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Abstract

Reception of partially correlated fields by two closely coupled electrical dipoles is discussed as a function of load impedances and open-circuit correlations. Two local maxima of the power may be achieved for two different load impedances, but in those cases the output correlations are high. Choosing the loads to give zero output correlations is possible for almost any real-valued open-circuit correlation with a resulting reduction of received power or gain. The excess loss is however only of the order 1.5 dB for a spacing as small as 0.05 wavelength.

Keywords. Reception, dipoles, random fields

I. INTRODUCTION

The paper deals with two coupled electrical dipoles which are coupled only through the mutual impedances. In this paper we shall concentrate on the receive case, where antennas are immersed in a random field. The voltages across the open-circuited antenna ports are characterized by an open-circuit correlation coefficient. By choosing the load impedances it is possible to some extent to control the radiation patterns, and thus the output correlations and received power. The situation has been treated earlier by Wallace and Jensen [1,2] in great detail, and they have especially shown that a more extensive coupling network is needed for both a matched and lossless system. Mutual coupling effects are also studied theoretically in [3], but without considering the effects of different loads and the possibility of zero correlation. Practical network cases have been treated in [4,5]. We treat here the simpler case of no coupling network and look especially at the effect of the load impedances and open-circuit correlations. The same situation has been treated in [6] with different loading conditions. Here we do not consider a specific noise

model, since the interest is in received signal power and output correlation. Recent results [7] have shown that the performance of multiple antenna systems can depend on the underlying noise model. In the numerical examples we use two infinitely thin identical half-wavelength receiving antennas with a spacing of 0.05λ. The antennas have identical loads Z_L.
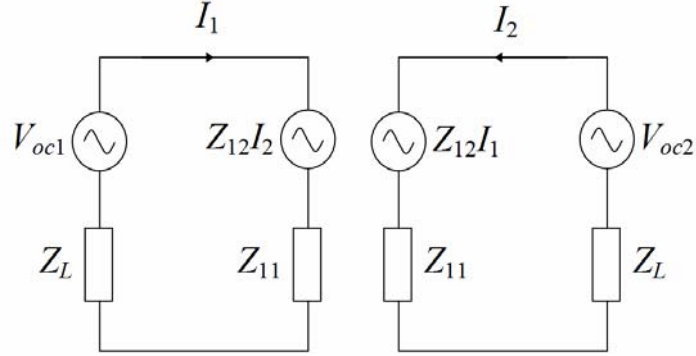

Figure 1. Equivalent circuits of two coupled dipoles.

The open-circuit induced voltages, V_{oc1} and V_{oc2}, are random variables which depend on the scattering environment, and due to the close spacing they will be partly correlated, where the correlation coefficient will depend on the spacing and the angular spread. We shall assume a complex (open-circuit) correlation coefficient of α, i.e.

$$\alpha = \frac{E\left\{ V_{oc1}V_{oc2}^{*}\right\}}{E\left\{ V_{oc1}V_{oc1}^{*}\right\}} \ , \tag{1}$$

assuming zero mean values and equal powers. It is well known that by choosing different load impedances the currents, and thus the voltages over the loads, may be partly decorrelated.

The network equations are

$$V_{oc1} = (Z_{11} + Z_{L})I_{1} + Z_{12}I_{2}$$
$$V_{oc2} = (Z_{11} + Z_{L})I_{2} + Z_{12}I_{1} \ . \tag{2}$$

Solving for I_1 gives

$$I_{1} = \frac{V_{oc1}(Z_{11} + Z_{L}) - V_{oc2}Z_{12}}{(Z_{11} + Z_{L})^{2} - Z_{12}^{2}} \ . \tag{3}$$

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and similarly for I_2.

II. MEAN RECEIVED POWER PER ANTENNA

The mean received power at antenna 1 is given by $P_1 = E\left\{R_L |I_1|^2\right\}\Big/ E\left\{R_{11}|I_0|^2\right\}$ and utilizing (1) and (3) we find

$$P_1 = \frac{4R_L R_{11}(|Z_{11} + Z_L|^2 + |Z_{12}|^2 - 2\,real(\alpha(Z_{11} + Z_L)Z_{12}^*))}{\left|(Z_{11} + Z_L)^2 - Z_{12}^2\right|^2} \quad , \tag{4a}$$

and similarly for antenna 2

$$P_2 = \frac{4R_L R_{11}(|Z_{11} + Z_L|^2 + |Z_{12}|^2 - 2\,real(\alpha^*(Z_{11} + Z_L)Z_{12}^*))}{\left|(Z_{11} + Z_L)^2 - Z_{12}^2\right|^2} \quad , \tag{4b}$$

where the powers are normalized to the power received by a conjugate matched antenna in isolation (current I_0). We may also call it the relative antenna gain in that particular environment, akin to the concept of mean effective gain [8]. Note that the mean powers depend on the correlation coefficient α, and that they are equal for α real.

It is of interest to find the dependence on P_1 of the load impedance, what is the optimum load giving maximum power? This is not easy analytically, so we show a contour plot of P_1 (and P_2) in dB in figure 2. Thin dipoles are assumed with $Z_{11} = 73.1 + j\ 43\ \Omega$, $Z_{12} = 71.6 + j\ 24.3\ \Omega$. The open-circuit correlation coefficient is assumed to be $\alpha = J_0\left(2\pi\left(0.05\right)\right) = 0.9755$, corresponding to uniform 2D angular power spectrum for the chosen spacing.
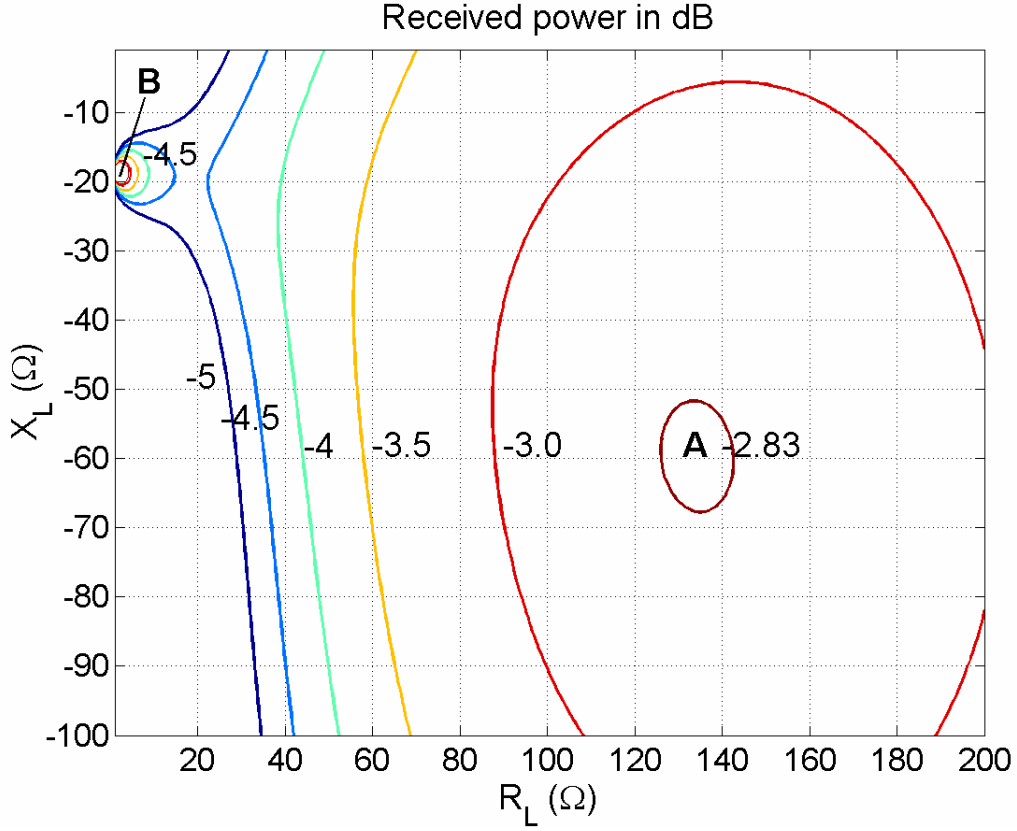
Figure 2. Contour plot of received power in dB at one antenna as a function of real and imaginary part of load impedance. The power is normalized to the power received by one antenna in isolation. The open voltage correlation coefficient α is 0.9755, spacing d = 0.05λ.

There are two local maxima for the gain, one (A) is at Z_L =135 − j 60 Ω and one (B) at Z_L = 2.5 − j 18 Ω. The presence of two local maxima is a new phenomenon, and is distinct from the case of maximum power transfer for single antennas with a unique conjugate impedance load. For (A) the gain is about −2.8 dB, in general a broad matching area for −3 dB. This is the power received by one antenna only, so the total power received by both antennas is close to zero dB, the same as for one antenna in isolation. This is not so surprising considering the close spacing, the receiving aperture is almost the same as for one antenna. The smaller gains at other loads may be interpreted as mismatch losses. As will be seen later the output correlation at (A) is high, above 0.9, so it is not very practical for a MIMO or diversity system. For (B) the optimum is rather narrow with a higher gain than for (A) of −2 dB, and the correlation is around −0.9.

III. OUTPUT CORRELATION

The correlation between the voltages over the loads (or output correlation) is the same as the correlation between the currents. By using (1) and (3) again we find an expression similar to the powers,

$$\rho = \frac{\alpha|Z_{11} + Z_L|^2 + \alpha^*|Z_{12}|^2 - 2\,real((Z_{11} + Z_L)Z_{12}^*)}{\sqrt{|Z_{11} + Z_L|^2 + |Z_{12}|^2 - 2\,real(\alpha(Z_{11} + Z_L)Z_{12}^*)}\sqrt{|Z_{11} + Z_L|^2 + |Z_{12}|^2 - 2\,real(\alpha^*(Z_{11} + Z_L)Z_{12}^*)}}$$

(5)

A similar expression is given in [9], although the self-impedances are omitted. In all calculations we assume a real α, which also simplifies (5) and makes   real. The correlation is shown as a contour plot in Figure 3.
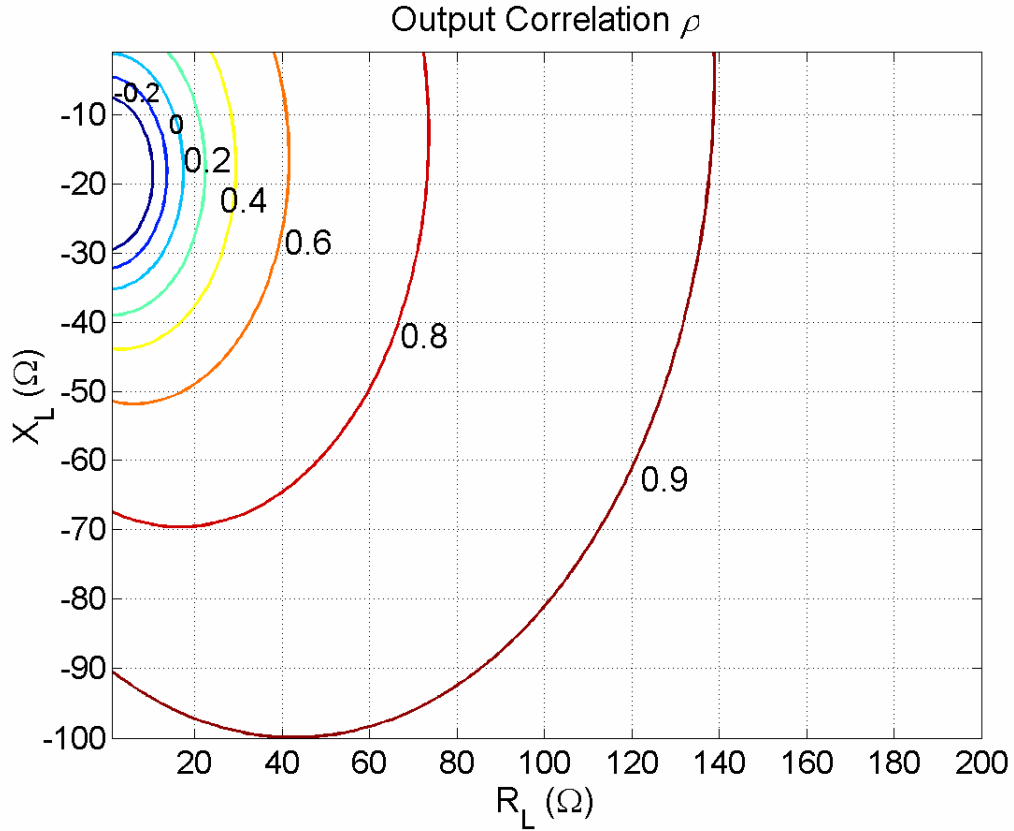

Figure 3. Contour plot of correlation between output signals for various load impedances.

There is a region of low correlation in the upper left corner, indicating that the optimum load impedance is a not a number but a continuous set of numbers. Values of Z_L giving zero correlation may be found easily from (5) and they are shown in Figure 4 together with the power received. In general the curve for correlation ρ is a circle with center

$$Z_L = Z_{12}\frac{1-\alpha\rho}{\alpha-\rho} - Z_{11} \quad \text{and radius} \, r = |Z_{12}|\frac{\sqrt{(1-\alpha^2)(1-\rho^2)}}{|\alpha-\rho|}, \quad \text{where real } \alpha \text{ has been}$$

assumed. The circles may also be found in Figure 3. The gains at zero correlation are around −4.5 dB, so compared to the optimum power match we suffer an additional mismatch loss of 1.5 dB when matching for zero correlation. The load for optimum match is $17.5 - j\, 18\ \Omega$.
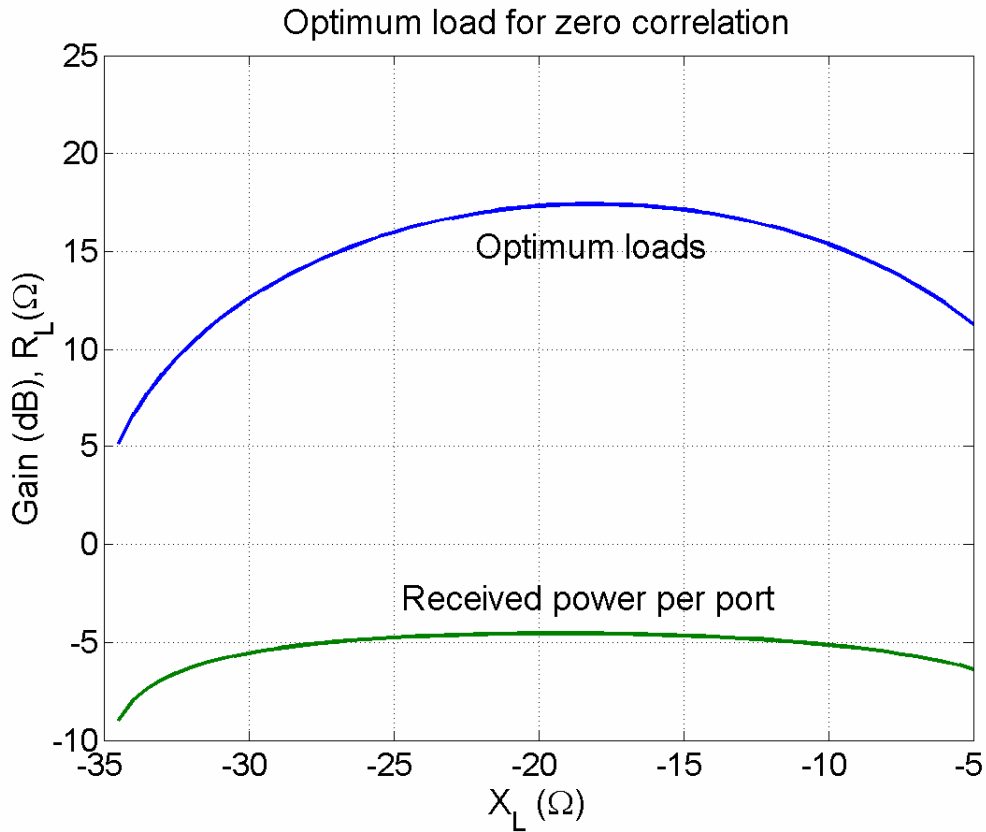

Figure 4. Load impedances for zero correlation and associated power per antenna.

It is interesting that the zero correlation optimal loads are only weakly dependent on the reactance, indicating that a fairly broad frequency match may be possible in contrast to

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the multiport match, which inherently is narrowband [4,5]. It may be shown that zero output correlation may be obtained for almost any input correlations except for those extremely close to 1 (< 0.9998 for the present spacing). It should be noted that the situation changes when is complex.
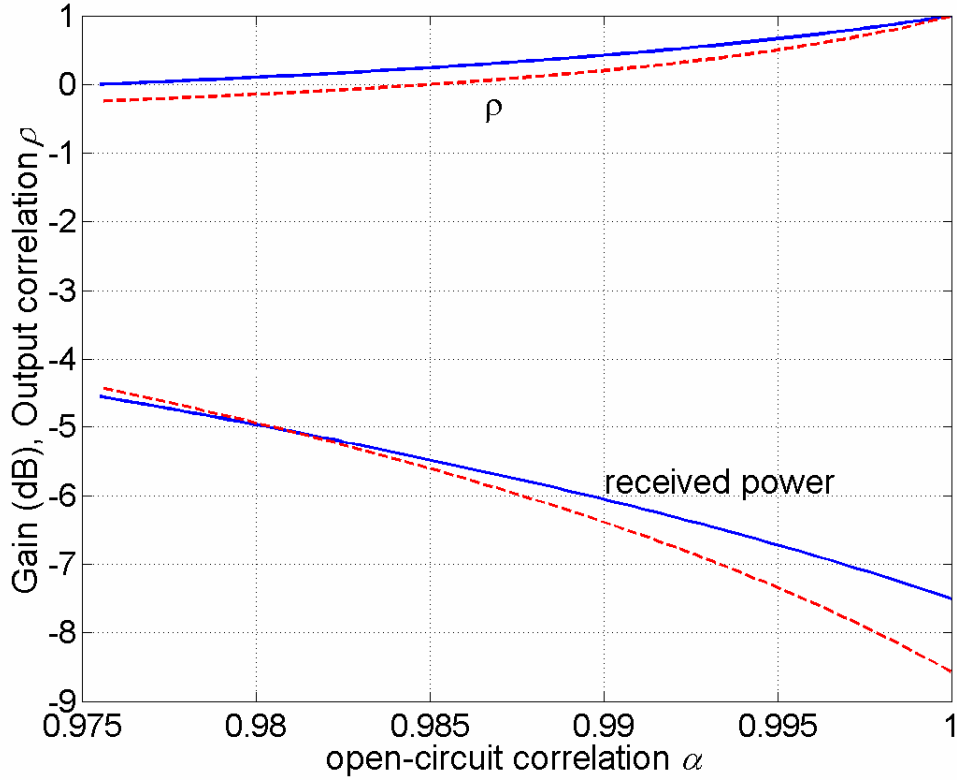

Figure 5. Received power and output correlation as a function of input correlation for two different match conditions, one matched for zero correlation at α=0.9755 (solid line) and one matched for zero correlation at α=0.985 (dashed line).

IV. EFFECT OF ENVIRONMENTAL SPREAD

The effect of varying angular spreads is conveniently expressed indirectly through the correlation coefficient α. The previous results were based on uniform 2D angular power spectrum with a correlation of $J_0(kd)$. In practice this may be too optimistic and it is of interest to study the effect of increasing α towards 1, assuming α real. Two cases are shown in Figure 5, zero correlation match at 0.9755 (uniform environment, solid lines)

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and zero correlation match at 0.985 (reduced spread, dashed lines). The latter match is advantageous since it has a low correlation for a range of environments with only minor penalty in gain.

V. CONCLUSION

Reception of correlated fields has been studied for two closely coupled dipoles in terms of the mean gain (relative received power) and output correlation. A gain of -3 dB may be achieved by optimal matching, but the correlation is high. Alternatively, it is possible to match the loads to a zero correlation case, accepting an additional loss of 1.5 dB. The results have been shown for a distance of 0.05 wavelength between antennas; if this is increased the gains increase considerably.

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