Appropriate Antenna Patterns For A Compact MIMO Receiver

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Abstract— **A compact MIMO receiver is reported previously [1] which uses only a single active receiving antenna and multiple passive elements to achieve spatial diversity. The passive elements are used to construct suitable antenna patterns which can be rotated 360 degrees around to achieve a MIMO effect. This paper discusses some antenna patterns which can be used for this purpose. An example of an antenna with one active dipole and 6 passive dipoles distributed on a circle around it is given. The distance between the active dipole and the passive elements is chosen to be $\frac{\lambda}{8}$, which means that the antenna system will have a diameter of approximately $\frac{\lambda}{4}$. Further the broadband properties of this antenna system is considered in terms of mutual information for different frequencies.**

I. INTRODUCTION

One of the disadvantages of MIMO systems is the relatively large size needed of a wireless terminal. This is due to the requirement of an antenna spacing equal to half the wavelength to achieve sufficiently uncorrelated signals at the antenna connectors. [1] shows that a MIMO effect can be obtained by forming a directive antenna which rotates once or several times during a symbol period. The received signal will now be expanded in frequency and the different frequency bands will have the same effect as multiple antennas. This paper will propose some ways of achieving directive antenna patterns by using passive elements in the form of passive dipoles. Other papers have considered using passive elements to achieve directive antenna patterns [6], [7], [8]. However they have not considered the rotation of the antenna pattern during a symbol period to achieve the MIMO-effect. Some has also considered super-directive antenna patterns using passive reflectors [9]. The disadvantage here is that the antenna configuration prevents the possibility of rotation.

The paper is organized as follows: Previous results which this paper is based on is given in section II. Section III addresses the narrowband properties of the antenna patterns. The broadband properties will be discussed in section IV. Finally the conclusion is given in section V.

II. ROTATING ANTENNA

If we have a directive antenna which can be rotated 360 degrees around once or several times during the duration of a symbol then the received signal can be expressed as [1]:

$$r(t) = \sum_{p=1}^{P} a(\omega t + \alpha_p) s_p(t) \tag{1}$$

Where $a(\omega t)$ is a function describing the antenna pattern, ω is the rotation angular frequency and α_p is the angle from which the signal $s_p(t)$ is arriving. With a fourier series expansion of the periodic function $a(\omega t)$ the received signal can be expressed:

$$r(t) = \sum_{l=-L}^{+L} exp(jl\omega)\, a_l \underbrace{\sum_{p=1}^{P} exp(jl\alpha_p) s_p(t)}_{r_l(t)} \tag{2}$$

In matrix notation:

$$\underbrace{\begin{bmatrix} r_{-L}(t) \\ \vdots \\ r_{+L}(t) \end{bmatrix}}_{\mathbf{r}(t)} = \underbrace{\begin{bmatrix} a_{-L}(t) & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & a_{+L} \end{bmatrix}}_{\mathbf{A}} \times \underbrace{\begin{bmatrix} e^{-jL\alpha_1} & \vdots & e^{-jL\alpha_P} \\ \vdots & \ddots & \vdots \\ e^{+jL\alpha_1} & \dots & e^{+jL\alpha_P} \end{bmatrix}}_{\mathbf{V}} \underbrace{\begin{bmatrix} s_1(t) \\ \vdots \\ s_P(t) \end{bmatrix}}_{\mathbf{s}(t)} \tag{3}$$

What can be seen from this equation is that the number of degrees of freedom is equal to the number of spectral components of the antenna pattern. Some antenna pattern that achieves a fair amount of spectral harmonics will be presented in the section that follows.

III. NARROWBAND PROPERTIES OF THE ANTENNA PATTERN

In the previous section it was assumed that the antenna pattern was rotated continuously. A more realistic approach is to have a discrete rotation. For the rotation to have a meaning at all the antenna pattern should be directive in some sense such that it achieves a sufficient amount of spectral components. It should be noted that it's not necessary to opt for just one narrow antenna beam. Many spectral components

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could very well be achieved with many sidelobes as long as the pattern is peaky in some sense. However in this paper we focus on getting an antenna pattern which has one main lobe. The way we try to achieve a directive antenna in this paper is by using passive elements distributed on a circle around the active dipole [2]. This case is considered in [1] as well. By employing electronic switches in the middle of the passive elements one can decide whether the passive element should influence the electromagnetic field or not. When the switch is closed this means that the passive element is resonant with the electromagnetic field, and when it's open the interaction will be small. The discrete rotation can be achieved by letting the switch of one passive element be closed at a time while the others are open and then let the next passive element be closed and the others open. This gives a certain directivity, but even higher directivity can be achieved by more sophisticated means. The next section discusses how to achieve a directive pattern by using reactive loads.

A. Reactively Loaded Antenna

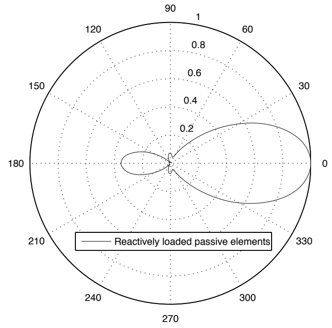
[3] considers how to achieve a directive antenna pattern by using passive elements distributed on a circle around an active dipole. There it was also given an expression for the gain function:

$$G = \frac{k^2\eta}{4\pi}\frac{|\mathbf{v}_0^T[\mathbf{Z}_A + \mathbf{Z}_L]^{-1}\mathbf{v}|^2}{\mathbf{i}^H\mathbf{R}\mathbf{i}} \tag{4}$$

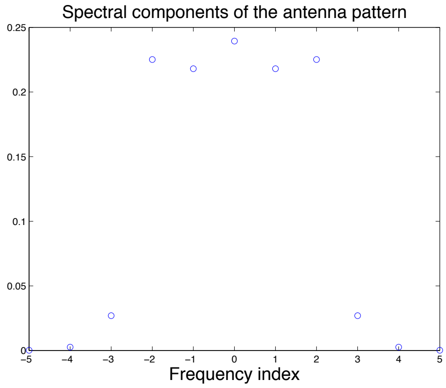
$\mathbf{Z}_A$ is the antenna impedance matrix, $\mathbf{Z}_L$ is a diagonal load matrix which is imaginary since it consists of only reactive elements, $\mathbf{R}$ is the real part of $\mathbf{Z}_A$, $\mathbf{v}$ is the voltage excitation vector, $\mathbf{i}$ is the antenna port current, $\mathbf{v}_0$ is the open circuit port voltage of the antenna system when excited by a plane wave from the direction of gain evaluation.

The parameters to be found to maximize the gain function are the elements in $\mathbf{Z}_L$. This can be done by a numerical optimization method. The other parameters such as the values of $\mathbf{Z}_A$ are fixed. This is because the position of the passive elements relative to the active dipole is picked beforehand. For our calculations we have picked the passive elements to be located at a distance $\frac{\lambda}{8}$ from the active dipole. This gives a total diameter of $\frac{\lambda}{4}$ of the antenna system. When performing the numerical optimization many solutions were found that gave approximately the same gain. This was already known by [3]. The antenna pattern resulting from this numerical optimization is pictured in figure 1. For this case we have chosen 6 passive elements around the active dipole. This antenna pattern achieves 5 almost equally strong spectral components. The harmonics are plotted in figure 2.

Until now we have only considered how to get a narrow beam in one direction. To be able to rotate the antenna beam discretely we would need to switch between different reactive loads. The number of reactive loads to switch between increases with the number of discrete rotation steps we want to have during a complete rotation of 360 degrees. If we are satisfied with 6 discrete rotation steps then it is sufficient with four different reactive loads. This is because we have 6 passive elements, and some of the passive elements are loaded with the same reactive values.



1: The antenna pattern obtained with reactively loaded passive elements. The antenna patterns are found by using an electromagnetic simulation program called WIPL-D [5]



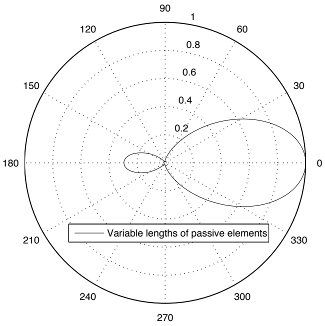
2: The spectral components of the antenna pattern obtained with reactively loaded passive elements.

In the next subsection we will consider a different way of achieving a directive antenna pattern.

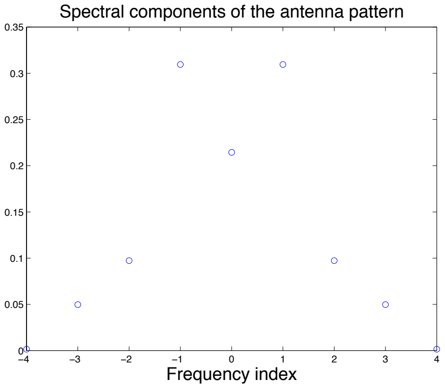
B. Variable Lengths Of The Passive Elements

One can also obtain a directive antenna pattern by choosing the lengths of the passive elements to be different to $\frac{\lambda}{2}$. Then the discrete rotation implies that the passive elements need to have multiple lengths. This can be obtained by electronic switches as before. To find the lengths needed to obtain a directive antenna pattern we can use the same gain function as given in equation (4). But now we set the load matrix $\mathbf{Z}_L$ equal to zero. When using a numerical optimization algorithm to maximize the gain function we need to recalculate the antenna impedance matrix $\mathbf{Z}_A$ every time we choose a different length for one of the passive elements.

The beam pattern for one of the solutions to the maximization of the gain function is given in figure 3. This beam pattern is not as directive as the pattern obtained by reactive loading. The reason for this might be that the assumptions we make when finding the antenna impedance matrix $\mathbf{Z}_A$ is not good enough and thus preventing us from finding the most directive solutions. When calculating the antenna impedance matrix we



3: The antenna pattern obtained when the passive elements have variable lengths.



4: The spectral components of the antenna pattern when the passive elements have variable lengths.

assume that the currents on the passive elements are sinusoidal. The current is then expressed as $I(z) = I_0 \frac{sin(k(h-|z|))}{sin(kh)}$, where h is the half length of the antenna element, and k is the wave number. This a good approximation when the antenna length is equal to half a wavelength, however when the lengths deviates from this the approximation becomes less suitable.

IV. BROADBAND PROPERTIES OF THE ANTENNA PATTERN

Directive patterns tend to be frequency dependent. Which means that a directive pattern at the design frequency might not be as directive at other frequencies. Therefore it is appropriate to evaluate the mutual information at different frequencies. For the mutual information calculations we are assuming the channel to be known to the receiver and unknown to the transmitter. The received signal can be written in matrix notation:

$$\mathbf{r} = \mathbf{AVHx} + \mathbf{n} \tag{5}$$

$\mathbf{x}$ is the signal transmitted from the different transmitter antennas at the basestation, $\mathbf{H}$ is the channel from the transmitter to the scatterers, $\mathbf{V}$ is the matrix consisting of the angular phases and $\mathbf{A}$ contains the spectral components of the antenna pattern. $\mathbf{V}$ and $\mathbf{A}$ are the same matrices as in equation (3). The mutual information can be expressed as:

$$\begin{aligned} & I(\mathbf{r};\mathbf{x}) \\ &= \log_2(\det(\mathbf{I}_{2L+1,2L+1} + \mathrm{SNR}\cdot \mathbf{AVHH}^H\mathbf{V}^H\mathbf{A}^H)) \\ &= \sum_i \log_2(1+\mathrm{SNR}{\lambda_i}^2) \end{aligned} \tag{6}$$

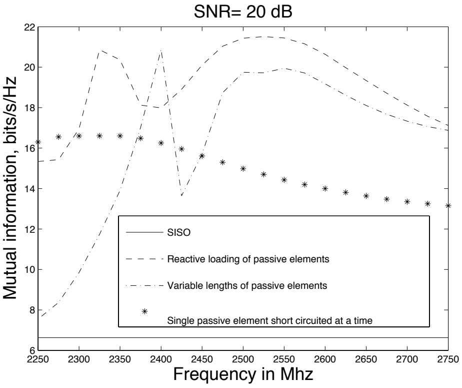
Where the matrices are normalized such that $\mathrm{tr}(\mathrm{E}_{\mathbf{H},\mathbf{V}}(\mathbf{AVHH}^H\mathbf{V}^H\mathbf{A}^H)) = 1$.

We have considered mutual information for four different cases. The first case is when reactively loading the passive elements, the second case is when the passive elements have variable lengths, the third case is when a single passive element is short circuited at a time and all the others open circuited (also considered in [1]), and the fourth is the SISO case which means there is a single transmitter and receiver antenna. For the reactive loading case constant loads are considered. This means that the reactive load has the same value for different frequencies. Later frequency dependent loads will be considered.

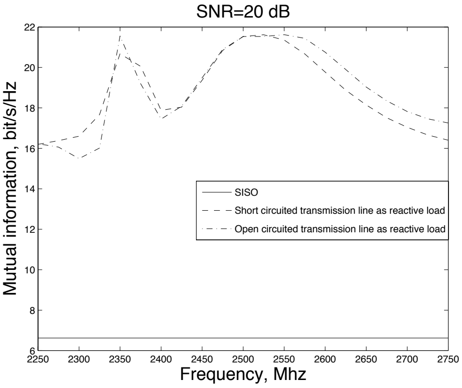
We found the expected mutual information $E_{\mathbf{H},\mathbf{V}}(I(\mathbf{r};\mathbf{x}))$ by doing monte carlo simulations, with the channel-path-weights created by ray-tracing. For these simulations we assumed the number of transmitters to be 20 and the number of scatterers to be 120. The high number of transmitters is chosen in order not to be limited by saturation effects by the transmitter. And the high number of scatterers is chosen because a low number of scatterers compared to the number of transmitter antennas creates statistical dependencies in the channel matrix [4]. The simulations are performed for a SNR of 20 dB.

Figure 5 shows how the mutual information varies with frequency for the four different cases mentioned previously. A frequency span of 500 MHz is considered. The numerical optimizations for the reactive loading and the variable lengths case were performed at the frequency 2.5 GHz. At this frequency the reactive loading achieves 21.43 bits/s/Hz while the case when short circuiting a single passive element at a time achieves 14.98 bits/s/Hz. The variable length case achieves somewhat smaller mutual information than the reactive loading, about 19.75 bits/s/Hz. Regarding the frequency behaviour of the mutual information we see that the variable length case is the one that has the largest fluctuations in mutual information. Especially for the lowest frequency part the mutual information is quite low. It almost falls down to the level of mutual information which is achievable for the SISO case. The mutual information for the reactive loading is higher than when a single passive element is short circuited at a time, almost for the entire frequency band. However there is a crossing point around 2.3 GHz where the mutual information of the single passive element short circuited at a time exceeds the mutual information of the reactive loading. Based on figure 5 the reactive loading should be the preferred choice of antenna configuration.

Now we need to consider how to achieve the reactive loading. There are different ways to realize reactive loading,



5: Mutual information for a frequency band of 500 Mhz.



6: Mutual information for a frequency band of 500 MHZ. Passive elements loaded with transmission-lines.

but assuming the loads to be independent of frequency is not realistic. In this paper the reactive loading is done by connecting transmission lines of appropriate lengths in the middle of the passive elements. To get the desired reactive load values the required lengths of the transmission lines need to be found. The reactive impedances that these transmission lines give would now be frequency dependent. There are two ways of using transmission lines. One way is connecting short circuited lines, the other is using open circuited lines. The lenghts of the lines will never exceed $\frac{\lambda}{2}$, since the impedances which are possible to create by these transmission lines are repeated for lengths longer than $\frac{\lambda}{2}$. We are assuming the lines to be lossless. To achieve the rotation of the antenna pattern we would need to switch between the different transmission lines. The expected mutual information when using transmission lines is given in figure 6. The two ways of realizing reactive loads by transmission lines show almost the same frequency behaviour of mutual information. And if we compare this behaviour to the frequency behaviour of the constant reactive load case we observe pretty similar frequency behaviour there as well.

V. CONCLUSION

We have investigated antenna patterns which are suitable for a compact MIMO receiver. Two main approaches are taken to find patterns that have several harmonics. Both approaches are similar in the way that they involve passive elements distributed on a circle around an active receiving dipole. Examples are given to show these two approaches, where a distance of $\frac{\lambda}{8}$ is considered between the active receiving dipole and the passive elements. One of the two ways considered to achieve a pattern with many spectral harmonics is by putting reactive loads in the middle of the passive elements. An antenna pattern was presented for this case that achieved 5 almost equally strong harmonics at the design frequency and two much weaker components in addition. This gives an expected mutual information of 21.43 bits/s/Hz for a SNR of 20 dB, compared to 14.98 bits/s/Hz which was presented in a previous paper [1]. The other way of achieving an antenna pattern with many spectral component is by having variable lengths of the passive elements. The mutual information obtained for the example which was given for this case was 19.75 bits/s/Hz. The frequency behaviour of mutual information obtained with the different antenna patterns was also considered. Leading to the conclusion that reactive loading is the better solution. Two ways of realizing the reactive loading was also presented.

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