Decorrelating Closely-Placed Antennas by Pattern Design in Uniform Scattering Environments

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***Abstract*—[1] MIMO system's performance depends greatly on the correlation of employed antennas. The more the correlation is, the worse the performance will be. We propose a solution to the problem of decorrelating closely spaced antennas assuming the antennas have identical radiation patterns with the same steering angles. In fact, we will show that by proper steering of the antenna patterns, the decorrelation distance is reduced to 0.25λ which is a great improvement comparing with the well-established 0.4λ result coming from the Bessel-shaped correlation expression. Also, we analyze this result in the regime of very closely placed antennas and by proposing the definition of Decorrelation Factor of an antenna pattern, provide the framework of comparing the correlation behavior of different antennas. Furthermore, we apply our results to two practical directional antennas, namely, the half-wavelength dipole and the vertical electric dipole antennas.**

I. Introduction

Recently, there has been a great interest in employing multiple antennas at the transmitter and/or the receiver to enhance the system capacity, and it has been shown that this technique considerably enhances the system capacity [1]. Each antenna element in a MIMO wireless system has its own physical characteristics such as polarization behavior and radiation pattern. It has been studied in the literature that these characteristics have great effects on the overall MIMO system performance [2], [3]. In [2], a capacity analysis is proposed based on indoor measurements which reveals the effect of antenna polarization on the system capacity. Also, in [3], with the aid of experimental results, the effect of different possible pattern and polarization configurations on the system performance is studied. Another paper considering the same problem is [4], which has proposed a measurement-based framework to analyze the effect of directional antenna arrays on the performance of indoor and outdoor MIMO systems. Also, in [5] the authors use numerical examples to discuss the information capacity of directional antennas in comparison with omnidirectional antennas.

A very important effect of antenna characteristics on the channel of a MIMO system is the effect on the correlation of antennas. As it is well known, the MIMO system performance depends greatly on the correlation of the employed antennas [6]. It is usually desirable to reduce the correlation of antennas to exploit the spatial diversity provided by them. In a recent work in [7], the effect of antenna physics on the multielement system capacity has been investigated. In a simulation model context, it has been shown in [7] that using directive antennas as elements of MIMO systems can affect the antenna correlation and thus can enhance the system capacity. The channel model employed in [7] is the extension of the "one-ring" model to spherical scattering environments which has enabled the authors to analyze the system performance in 3D Rayleigh fading environments. Also, in [9] it has been shown that by employing directional antennas one can reduce the correlation of the antennas and thus can enhance the system capacity. In addition, the mutual coupling of closely placed antennas has a great effect on the antennae's correlation which has been the topic of many research papers such as [10] and [11].

In this paper we investigate the problem of decorrelating closely placed directional antennas, in the case of isotropic scattering environments, and when antennas with identical patterns and the same steering angles are employed . We show that by proper steering of antennas, they are completely decorrelated when placed at a distance more than a quarter of the wavelength. Also, In the distances smaller than that, the correlation is reduced compared with the omnidirectional antennas. We analyze this decorrelation effect in the low antenna spacing regime, and also we numerically evaluate our results by applying them to two practical antennas, namely, the half-wavelength dipole and the vertical electric dipole antennas.

II. Decorrelating Directional Antennas in Isotropic Scattering Environments

Correlation of two antennas placed at the distance Δ apart, having the same power gain pattern, is as the following:

$$R = 2\pi \int_0^{2\pi} e^{j2\pi\frac{\Delta}{\lambda}\cos(\theta)} G(\theta) f_\Theta(\theta) d\theta, \qquad (1)$$

where $f_\Theta(\theta)$ is the probability distribution function (p.d.f.) of the arrived signal from the scatterers around the antennas [8], $G(\theta)$ represents the antennae's pattern, and λ is the system wavelength. In isotropic scattering environment, by using omnidirectional antennas (1) reduces to $J_0(2\pi\Delta/\lambda)$. By

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assuming an isotropic scattering environment, and using directional antenna elements, the absolute value of the correlation would be

$$\begin{aligned} |R| &= |\int_0^{2\pi} e^{j2\pi\frac{\Delta}{\lambda}\cos(\theta)} G(\theta)d\theta| \\ &= (|\int_0^{2\pi} \cos(2\pi\frac{\Delta}{\lambda}\cos(\theta))G(\theta)d\theta|^2 \\ &+ |\int_0^{2\pi} \sin(2\pi\frac{\Delta}{\lambda}\cos(\theta))G(\theta)d\theta|^2)^{\frac{1}{2}} \\ &= ((R_1)^2 + (R_2)^2)^{\frac{1}{2}}. \end{aligned} \tag{2}$$

The problem which we propose is: what is the optimum $G(\theta)$ which minimizes $|R|$ and such that $\int G(\theta)d\theta = 1$ (total power radiated constraint)?

To answer this question we propose a solution which at the first step makes R_2 vanish and then minimizes R_1 . We restrict the choice of antenna patterns to those having *symmetrical backlobe* which means:

$$G(\theta + \pi) = G(\theta), \tag{3}$$

In other words, we look for antennas which have a backlobe the same as their mainlobe. By This assumption we will have:

$$R_2 = \int_0^{2\pi} \sin(2\pi\frac{\Delta}{\lambda}\cos(\theta))G(\theta)d\theta = 0, \tag{4}$$

which implies that the phase correlation vanishes by this method. Thus, the minimization problem of $|R|$ introduced in (2) reduces to the minimization of following:

$$\begin{aligned} |R| &= |R_1| \\ &= |\int_0^{2\pi} \cos(2\pi\frac{\Delta}{\lambda}\cos(\theta))G(\theta)d\theta|, \end{aligned} \tag{5}$$

where we have the restriction of (3) on the antenna pattern. The pattern which minimizes this expression is:

$$G_{opt} = \frac{1}{2}\{\delta(\theta - \theta_m) + \delta(\theta - (\theta_m + \pi))\}, \tag{6}$$

where

$$\theta_m = \begin{cases} 0 & , \quad \frac{\Delta}{\lambda} \leqslant \frac{1}{4} \\ \arccos(\frac{1}{4\frac{\Delta}{\lambda}}) & , \quad \frac{\Delta}{\lambda} \geqslant \frac{1}{4} \end{cases} . \tag{7}$$

By employing this pattern, for correlation expression we will have:

$$R_{opt} = \begin{cases} \cos(2\pi\frac{\Delta}{\lambda}) & , \quad \frac{\Delta}{\lambda} \leqslant \frac{1}{4} \\ 0 & , \quad \frac{\Delta}{\lambda} \geqslant \frac{1}{4} \end{cases} . \tag{8}$$

However, the result in (8) is valid for the antennas having unlimited directivity. For practical antennas having limited directivity, by using (5) we have the following expression for the correlation:

$$R = \int_0^{2\pi} G_0(\theta - \theta_{opt})\cos(2\pi\frac{\Delta}{\lambda}\cos(\theta))d\theta, \tag{9}$$

where θ_{opt} is defined in (7), and $G_0(\theta)$ represents the pattern of the antenna with the main beam directed to $\theta = 0$.

III. Decorrelation Analysis

In this section we analyze the results of the previous section in the regime of $\frac{\Delta}{\lambda} \ll 1$. We have derived the correlation expression in (8) for the optimal antennas (which we refer to as R_{opt}), the correlation expression in (9) for practical antennas (which we refer to as R) and the expression $R_0 = J_0(2\pi\Delta\lambda)$ for the omnidirectional antennas in isotropic environment. In low Δ/λ regime we derive the following expressions:

$$R_0 = 1 - \pi^2(\frac{\Delta}{\lambda})^2 + O((\frac{\Delta}{\lambda})^3) \tag{10}$$

$$R_{opt} = 1 - 2\pi^2(\frac{\Delta}{\lambda})^2 + O((\frac{\Delta}{\lambda})^3) \tag{11}$$

$$R = 1 - \{2\pi^2 \int_0^{2\pi} G_0(\theta)\cos^2(\theta)d\theta\}(\frac{\Delta}{\lambda})^2 + O((\frac{\Delta}{\lambda})^3) \tag{12}$$

By defining the Decorrelation Factor (DF) as:

$$DF = \lim_{\Delta/\lambda \to 0}(\frac{1-r}{(\Delta/\lambda)^2}), \tag{13}$$

we will have

$$R_{opt} = \begin{cases} DF_0 & = \pi^2 \\ DF_{opt} & = 2\pi^2 \\ DF & = 2\pi^2 \int_0^{2\pi} G_0(\theta)\cos^2(\theta)d\theta \end{cases} . \tag{14}$$

It should be noted that

$$\pi^2 \leqslant DF \leqslant 2\pi^2, \tag{15}$$

where DF reduces to DF_0 and DF_{opt} in the extreme cases.

Therefore, thanks to the definition of Decorrelation Factor in (13), we have a measure of how much a directional antenna with pattern $G_0(\theta)$ can reduce the correlation, when the antennas are closely placed.

We can further simplify DF:

$$\begin{aligned} DF &= \{2\pi^2 \int_0^{2\pi} G(\theta)\cos^2(\theta)d\theta\} \\ &= \pi^2(1 + \int_0^{2\pi} G(\theta)\cos(2\theta)d\theta) \\ &= \pi^2(1 + 2\pi\mathcal{G}_2), \end{aligned} \tag{16}$$

where $\mathcal{G}_k = \frac{1}{2\pi}\int_0^{2\pi} G(\theta)\cos(k\theta)d\theta$ are the Fourier series coefficients of $G(\theta)$ which is a periodic function by the period 2π.

IV. Numerical Illustrations

In this section we numerically evaluate our results by some examples. To start, we introduce two directional antennas and their field patterns. Half-wavelength dipole is a directional antenna with the following pattern:

$$F(\theta) = \frac{\cos(\frac{\pi}{2}\cos(\theta))}{\sin(\theta)}. \tag{17}$$

In addition, the field pattern of a vertical electric dipole antenna is

$$F(\theta) = \sin(\theta)[2\cos(2\pi\frac{L}{\lambda}\cos(\theta))], \tag{18}$$

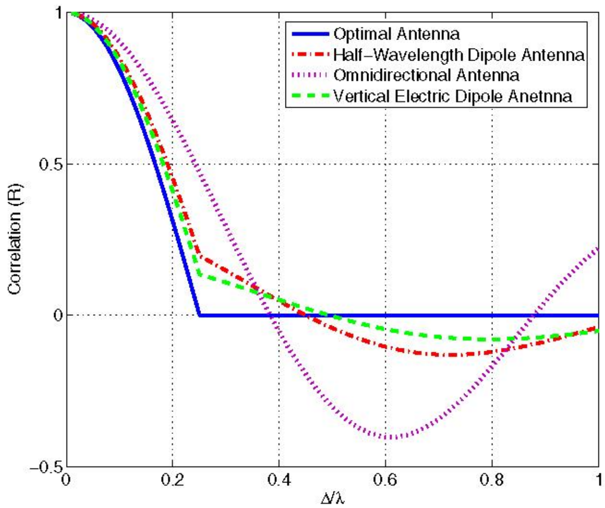

Fig. 1. Correlation behavior for four cases:omnidirectional antenna , the optimal antenna , half-wavelength dipole and the vertical electric dipole with the size of $L = 0.2\lambda$ versus the distance of the antennas normalized to the wavelength.

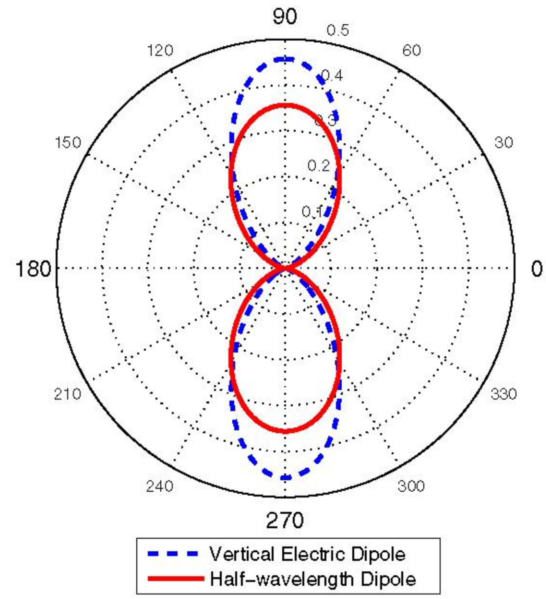

Fig. 2. Antenna pattern for the half-wavelength dipole and vertical electric dipole.

where L is the antenna size.

The main beam of these antennas is towards $\theta = \pi/2$ and consequently we will have:

$$G_0(\theta) = \frac{F(\theta - \pi/2)^2}{\int F(\theta)^2 d\theta}. \quad (19)$$

Figure 1 depicts the correlation in isotropic environment for four cases: omnidirectional antenna resulting in the famous Bessel-shaped correlation, the optimal antenna which has unlimited directivity, half-wavelength dipole with the field pattern stated in (17) and the vertical electric dipole with the field pattern stated in (18), versus the distance of the antennas normalized to the carrier wavelength. In the case of omnidirectional antennas, the correlation function is Bessel having its first zero at about $\Delta/\lambda = 0.4$. In the optimal antenna case the correlation is stated in (8), where the antennas are completely uncorrelated if the distance of antennas is more than $\lambda/4$. By noticing the remaining curves we note that vertical electric dipole of the size (0.2λ) has better correlation behavior comparing with the half-wavelength dipole. That is because of the higher directivity of the vertical electric dipole than that of half-wavelength dipole depicted in Figure 2.

Figure 3 depicts the Decorrelation Factor (DF) defined in (13) for three cases: omnidirectional antenna, optimal antenna and vertical electric dipole versus the size of antenna. As it is clear in the figure, the upper bound and lower bound for the decorrelation factor of an antenna refers to the optimal antenna and omnidirectional antenna respectively.

V. Conclusion

In this paper we have investigated a method for decorrelationg closely placed directional antennas having identical radiation patterns with the same steering angles. It is shown that by proper steering of the antenna patterns, the correlation of the antennas is greatly reduced. In addition, we have analyzed this result in the regime of very closely placed antennas and have defined a metric to compare the correlation behavior of different antennas. Furthermore, we have applied our results to two practical directional antennas, namely, the half-wavelength dipole and the vertical electric dipole antennas.

One shortcoming of this analysis is that this approach designs the antennae's patterns to minimize the correlation of just two antennas. However, in a MIMO system an array of antennas may be used and pairwise correlation of antennas should be taken into account. For example, consider the MIMO configuration in Figure 4. In this case three directional antennas are placed on the vertices of a triangle. It is clear that applying the method introduced in this paper cannot minimize the correlation of every two subset of antennas simultaneously. Thus, we are going to extend our analytical framework to address this problem considering the total capacity of the system. One symmetrical candidate solution is depicted in Figure 4.

Furthermore, another important topic is applying the results of this paper to the case of array of antennas having mutual field coupling.

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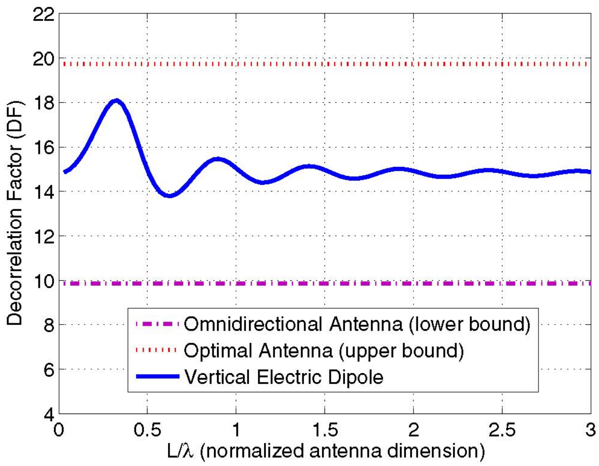

Fig. 3. Decorrelation Factor (DF) defined in (13) for three cases: omnidirectional antenna, optimal antenna and vertical electric dipole versus the size of antenna.

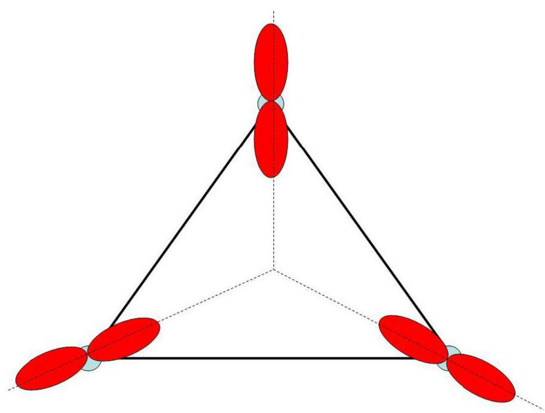

Fig. 4. Triangular configuration of three directive antenna

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