-weight applications, like UAV and HAP, microstrip antenna arrays are the first choice in spite of the narrow bandwidth and low gain of a microstrip antenna. But multilayered micorstrip antenna can be used for bandwidth enhancement [75, 76]. One of the potential sources of performance degradation of micortsip array is mutual coupling between the antennas, and this performance degradation can be reduced by the selection of proper elements and proper orientation of the patches [14, 77]. A higher dielectric constant of the substrate of a microstrip antenna can increase the mutual coupling effect, whereas a lower dielectric constant reduces it but increases antenna size. If the substrate thickness is more, the mutual coupling effect in a microstrip array is less [78].

## 7. CONCLUSION

The effect of mutual coupling in an SA affects antenna gain, beamwidth, radiation pattern, and input impedance. It also causes the shift of the main beam and null from the desired directions. These effects are severe for 5G and 6G wireless communications, where for long-distance communications large antenna arrays with relatively smaller antenna spacing are used. This paper presents in detail the effects of mutual coupling in direction of arrival estimation as well as adaptive beamforming of smart antennas separately, including the design considerations for large arrays, like mMIMO. The survey on the

different types of compensation methods is also included. Since smart antenna is one of the pivotal technologies in next-generation cellular communication, this paper can show the prospective direction of research on this topic. It is found that in most of the papers, authors have taken account of the effects of mutual coupling but not used compensation methods. Most of the papers reflect on the effect of mutual coupling on linear arrays using isotropic antennas. In realistic status, densely populated antenna arrays are planar. Because of their low-profile nature, microstrip antennas are useful for large array applications in 5G and 6G applications. The effect of mutual coupling in the case of a planar microstrip array is very significant because for a microstrip array, mutual coupling depends on the relative position of the microstrip antennas. The main contribution of this paper is to present the issue of mutual coupling in the design of densely populated antenna arrays for mMIMO systems. The paper describes the survey on the methods of analysis of the mutual coupling effect in array design along with the mutual coupling compensation methods. The future investigation is to review and analyze mutual coupling in lightweight planar arrays for 6G sky connection. Also, the future work will be to survey the experimental methods of compensating for the mutual coupling effect in antenna arrays.

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