Decoupling Methods for the Mutual Coupling Effect in Antenna Arrays: A Review

Hon Tat Hui*

Department of Electrical and Computer Engineering, National University of Singapore, 10 Kent Ridge Crescent Singapore 119260, Singapore

Received: February 9, 2007; Accepted: April 19, 2007; Revised: April 23, 2007

Abstract: Mutual coupling is a common problem in the applications of antenna arrays. It significantly affects the operation of almost all types of antenna arrays. Over the past years, there have been many different kinds of methods suggested to decouple (or to compensate for) the mutual coupling effect in antenna arrays. The effectiveness of these methods varied and depended upon the types of antenna arrays being considered and the applications in which the antenna arrays were used. In this paper, a brief review of the decoupling methods for the mutual coupling effect in antenna arrays is presented. These include patented and non-patented methods. The methods are grouped under seven categories for antenna arrays in communications and four categories for antenna arrays in magnetic resonance imaging (MRI). The various methods will be first briefly described and their operation principles will be explained. Then some comments on their scopes of application and their comparisons or relations to other methods will be given. The problems associated with these methods will also be analysed. This is the first review on this topic and we believe that it helps to give an overview of the decoupling methods which have been so far proposed in the literature. We also believe that this review will help clarify some main differences and relations between the various decoupling methods and provide some information for future research on the problem of mutual coupling.

Keywords: Mutual coupling, decoupling method, compensation method, communication, magnetic resonance imaging (MRI), antenna array, MRI phased array, surface coil array, mutual impedance, receiving mutual impedance, element pattern, calibration, open-circuit voltage, capacitive decoupling network.

1. INTRODUCTION

Mutual coupling is a common problem in the applications of antenna arrays. It significantly affects the operation of almost all types of antenna arrays. The study of mutual coupling problem started several decades ago and attracted the interest of not just antenna engineers and researchers but also many researchers from other disciplines such as communications and biomedical imaging where antenna arrays are frequently used. Compared with a single antenna, an antenna array is able to provide spatial information of the signal distributions. However, this function critically relies on the independence or distinctiveness of the signals received or transmitted from different antenna elements in the array. In reality, this is simply impossible because antenna elements will interact with each other, i.e., they will mutually couple with each other. In order to restore the independent signals received or transmitted from the antenna elements, the coupled effect has to be removed or reduced. Hence, it is very important to find ways to decouple the array signals received or transmitted from antenna arrays. Over the past years, there have been many different kinds of methods suggested to decouple the coupled array signals. The effectiveness of these methods varied and depended upon the types of antenna arrays being considered and the applications in which the antenna arrays were used. In this paper, we present a brief review of these decoupling methods (also known as compensation methods in some cases) for antenna arrays which have been suggested in the literature. Many of these decoupling methods have not been patented but some of these, especially those found in magnetic resonance imaging (MRI), are almost all patented. We shall review those non-patented ones first while those patented ones will be discussed later. In the review, the various methods will be first briefly described and their operation principles explained. Then some comments on their scopes of application, their comparisons, or their relations to other methods will be given. The problems associated with these methods will also be analysed. It should be noted that for a detailed understanding or for a direct reference to the specific results regarding a particular method, readers have to be referred to the particular paper or patent in which the method was first reported. In our review, citations of previous literature or patents will be grouped under the same method and will not be individually addressed for the sake of brevity. Readers can choose to look into a particular paper or patent listed under the same category which they find more interested in. A section on “Current and Future developments” serves to conclude this paper.

2. REVIEW OF DECOUPLING METHODS

There have been many decoupling methods suggested to tackle the mutual coupling problem in antenna arrays. Each based on different principles and is designed for different applications. It is necessary to categorize them so that they can be analysed and reviewed together with other similar methods. We first review those methods designed for conventional antenna arrays, i.e., those found in communications. In the next section, we will review those methods designed specially for magnetic resonance imaging (MRI) antenna arrays.

2.1. Open-Circuit Voltage Method

The open-circuit voltage method (typically represented by [1-12]) is the earliest method used to analyse the mutual coupling effect in antenna arrays. It was suggested by Gupta and Ksieniski [1]. In this method, mutual coupling between two antennas is characterized by a mutual impedance whose definition is taken from that used originally in circuit analysis, i.e., the Z parameters in network analysis. Accordingly, it treats the antenna array as an N-port network and relates the antenna terminal voltages $V_j$ ($j = 1, 2, \ldots, N$) to the so-called open-circuit voltages $V_{ocj}$ through an impedance matrix as

$$
\begin{bmatrix}
Z_{11} & Z_{12} & \cdots & Z_{1N} \\
Z_{21} & Z_{22} & \cdots & Z_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
Z_{N1} & Z_{N2} & \cdots & Z_{NN}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
\vdots \\
V_N
\end{bmatrix}
= 
\begin{bmatrix}
V_{oc1} \\
V_{oc2} \\
\vdots \\
V_{ocN}
\end{bmatrix}
$$

(1)
where $Z_{ij}$ ($i, j = 1, 2, \ldots, N$) are the mutual impedances between the antenna elements and $Z_{ii}$ are the self-impedances of the antennas. The mutual impedances or the self-impedances in (1), for example for wire antennas, are defined as below [13]

$$\begin{align*}
Z_{ij} &= \frac{V_{\text{net}}}{I_{j}(0)} = -\frac{1}{I_{j}(0)} \int_{0}^{L} E_{j}(r) \cdot I_{j}(r) \, dr \\
&= \frac{1}{I_{j}(0)} \int_{0}^{L} \left[ E_{j}(r) - E_{i}(r) \right] \cdot I_{j}(r) \, dr
\end{align*}$$

(2)

where $I(0)$ is the value of the current distribution $I(r)$ at the feedpoint (and similarly for $I_{j}(0))$, $E(r)$ is the radiation electric field at the surface of the $i$th antenna (with its terminals being shorted) which is generated by the current distribution at the $j$th antenna, and $L$ is the physical length of the $i$th antenna. The definition in (2) is for a self-impedance if $i = j$ and for a mutual impedance if $i \neq j$. Note that in (2), the current distribution $I(r)$ is obtained by driving the $i$th antenna in the transmitting mode while the $j$th antenna’s terminals are shorted (and similarly for $I_{j}(r)$). Eq. (2) can be calculated by using the EMF method [14] or the moment method [15]. The following comments are made about this method:

1. 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 but by an external source (the impinging wave) which is incorrect as seen why the open-circuit voltages are supposed to be free of mutual coupling. This is because when all the antenna elements are open-circuited (with no current flowing), there would be no radiation from the antennas and so the voltages developed on the antenna terminals (open-circuited) are solely due to the external source. In a strict sense, this argument is fallacious because an open-circuit antenna will still radiate.

2. The mutual impedance $Z_{ij}$ in (2) is defined with one antenna (the $j$th antenna) excited by an active current source and its radiation in turn excites the other antenna (the $i$th antenna). Furthermore, it assumes that the $j$th antenna is shorted while the $i$th antenna is open circuit. The open-circuit voltage $V_{\text{net}}$ in (2) is calculated through a short circuit current by using the Thevenin’s equivalent source method. The open-circuit voltage is obtained by multiplying the short circuit current with an equivalent impedance obtained by looking into the terminals of the $i$th antenna. The concept of the open-circuit voltage is taken from circuit analysis in which a circuit component or a network port can be equivalent to an open circuit voltage source in series with an equivalent impedance (the well-known Thevenin’s theorem). Once the open-circuit voltage and the equivalent impedance are known, we can easily calculate the current through any terminal load that will be connected to that circuit component or network port under the assumption that the open-circuit voltage source is not changed by the terminal load. However, strictly speaking, the open-circuit voltage concept cannot be directly applied to antennas. This is because when a different terminal load is connected to a pair of open-circuit terminals, a different current distribution is produced, i.e., $I(r)$ in (2) will be different and is not simply scaled uniformly by a constant. That means that the open-circuit voltage is changed and this change cannot be offset by a corresponding change in $I_{j}(0)$ in the denominator of (2). Hence the mutual impedance $Z_{ij}$ is changed. This argument shows that the previous assumption in the definition of the mutual impedance in (2) being independent of the terminal load connected to the antennas is wrong. This gives an error when using (1). This argument also shows that an accurate definition of mutual impedance should take the antenna terminal loads into account.

3. Except the above two problems with the open-circuit voltage method, the use of the open-circuit voltage concept in modelling an antenna, especially a receiving antenna, into a circuit element has still a number of problems and uncertainties being unsettled as seen from some recent studies [16-21]. A common view from these studies is that the Thevenin equivalent source model with an open-circuit voltage source in series with an equivalent impedance is not sufficient to model a receiving antenna.

Notwithstanding these problems, the open-circuit voltage method has actually become the most widely accepted method for mutual coupling analysis in antenna arrays. This is probably due to its ease of application with a formulation using circuit concepts. To decouple the antenna voltages, we just need to calculate the system in (1) with known (measured) antenna terminal voltages $V_{j}$ ($j = 1, 2, \ldots, N$) to obtain the open-circuit voltages $V_{\text{net}}$ ($j = 1, 2, \ldots, N$) on the right-hand side, which are supposed to be caused by the external source alone on the respective antenna elements. It is rather easy to see why the open-circuit voltages are supposed to be free of mutual coupling. This is because when all the antenna elements are open-circuited (with no current flowing), there would be no radiation from the antennas and so the open-circuit voltages are expected. This can be seen from some recent studies on this topic [22-29].

2.2. S-Parameter Method

In the s-parameter method (typically represented by [30-32]), 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 its terminals (open-circuited) are solely due to the external source. 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 $\text{20log(coupled signal/uncoupled signal)}$) is similar to that of the open-circuit voltage method and it suffers from the same problems as that method.

2.3. Full-Wave (Moment) Method

The full-wave method (typically represented by [32-35]) seeks to solve the entire boundary value problem of the electromagnetic field for the whole antenna array by the moment method [15]. It uses the known array measurable quantities, such as terminal voltages and currents (which come with mutual coupling), to calculate the incident field on the array, which is coupling free. However, since only terminal voltages or currents are known but not the entire current or voltage distributions on the antenna elements, this method results in an under-determined system of equations. In order to solve the under-determined system, usually some approximations have to be made, such as an assumed current distribution [32], a known coming direction of the incident field [34], or solving the under-determined system directly using a compromised method [35]. The performance of this method depends on the approximations made, which sometimes may not be realistic, and its scope of application is therefore limited. On the other hand, if we assume the incident field is completely unknown,
then this method can serve as an accurate analysis tool to investigate mutual coupling effect on the performance of an antenna array [33].

2.4. Element Pattern Method

A. Isolated Element Pattern Method (Typically Represented by [36-41])

This method was first proposed by Steyskal and Herd in 1990 [36]. 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, \( c_{ij} \), 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.

B. Coupled Element Pattern Method (Typically Represented by [42-45])

A similar method to the isolated element method is the coupled element method. In this method, the aim is to obtain the coupled voltages from the antenna elements instead of the coupling free voltages. More specifically, the aim is to be able to predict the received coupled voltages through the responses of the so-called coupled radiation patterns of the antenna elements. The coupled radiation pattern of an antenna element is its radiation pattern obtained in the presence of all other antenna elements in the array (but which are not excited). That is, all the mutual coupling effect is taken into account. By using this method, the total array response will be expressed as a function of the coupled radiation patterns instead of the isolated radiation patterns. Hence this method does not decouple the coupled signals but rather takes the mutual coupling effect into account. All signal processing algorithms working with this method must be redesigned using coupled radiation patterns instead of isolated radiation patterns. A disadvantage of this method is the need to have a huge memory to store all the coupled radiation patterns for the signal processing algorithms because these coupled radiation patterns are in general 2D patterns. This method is suitable for analysis purposes in which real time processing is not required.

2.5. Calibration Method

In the calibration method (typically represented by [46-51]), 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 [52,53]. For example, in [52] a two-element planar Yagi antenna array shows a very low mutual coupling (\( S_{21} < -22 \) 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 results in a low mutual coupling level. In [53], 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.

2.7. Receiving Mutual Impedance Method

The receiving mutual impedance method (typically represented by (22-29)) is a method which aims to solve the problems faced by the open-circuit voltage method as mentioned in Section 2.1. This method was proposed by Hui in 2003 [22]. It defines a receiving mutual impedance [25, 54] which takes into account of the antenna terminal loads and the external signal source. Unlike the open-circuit voltage method, it seeks to obtain the decoupled voltages across the terminal loads of the antennas rather than the open-circuit voltages. Hence it does not suffer from the problems with the use of the open-circuit voltage concept. Similar to the open-circuit voltage method, it also models the antenna array as an \( N \)-port circuit network but bases on different circuit parameters, such as receiving mutual impedances, terminal currents and voltages, but not Thevenin equivalent sources or impedances. It relates the measured terminal voltages (coupled voltages) \( V_i (i = 1, 2, \ldots, N) \) to the decoupled terminal voltages across the same antenna terminal loads through an impedance matrix which contains the receiving mutual impedances [24, 27], i.e.,

\[
\begin{bmatrix}
1 & -\frac{Z_{12}^2}{Z_L} & \cdots & -\frac{Z_{1N}^2}{Z_L} \\
-\frac{Z_{21}^2}{Z_L} & 1 & \cdots & -\frac{Z_{2N}^2}{Z_L} \\
\vdots & \vdots & \ddots & \vdots \\
-\frac{Z_{N1}^2}{Z_L} & -\frac{Z_{N2}^2}{Z_L} & \cdots & 1
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
\vdots \\
V_N
\end{bmatrix}
= \begin{bmatrix}
U_1 \\
U_2 \\
\vdots \\
U_N
\end{bmatrix}
\]

(3)

where \( U_j (j = 1, 2, \ldots, N) \) are the decoupled terminal voltages and \( Z_j^v \) is the receiving mutual impedance between the \( j \)th and the \( i \)th antennas. Once the impedance matrix on the right hand side of (3) is known, the decoupled terminal voltages can be obtained from the measured coupled terminal voltages. The definition, the calculation method, and the measurement method for the receiving mutual impedance are all different from those of the conventional mutual impedances in (2) and can be found in [25,29,54]. It has been shown in a number of applications that the performance of the receiving mutual impedance method is much better than that of the open-circuit voltage method. This can be seen in direction finding [22, 25, 26], in adaptive nulling [23, 24], and in magnetic resonance imaging (MRI) [27, 28]. Note that this method is easy to apply,
3. DECOUPLING METHODS IN MAGNETIC RESONANCE IMAGING (MRI) PHASED ARRAYS

Decoupling methods for MRI phased arrays deserve some special attention because most of the patented decoupling methods belong to this category. Some recent ones can be found in [60, 62-67]. In MRI, antenna arrays are found increasingly important because of the rapid development in parallel MRI [58, 59, 61] which can substantially shorten the imaging time and increase the image signal-to-noise ratio (SNR) for imaging over larger areas. In MRI, antenna arrays are called phased arrays and they bear some distinct differences from the antenna arrays in communications. These include: (i) they receive in the near-field region rather than in the far-field region as in communication arrays, (ii) their inter-element spacings (around 0.1 wavelength) are much smaller than those in communication arrays (around 0.5 wavelength) because of the much lower operation frequencies in MRI arrays, and (iii) they use magnetic field antennas rather than electric field antennas as in communication arrays. These differences make MRI arrays even more susceptible to the mutual coupling effect than communication arrays and most of their decoupling methods are also different from those for communication arrays. Basically, for MRI arrays, such as phased coil arrays, there are three categories of decoupling methods: (i) overlapping of adjacent coils combined with low input impedance pre-amplifiers, (ii) capacitive or inductive decoupling networks, and (iii) open-circuit voltage method. They are discussed below.

3.1. Overlapping of Adjacent Coils Combined with Low Input Impedance Pre-Amplifiers

This method was first proposed by Roemer and Edelstein [60, 61] for MRI surface coil arrays. Roemer and Edelstein noticed that mutual coupling between surface coils is mainly in the form of mutual induction, called inductive coupling, which is caused by magnetic flux linkage between the coils. Hence they suggested overlapping some parts of the adjacent coils in an array so that they share a common area and the magnetic flux (coupled) through this common area can cancel the magnetic flux through the non-overlapping area and the inductive coupling can be substantially reduced. This can be seen from the schematic drawing in Fig. (1). This really works but overlapping is only possible between adjacent coils. For non-adjacent coils (i.e., coils separated farther than adjacent coils), mutual coupling still exists although not as significant as that between adjacent coils. To reduce the mutual coupling between non-adjacent coils, Roemer and Edelstein further suggested using low-input-impedance pre-amplifiers. These low-input-impedance pre-amplifiers are connected to the coils through an impedance matching circuit which transforms the low input impedance of a pre-amplifier to a very large impedance looking at the terminals of a coil. This large impedance effectively limits the current flowing through the coil and hence minimizes the mutual coupling. This technique of course also applies to adjacent coils on top of the overlapping technique. It turns out that Roemer and Edelstein’s method is rather effective and was widely accepted in the design of MRI surface coil arrays. This can be seen in [62] in which a quadrature coil array adopted the same decoupling techniques. In [63], an array of surface coils also used the same decoupling techniques and it further demonstrated that the same techniques could even be used for 2D arrays to provide a better coverage of the human body. A modification to the original overlapping method is seen in [64] in which overlapping of two adjacent coils can be made in a vertical plane perpendicular to the plane of the surface coils. This modification consists of a separate intermediate coil placed between the two coplanar surface coils to be decoupled. The intermediate coil was bent into two halves at a right angle to each other so that one half overlapped with one surface coil while the other half is placed at the vertical plane to be joined to the other surface coil. A part of the other surface coil is also bent through a right angle to the vertical plane joining the first surface coil. In this way the two surface coils can be effectively overlapped at the vertical plane through the intermediate coil. It was claimed that such a design can allow the overlapping of two surface coils or two surface coil sub-arrays in a very convenient way, especially when the surface coils or surface coil sub-arrays are already designed to be fixed inside some fittings and cannot be made overlapped with each other.

Notwithstanding the widely accepted use of Roemer and Edelstein’s overlapping method in MRI arrays, this method, like other decoupling methods, has its limitations. Basically the overlapping technique can be considered as the method of decoupling by antenna design mentioned in the previous section (Section 2.6) and has the same limitation as explained there. Except that, in MRI, the use of phased arrays is mainly for expanding the imaging area (a larger field-of-view). However, overlapping of adjacent coils obviously works against this objective and results in a smaller imaging area. Furthermore, overlapping of adjacent coils

![Fig. (1). The Overlapping method.](image-url)
only decouples the magnetic coupling effect but not the electric coupling effect which couples through the electric field. Hence it can be expected that the decoupling power of this method is limited, around -10dB as reported previously. The use of low-input-impedance pre-amplifiers is not a justifiable method by itself because it seeks to reduce the coil currents in order to reduce mutual coupling. Coil currents are the power sources which send image signals to the processing circuits. An attempt to reduce the coil currents will also reduce the signal powers in an equal amount as the reduction in the mutual coupling. Thus this method reduces mutual coupling and the signal power together. Because of these problems, decoupling networks based on circuit construction were proposed as described below.

3.2. Capacitive or Inductive Decoupling Networks

An inductive decoupling network was reported in [65] 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 in [66-68]. Adjacent coils and non-adjacent coils are connected 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 [66] or volume coils [67, 68]. In [69], 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.

3.3. Open-Circuit Voltage Method

The open-circuit voltage method was proposed by Lee et al. [70]. It is basically the open-circuit voltage method (mentioned in Section 2.1) applied to MRI phased arrays. In [70], the impedance matrix was realized as a 2N-port circuit network: N input ports from the phased coil array and N output ports to the signal processing circuits. The inputs from the phased coil array to the decoupling network are coupled signals while those output from the decoupling network to the processing circuits are decoupled signals. The problems of this method have been discussed in Section 2.1. In MRI, as the coils are separated much closer together than the antenna elements in communication arrays, these problems become even more serious in MRI phased arrays.

3.4. Receiving Mutual Impedance Method

As mentioned in the last section (Section 2.7), the receiving mutual impedance method is a more accurate method than the open-circuit voltage method. Actually this method is even more suitable for MRI phased arrays. As mentioned in Section 2.7, this method takes into account the external source. This is done through the definition of the receiving mutual impedance in which the current distribution on the exciting antenna is excited by an external source [27, 28, 54]. In MRI, the external source for the phased array is the active slice excited by the RF pulse. The position of the active slice is accurately controlled by the static magnetic field and the gradient magnetic fields. Hence the position information of the active slice is available and can be used to define the receiving mutual impedance for MRI phased arrays in a very accurate manner. Studies using this method to decouple the array signals have been found in MRI surface coil arrays [27] and MRI quadrature coils [28]. It was shown that mutual coupling could be almost totally removed and nearly coupling-free array signals can be obtained. Comparisons with the open-circuit voltage method have also been provided in these studies. However, care must be taken that studies with this method are still limited to theoretical investigations or experimental measurements in a simulated MRI environment only. It should be noted that for the most effective operation of the receiving mutual impedance method in MRI, the receiving mutual impedances have to be measured in situ with the MRI machine or be calculated with the practical MRI machine environment taken into account.

CURRENT & FUTURE DEVELOPMENTS

Mutual coupling is a notorious problem in antenna arrays. With the use of antenna arrays in an ever-increasing number of situations, decoupling methods are found to be very important and necessary. It is interesting to note that most of the patented decoupling methods are found in MRI applications and almost none found in the communication area. Currently, the open-circuit voltage method is still the most popular decoupling method used in communication arrays. This method was proposed over two decades ago and notwithstanding some of its shortcomings such as lack of accuracy, it has solid concepts based on circuit analysis and hence it is the easiest method to understand and apply. Other more sophisticated methods such as the element pattern method and the s-parameter method are also frequently used in mutual coupling analysis and array signal processing. The element pattern method offers a higher decoupling power but is also more difficult to apply. The full-wave (moment) method is more suitable for analysis purposes rather than to decouple the coupled array signals in a real time processing environment. The receiving mutual impedance method is a new attempt to overcome the problems with the open-circuit voltage method and retains most of the advantages of the open-circuit voltage method. In some recent studies, this method has been demonstrated to have a potential to become a powerful decoupling method for antenna arrays. In MRI arrays, the overlapping method combined with low input impedance pre-amplifiers is still the most popular method currently in use. The use of inductive or capacitive decoupling networks has been seen to attract more attention recently. One of the reasons may be its greater flexibility in application and its relatively higher decoupling power. However, the open-circuit voltage method is not so frequently used in MRI phased arrays. This may be probably due to its lower decoupling power than other methods because of its inherent problems as mentioned earlier. Again, for the receiving mutual impedance method, some recent studies have shown that it can provide an enormous decoupling power for MRI phased arrays. However, as indicated in the past reports, studies with this method are still limited to theoretical investigations or experimental measurements in a simulated MRI environment. More stringent tests of this method in real clinical MRI environments are still required and necessary. Looking into the future, antenna arrays will find increasing importance in a number of application areas. This parallels the rapid development of array signal processing techniques in such areas as communications, biomedical imaging, radar detection, remote sensing, etc. The successful application of antenna arrays in these areas critically relies on the availability of powerful signal processing algorithms as well as equally powerful and reliable decoupling methods to combat the problem of mutual coupling. A future trend of antenna array design is seen towards smaller or compact-size arrays for the purpose of portability such as antenna arrays in mobile phones or in laptop computers. Obviously this only exacerbates the problem of mutual coupling and makes it
even more important and necessary to find solutions to this problem. Because of these considerations, decoupling methods need to be further developed to suit for new situations. New decoupling methods are also required to provide better solutions in the new situations. All existing decoupling methods, patented or unpatented, as reviewed above have some kind of problems that need to be solved or improved under different conditions. It can be expected that there still have a lot to do with decoupling methods for antenna arrays and the number of patents on these methods will be likely to increase in the near future.

REFERENCES


