Efficiency characterisation of multi-port antennas

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Abstract

A simple radiation efficiency metric is introduced to include the effects of non-ideal source or receiver impedances. The features of this parameter are highlighted and its compact formula is derived. The notion of mean matching efficiency is established. Simulations prove that this matching efficiency is quite useful in a quick estimation of diversity performance of multiport antennas in rich isotropic multipath environments.

1 Introduction

Radiation efficiencies of multiport antennas have been characterised by different parameters, among which the total active reflection coefficient (TARC) [1], mean effective gain (MEG) [2], total embedded element efficiency [3], and decoupling efficiency [4] are the most common. TARC has the advantage of providing a single metric for any arbitrary excitation scheme at different ports. However, since it is defined based on the radiated power, it is troublesome for a compact formulation and a quick measurement. MEG is solely credible for a single-port excitation/receiving circumstance. Associated with each port, there comes an MEG whose constituents are the corresponding total embedded efficiency as well as the mean effective directivity. The latter depends not only on the embedded far field function of the elements, but also upon the distribution of the incoming waves, thus making it unsuitable as an intrinsic antenna parameter. Similar to TARC, measurements of the embedded element efficiencies require evaluation of the radiated power. In addition, it only applies to a single-port excitation/receiving mode, in the sense that it is undefined for the case wherein two or more ports are excited. In contrast, the decoupling efficiency has been defined based on the input network parameters alleviating the burden of radiated power measurements. It is easy to measure and formulate and, in principal, is not limited to a single-port excitation. But, it does not include the effects of losses in case of a lossy structure.

Conversely, in a compact multiport antenna the terminating impedances are known to affect not only the embedded far field functions and thus the correlations, but also the total embedded radiation efficiencies of the structure. Being defined based on the incident power to the antenna system, the decoupling efficiency is lacking inasmuch as it does not include the effects of source impedances properly. This fact creates the requirement to generalise the definition of the decoupling efficiency to include the influence of source impedances too. This novel parameter, called multiport matching efficiency, has all the features of the decoupling efficiency, and contains the source impedances' effects, but does not include the ohmic losses in the radiation system. Nevertheless, in a lossless structure, it equates the total embedded element efficiency, a useful metric for performance evaluation of multiport antennas. In this letter, the vectors and the matrices are denoted by bold small and capital letters, respectively. The $\mathbf{I}$ stands for an $n \times n$ identity matrix (n is the number of the ports) and a dagger sign goes for conjugate transpose.

2 Multiport Matching Efficiency

Being similar to its single-port counterpart, the multiport matching efficiency, e_{mp}, is simply defined as the ratio between the accepted power (P_{acc}), and the maximum available power from the source(s) (P_{avs}). To describe its formulation, a circuit model of a multiport antenna is shown in Fig. 1. Based on this Figure, by virtue of the voltage division rule in fundamental circuit theory, we have:

$$\mathbf{a}_a = (\mathbf{I} + \mathbf{S}_a)^{-1}\mathbf{Q}^{-1}\ \mathbf{a}_s\ , \tag{1}$$

where $\mathbf{Q}$ is defined as

$$\mathbf{Q} = [(\mathbf{I} + \mathbf{S}_s)(\mathbf{I} - \mathbf{S}_s)^{-1}(\mathbf{I} - \mathbf{S}_a)(\mathbf{I} + \mathbf{S}_a)^{-1} + \mathbf{I}]\ . \tag{2}$$

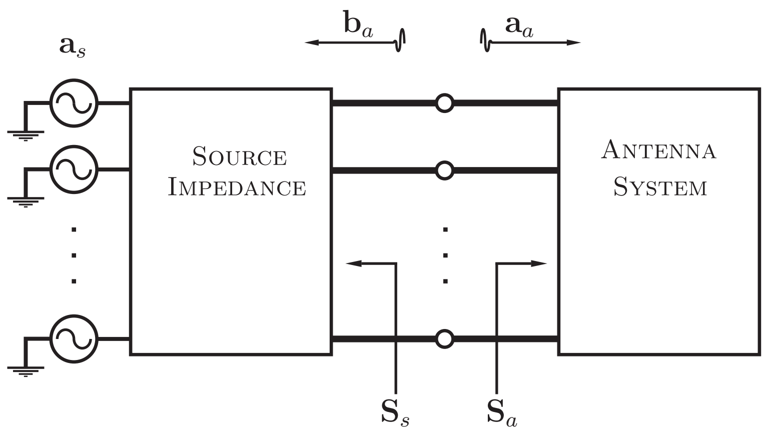

Figure 1: Circuit model of a multiport antenna connected to a set of sources.

Now the accepted power in terms of the source voltages can be written as

$$\begin{aligned} P_{\mathrm{acc}} &= \mathbf{a}_a^{\dagger}\,(\mathbf{I}-\mathbf{S}_a^{\dagger}\mathbf{S}_a)\,\mathbf{a}_a \\ &= \mathbf{a}_s{}^{\dagger}\,\mathbf{Q}^{-1\dagger}(\mathbf{I}+\mathbf{S}_a)^{-1\dagger}(\mathbf{I}-\mathbf{S}_a^{\dagger}\mathbf{S}_a)(\mathbf{I}+\mathbf{S}_a)^{-1}\mathbf{Q}^{-1}\,\mathbf{a}_s\ . \end{aligned} \tag{3}$$

The maximum power transform occurs when we have $\mathbf{S}_a = \mathbf{S}_s^{\dagger}$. Thus, dependent on the excitation vector, $\mathbf{a}_s$, the P_{avs} is achieved by

$$P_{\mathrm{avs}} = P_{\mathrm{acc}}|_{\mathbf{S}_a=\mathbf{S}_s^{\dagger}}\ . \tag{4}$$

The ratio between (3) and (4) bestows the *multiport matching efficiency* (see Fig. 3). Note that, multiport matching efficiency is applicable to both a single-port excitation (*e.g.*, for independent receiving antennas) and a multiport excitation scheme (*e.g.*, for beam-forming purposes). Yet, to distinguish between these cases, the multiport matching efficiency for the latter case can also be exclusively referred to as *active matching efficiency.*

3 Mean Matching Efficiency

Diversity antennas are generally used to combat narrowband fading in multipath environments. The operational frequencies of different elements in multiport antennas used for this purpose are presumably identical. Associated to each single-port excitation, there is a multiport matching efficiency. Therefore, for an n-port antenna system, there are n different multiport matching efficiencies. The *mean matching efficiency*, denoted by e_{mm}, is defined as the geometric mean value of all multiport matching efficiencies at different ports (5):

$$e_{\mathrm{mm}} = \left(\prod_{i=1}^{n} e_{\mathrm{mp_i}}\right)^{\frac{1}{n}}\ . \tag{5}$$

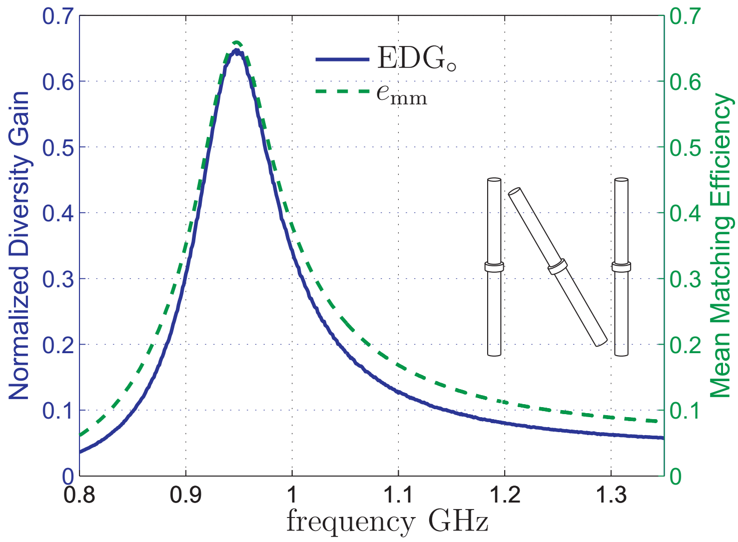

Figure 2: Effective diversity gain compared with mean matching efficiency for three dipoles in N-shape-configuration (the angle between the middle element and two lateral ones is $\alpha = 30°$).

The mean matching efficiency is a single efficiency metric describing the overall performance of a multiport antenna system. Furthermore, we numerically demonstrate that in a lossless multiport antenna system, where the correlations between different ports reside at an acceptable level (*e.g.*, $|\rho| < 0.6$), the e_{mm} can be used for a quick estimate of the effective diversity gain without resorting to cumbersome simulations of the corresponding CDF curves [3, Chapter 2], [5].

4 Simulation

The main goal in this Section is to show how mean matching efficiency can be used to estimate the effective diversity gain of a lossless multiport antenna system. Three different antennas have been chosen with identical elements: the N-shape dipoles in free space (Fig. 2), the four horizontal parallel equidistant dipoles at certain height above a perfect electric conductor (PEC) (Fig. 3), and six quarter-wavelength monopoles on a PEC (Fig. 3). Despite the fact that the resonance frequencies of these identical elements are the same ($f_\circ \approx 1$ GHz), due to unsymmetrical array configuration some of them present different multiport matching efficiencies being the same as the corresponding total embedded element efficiencies. The diversity gains of the structures have been achieved numerically, where the number of realisations exceeds a million rendering an accuracy of better than 0.05 dB. For these simulations, the maximum ratio combining scheme has been chosen. The diversity gains are normalised to the maximum achievable gains ($\mathrm{EDG}_\circ$) being dependent on the number of the ports and the corresponding diversity combining scheme [3, Table 2.1], [5, Figure 5]. These simulations, in which the absolute values of complex correlations do not exceed 0.6, show a brilliant agreement. Further simulations show that in case of considerable correlations between different elements, the

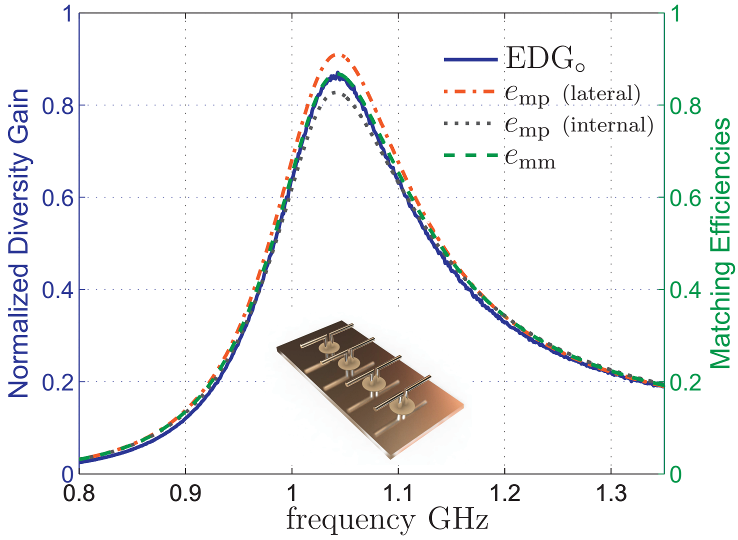

Figure 3: Effective diversity gain compared with mean matching efficiency for four horizontal dipoles above PEC plane (distance between elements is $d = 0.4\lambda_\circ$ and height is $h = 0.15\lambda_\circ$) (multiport matching efficiencies are also shown).

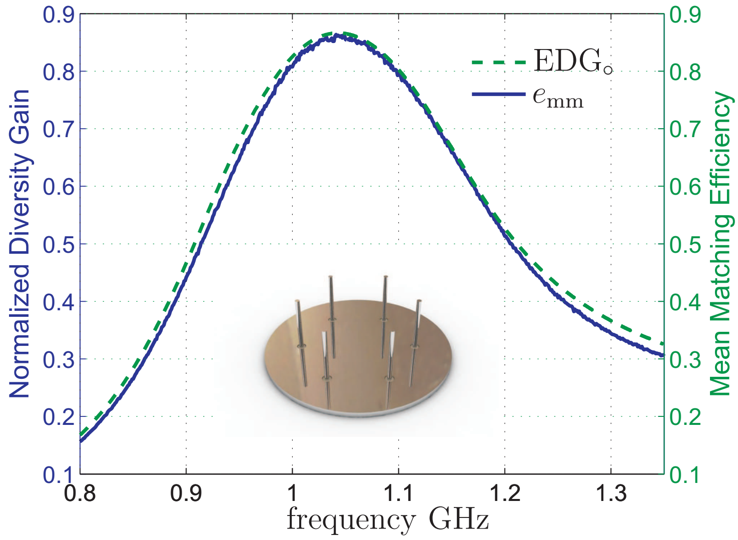

Figure 4: Effective diversity gain compared with mean matching efficiency for six equidistant monopoles above PEC plane (distance between elements is $d = 0.5\lambda_\circ$).

mean matching efficiency can still be useful in rendering an approximate upper bound for the ultimate diversity performance. In order to estimate the true diversity gain from the mean matching efficiency one needs to multiply the e_{mm} to the corresponding maximum achievable diversity gain.

5 Conclusion

Multiport matching efficiency has been introduced and a compact formula for its calculation has been provided. Being defined based on the input S-parameters, the main feature of this efficiency metric is its simple measurement. In a lossless multiport antenna, the multiport matching efficiency of each port equates its total embedded element efficiency. The notion of mean matching efficiency has also been introduced. It is numerically shown that in a lossless multiport antenna system with elements of identical frequency responses, the mean matching efficiency can be used to quickly estimate the effective diversity gain for the structures of moderate correlations. In multiport antennas with considerable correlations, this novel efficiency metric gives an upper bound for the maximum achievable effective diversity gain.

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