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Compact Multiple Antennas in a Random World

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ABSTRACT

Recent work on compact multiple antennas in a random environment is reviewed, including extensions of the energy density antenna and the MIMO cube. The performance of handsets with multiple antennas is dependent on many factors due to the close proximity of the antennas. The distribution of scatterers in the environment has an impact on the distributed directivity of the antennas, the powers absorbed in the loads, and the correlation between the open-circuit signals. Matching the antennas is non-trivial, since the matching changes the output correlations and the efficiency. The antennas may be matched for maximum MIMO capacity for a given environment. Basic bandwidth limitations will also be discussed.

INTRODUCTION

Modern wireless technologies make new challenges for the antenna engineer. It is no longer the case of minimizing the sidelobes or maximizing a gain in a particular direction, but rather understanding the new propagation environment of mobile terminals, and optimizing the antenna system to give maximum average power and maximum capacity for a multi-antenna system. Apart from these new challenges the old virtues of antenna design still prevail, like establishing high efficiency and the necessary bandwidth. In many cases there are space constraints for the antenna size and spacing, so compactness gives an additional constraint to the optimum solution. It is those conflicting requirements which are the topic of the presentation.

A basic understanding is obtained by studying the mean effective gain (MEG) of an antenna element in a random environment with mean values of the incident powers $P_\theta(\Omega)$ and $P_\varphi(\Omega)$

$$MEG = \int \left(\frac{XPD}{1+XPD} P_\theta(\Omega) G_\theta(\Omega) + \frac{1}{1+XPD} P_\varphi(\Omega) G_\varphi(\Omega) \right) d\Omega \quad , \tag{1}$$

where the G's are the antenna gains in the respective polarizations and XPD is the ratio between the two average polarization powers. Since $P_\theta(\Omega)$ and $P_\varphi(\Omega)$ in general are unknown the best

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we can do is to have an antenna with a dipolar like wide pattern. Note that if $P_\theta(\Omega)$ and $P_\varphi(\Omega)$ are constants the MEG reduces to 0.5, independent of the antenna, and the antenna engineer can then concentrate on matching and efficiency. This condition is partly satisfied in indoor environments as illustrated in [1], where it is shown that the location in a large room and the type of antenna is irrelevant for the slope of the exponential decay in the tail of the response and for the power level in the tail. The directivity of the antenna plays a role for the close line-of-sight situations.

Having two antennas, we are interested in the correlation between the two terminal voltages

$$\rho_{jk} = \int P(\Omega)\mathbf{h}_j(\Omega) \bullet \mathbf{h}_k(\Omega)\, d\Omega \ , \tag{2}$$

where ***h*** signifies the vector pattern of one antenna and where we have assumed equal powers in the two polarizations, $P(\Omega) = P_\theta(\Omega) = P_\varphi(\Omega)$. Note that again the distribution of sources or incident fields play a role, and if $P(\Omega)$ is constant then the real part equals the mutual resistance [2]. Thus there is a connection between antenna circuit theory and correlations for this particular environment. When the correlation is low there is a diversity gain to be achieved as is well known, a condition which is also beneficial for large MIMO capacity.

USING FIELD AND SPACE DIVERSITY

How many degrees of freedom can we have in an electrically small volume? This is related to the maximum capacity achievable, since the capacity is given by

$$C = \sum \log_2(1 + \lambda_i SNR_i) \ , \tag{3}$$

where λ_i are the gains of the individual channels, and SNR_i the allocated signal-to-noise ratios. Thus what counts is the number of independent (or uncorrelated) patterns and the power.

In free space the answer to the question is obvious and well-known; there are two orthogonal polarizations, e.g. vertical and horizontal. In a random environment in a half-space above a groundplane there are three orthogonal patterns, one from a vertical electrical dipole and two from two orthogonal magnetic dipoles. This is the energy density antenna known for a long time (Gilbert, 1965). Removing the ground plane allows three orthogonal electric and three orthogonal magnetic dipoles, a feat of six orthogonal patterns, first mentioned in [3]. The six patterns are listed in [2], pp. 587. The result has been questioned in the antenna community, since it is argued that the magnetic fields may be found from the electric fields, but as noted from Maxwell's equations we need electric fields at different points in order to calculate the spatial derivatives, so the electric field at one point is not sufficient. This type of diversity is also called field diversity.

The idea was taken one step further in [4] with 12 electrical dipoles arranged as edges of a cube, Fig. 1. Since a magnetic dipole may be synthesized by four electric dipoles arranged properly this is similar to the energy density antenna. The additional degrees of freedom from six to twelve arise from the spacing between the dipoles (the length of the side of the cube) which lead to space diversity in the random environment. The mean capacity for an SNR of 20 dB is shown in Fig. 2 as a function of side length. It reaches an impressive number of 62.5 bits/s/Hz which should be compared with 5.9 bits/s/Hz for a single dipole, more than a factor of ten. The capacity decreases with decreasing spacing due to the increasing correlation, and the effective number of channels reduces from 12 to 6. It should be noted that here the mutual coupling is not taken into account, a subject we shall discuss in a later section.

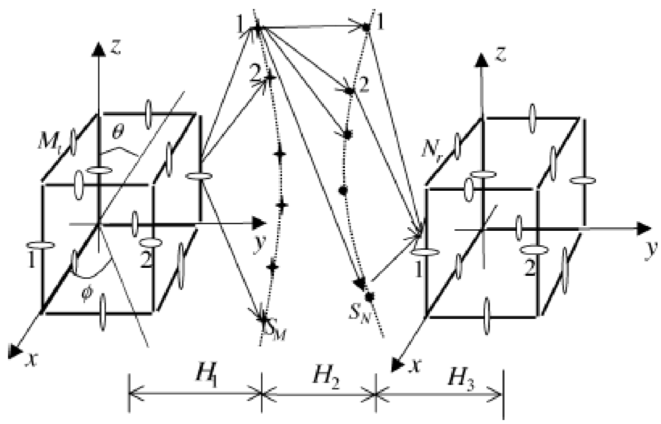

Fig. 1. Two MIMO cubes in a scattering environment.

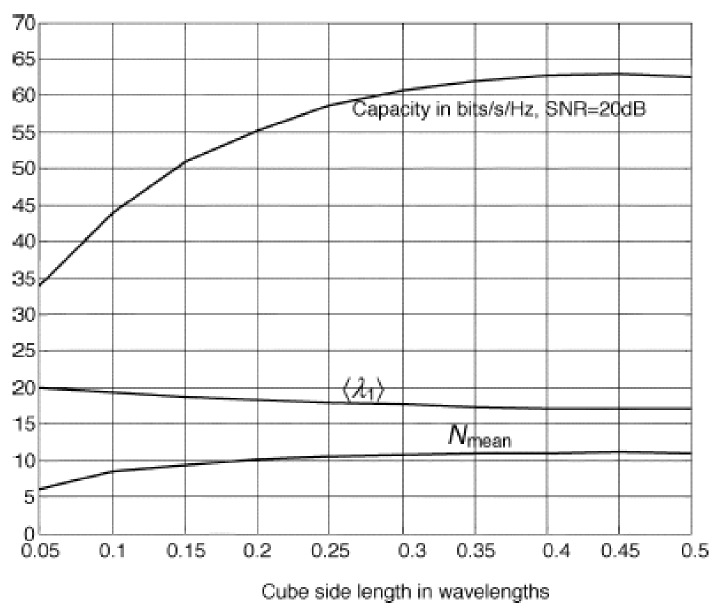

Fig. 2. Mean capacity, mean gain of largest eigenvalue and the number of effective eigenvalues for a MIMO-cube with an electrical dipole on each edge [3].

The MIMO cube is probably impractical from a construction point of view, and should be seen rather as a theoretical upper limit of what can be achieved with compact antennas including all possible polarizations.

LOAD MATCHING

When two dipoles are closely spaced, like 0.1 wavelength (λ) or less, they interact to modify the performance to a large extent. In the transmit case a considerable amount of power is lost in the neighboring antenna, depending on the load impedance, which is assumed to be the same for each antenna. Also the output correlation changes because the scattering from the second antenna changes the pattern of the first, so in the receiving case the output correlation is a function of the load impedance. This may be a beneficial effect, since it can be shown [5,8] that very low correlations (zero) may be obtained for a certain complex load. Unfortunately, these solutions are often those of low gain or efficiency, so engineering compromises must be made.

For a case of a spacing of 0.05 λ the maximum gain relative to a single antenna is about −5 dB. The optimum match for maximum gain gives a gain of −3 dB for each antenna, so the total received power is about the same as for one dipole. The advantage is a diversity gain at small outages. The MIMO capacity is sensitive to both the power and the correlation with power usually dominating [8]. The dependency of the load impedance is shown in Fig. 3 for a spacing of 0.05 λ. A simple 50 Ω match is not a bad choice. The correlation of the output signals at the optimum is −0.2.

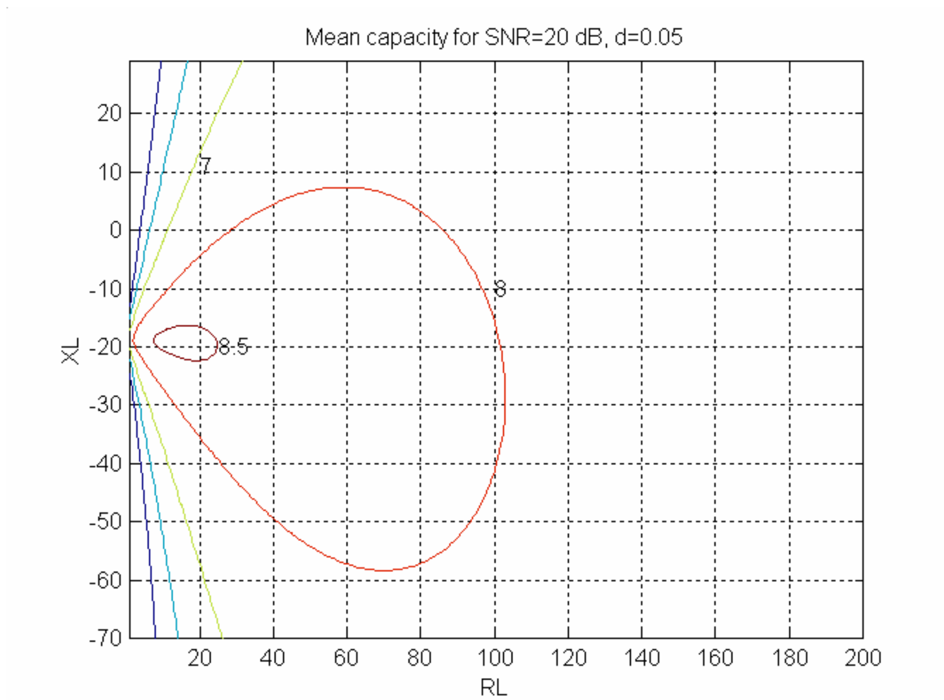

Fig. 3. Contours of mean capacity as a function of load impedance for 2 × 2 MIMO with correlation at one side only. Antenna spacing *d* = 0.05 λ and a reference SNR of 20 dB.

DECOUPLING NETWORK

The problems mentioned above of low efficiency and high correlations may be counteracted by having a lossless network between the antennas and the loads, in fact at a single frequency it is possible to have zero correlation and 100% efficiency at any spacing [6,7]. There is of course a cost, which is bandwidth. It was shown in [9] that both correlation and efficiency bandwidths decrease drastically at small antenna separations. As an example, at 0.01 λ spacing the correlation and efficiency bandwidths are 0.4% and 0.2%, respectively.

CONCLUSIONS

The tight coupling between closely spaced antennas on a small terminal leads to many challenging antenna engineering problems, such as maximizing the capacity bandwidth and solving non-trivial matching situations.

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