MIMO CAPACITY OPTIMIZATION OF CLOSELY SPACED PATCH ANTENNAS

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Abstract- Compact Multiple-Input Multiple-Output (MIMO) systems will be a significant improvement for future high-bit-rate wireless applications. Closely spaced antennas however suffer from mutual coupling and highly correlated signals. In order to keep good system performance, the integration of these antennas in small areas needs to be optimized.

Recent studies have analyzed a system model that takes into account all the radio chain parameters for basic dipoles. In this paper, a 2x2 MIMO system architecture consisting of coplanar patch antennas will be considered with the objective to find an optimal architecture for different indoor environments.

I. INTRODUCTION

It is well known that quality of the wireless systems can be improved using different forms of MIMO systems. The full benefit of diversity implementation can be achieved if the antenna signals are highly uncorrelated, have independent fading characteristics and similar strength [1]. Conventional designs that tend to consider the antenna as a stand-alone independently optimized device are not adequate for this new generation of compact multi-antenna mobile communication devices. Instead, a new concept of antenna system able to match its impedance and radiation characteristics to the different requirements of the system can bring additional improvements to the conventional diversity schemes while reducing the size and the cost of the system. In order to design this new generation of antenna devices a close look has to be done to some of the basics of antenna and global radio channel behavior.

Recent works on arrays of half wavelength dipoles [2] for MIMO applications have developed a complete RF system model for indoor environments. The objective of this paper is to extend this model to the case of optimally matched realistic antennas. The criterion for geometry optimization will be the channel capacity.

In the next section a generalized expression for the capacity of a symmetrical MIMO system is reviewed. The channel model is described in section 3. Section 4 describes the choice of the proposed antenna design for a 2X2 MIMO system. The obtained results and the optimal architecture are discussed in section 5. Finally, conclusions are depicted in section 6.

II. THE CAPACITY OF A MIMO SYSTEM

The capacity of a channel is defined as the maximal velocity of data transfer that can be obtained for a given quality of the received signal. It is normally expressed in units of bps/Hz or bits/cycle. The system optimization presented in this paper focuses on finding antenna configurations for optimizing the channel capacity.

For the case of one transmitting and one receiving antenna (SISO), the classical formula of the Shannon channel capacity (1) shows that in high signal to noise ratio (SNR) context, an enhancement of 3 dB in the SNR implies an improvement of 1bps/Hz for the capacity.

\[ C = \log_2 (1 + \text{SNR}) \text{ bps/Hz} \]  

(1)

For an M transmitting and N receiving MIMO antenna system, it is well known that an increase in SNR and, in consequence, in channel capacity can be obtained. The actual increase in capacity depends on the transmitting power distribution between the different antennas. If the properties of the propagation channel are unknown, the most convenient way is to equally distribute it among the antennas. In this case [3], having a symmetrical MIMO system, M=N=n, with a Gaussian noise assumption, the capacity of the MIMO channel can be expressed by:

\[ C = \log_2 (I_n + \frac{\rho}{n} \cdot HH^*) \text{ bps/Hz} \]  

(2)

where H is the normalized channel matrix, introduced in section 3, and \( \rho \) the mean received SNR in each of the n antennas. \( I_n \) is the identity matrix of dimension (NxN). It is worth to mention that highly scattering environments and low correlated antennas produces high ranked H matrices resulting in higher capacities of the system.
III. THE COMPLETE RF CHANNEL MODEL

The channel model for the MIMO system that will be adopted is explained in detail in [2]. It considers all the components from the transmission to the reception of the signal. Figure 1 illustrates the different elements that form our system.

![Fig.1: Transmission Chain for the complete RF System Model](image)

Each of the sub-blocks and the block to block interactions of the transmission chain are modelled by a scattering matrix. The total radio channel can then be represented by a global matrix \( H^{\text{ext}} \), called the extended channel matrix, as:

\[
H^{\text{ext}} = (Z_{0,\text{Rx}})^{1/2} (I + r_{\text{Rx}}^D) (I - S^{H}_{\text{RxTx}} r_{\text{Rx}}^D)^{-1} \cdot S^{H}_{\text{RxTx}} (I + S^{H}_{\text{TxTx}})^{-1} (Z_{0,\text{Tx}})^{1/2}
\]

(3)

where \( Z_{0,\text{Rx}} (N \times N) \) and \( Z_{0,\text{Tx}} (M \times M) \) are the characteristic impedance matrix for reception and transmission respectively and \( r_{\text{Rx}}^D \) (N×N) is the reflection matrix of the drain and it describes the reflections of the signal in the reception loads in case that the antennas are not perfectly matched. The matrix \( S^{H}_{\text{RxTx}} \) can be obtained, through the following expression [2]:

\[
S^{H}_{\text{RxTx},nm} = \left( \frac{C_{\phi,m} (\phi^m_{p}, \phi^p_{m}) \cdot C_{\psi,m} (\psi^m_{p}, \psi^p_{m})}{\sqrt{\mathcal{R}(Z_{\phi,m})}} \right) \left( \frac{\lambda_{e}}{4 \pi} \right) G \cdot G
\]

(4)

where \( G \) denotes the active gain of the antennas and \( C \) is the complex polarimetric pattern of the coupled antennas. \( \mathcal{R}(Z_{\phi,m}) \) is the real part of the self-impedance of the antennas and \( Z_{\phi} \) is the characteristic impedance for the S parameters. \( \Gamma \) is the transfer polarimetric matrix of a stochastic polarimetric channel including angles of paths departure and arrival, exposed in [4]:

\[
\Gamma_{p} = \begin{pmatrix}
\Gamma_{\phi\phi, p} & \Gamma_{\phi\psi, p} \\
\Gamma_{\psi\phi, p} & \Gamma_{\psi\psi, p}
\end{pmatrix}
\]

(5)

Where the subscript \( p \) indicates the number of relevant paths.

In order to lower the correlation between the antennas, a matching network connected to the antennas will be considered in next sections. The idea is shown in figure 2.

![Fig.2: Multiple paths between Tx and Rx antennas](image)

IV. MICROSTRIP ANTENNA DESIGN FOR A 2x2 MIMO SYSTEM

The patch antennas have been designed with HFSS simulation tool. Figure 3 shows the antenna geometry, working at a frequency of 1.85 GHz and fed through a coaxial cable. The metallic patch over a dielectric substrate of permittivity \( \varepsilon_{r} = 4 \) is approximately \( \lambda_{e} / 2 \) by \( \lambda_{e} / 4 \) in size. With the feeding point located at \( \lambda_{e} / 18 \) a 100 MHz bandwidth at -10dB is obtained as shown in Figure 4.

![Fig.3: Microstrip Antenna Design](image)

![Fig.4: S11 parameter in dB versus frequency in GHz](image)

To investigate the behaviour of the MIMO system, two cases will be treated. Case a) where the two antennas radiate with the same polarization (space diversity geometry, SDG) and
case b) where the antennas radiate with crossed polarizations (space-polarization diversity geometry, SPDG). The design of both cases appears in figure 5.

![Case a) Space Diversity Geometry (SDG) Case b) Space-Polarization diversity geometry (SPDG)](image)

Fig 5. Case a) Space Diversity Geometry (SDG) Case b) Space-Polarization diversity geometry (SPDG)

V. ARCHITECTURE OPTIMIZATION RESULTS

A. Inter-Antenna Space Optimization

![Graph showing Mean Capacity of MIMO systems in bps/Hz versus separation between the antennas in lambda terms](image)

Fig 6. Mean Capacity of MIMO systems in bps/Hz versus separation between the antennas in lambda terms for the following cases: a) Space Diversity Geometry in a Small Office indoor environment (SDG SO-Size). b) Space Diversity Geometry in a Building Hall indoor environment. (SDG BH-Size). c) Space-Polarization Diversity Geometry in a Small Office indoor environment (SPDG SO-Size) d) Space-Polarization Diversity Geometry in a Building Hall indoor environment (SPDG BH-Size)

In order to study the antenna architecture optimization process, two different environments have been defined, corresponding to a small office size (SO-Size) and building hall size (BH-Size), with approximate volumes of 40 m$^3$ and 130 m$^3$ respectively. In both cases, 15 paths ($p=15$) and 15 random realizations have been assumed into the radio channel model previously described.

Figure 6 shows results for capacity as a function of the antenna separation ($d/\lambda$) for both, SO-Size and BH-Size, environment cases. For the SO-Size case, optimum separation is obtained for $d=0.7\lambda$, with 3.5 bps/Hz and 4.7 bps/Hz for the SDG and SPDG capacities respectively. Smaller spacing between antennas reduces the active gain and increases correlation, both producing a loss in capacity. In the other side, when the antennas separation increases, mutual effects and path correlation decreases resulting in small fluctuations in capacity around a medium value. For the BH-Size case, the optimum capacity occurs for a separation of around $0.6\lambda$ with values of 6.4 bps/Hz and 8 bps/Hz for the SDG and SPDG cases respectively. As before, decreasing spacing reduces capacity.

B. Active Antenna Matching

In the previous results a $Z_0$ matching condition has been assumed into the antennas which not guarantees minimum correlation conditions. In order to obtain an additional increase on capacity, optimal matching conditions can be created. The envelope correlation for a two-antenna system can be expressed [5] using the scattering parameters by:

$$\rho_e = \frac{|S_{11}^*S_{12} + S_{21}^*S_{22}|^2}{\left(1 - |S_{11}|^2 + |S_{21}|^2\right)\left(1 - |S_{22}|^2 + |S_{12}|^2\right)}$$  (6)

where $S$ is the scattering matrix of the two-port antenna system. It is clear that by changing the magnitude and phase of either $S_{11}$ or $S_{12}$ the correlation for a certain separation distance $d$ between the two antennas can be decreased. A possible way of achieving this could be by using a matching network for connecting the antennas, as shown in figure 7.a, while keeping radiation efficiency at acceptable values. Minimal values for the correlation coefficient given in the expression shown in (6) can be found by either minimizing $S_{11}$, minimizing $S_{12}$ or by making $S_{11}$ in quadrature with $S_{12}$ with the performance of the antenna system given by $1 - |S_{11}|^2 - |S_{12}|^2$ [5]. For the case of making $S_{11}$ pure real and $S_{12}$ pure imaginary a network consisting of transmission lines are used for decoupling, making $S_{12}$ zero. A transmission line and an open circuit stub are then used for making $S_{11}$ minimal, resulting in the simulated graph shown in fig. 7.b.

The combination of the two previous mechanisms, space-polarization diversity and active matching conditions, will allow to extend the 0.5-0.7λ, optimal capacity values to ranges as low as 0.2λ, which involves capacity increases of around 2 bps/Hz for the two different scattering environments studied.
Integration conditions for realistic patch MIMO antennas in limited spaces has been studied considering the different factors that take part in the wireless chain. Antenna separation, polarization and matching conditions have been taken into account and preliminary results for optimization have been given.

Capacity values for spatial-polarization diversity have been found for two different indoor environments corresponding to small and medium size spaces. Optimal values around 0.5-0.7 λ have been obtained under conventional antenna matching conditions. Additional results for active matching condition are being investigated and simulated and experimental results will be presented.

Combining downsizing antenna techniques, space and polarization diversity and active matching conditions new compact multi-antenna architectures can be developed that simultaneously fit the demands on size reduction and capacity improvement.

REFERENCES