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Published in:
I E E E V T S Vehicular Technology Conference. Proceedings

DOI (link to publication from Publisher):
10.1109/VETECF.2011.6093117

Publication date:
2011

Document Version
Early version, also known as pre-print

Link to publication from Aalborg University

Citation for published version (APA):
Tatomirescu, A., Pelosi, M., Knudsen, M. B., Franek, O., & Pedersen, G. F. (2011). Passive Component Network for Antenna Isolation in MIMO Systems for Handheld Terminals. *I E E E V T S Vehicular Technology Conference. Proceedings*. https://doi.org/10.1109/VETECF.2011.6093117

Vehicular Technology Conference (VTC Fall), 2011 IEEE 74rd

Passive Component Network for Antenna Isolation in MIMO Systems for Handheld Terminals

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***Abstract*—This paper presents an improved method to isolate the ports for a MIMO antenna in hand-held devices using lumped components. It has been analyzed through simulation and measurement. The total efficiency and the envelope correlation have been evaluated.**

Compared to the case with no decoupling mechanism, the efficiency from the scattering parameters increases significantly and the envelope correlation coefficient decreases dramatically. Nevertheless, when choosing the components, the ohmic losses must receive extra consideration in order to maximize the system's total efficiency. Furthermore, the use of lumped components has the potential to make the presence of other components in the mobile device or the user, less harmful to the decoupling mechanism.

I. INTRODUCTION

Modern wireless communications have been revolutionized by the introduction of Multiple Input-Multiple Output (MIMO), also known as Multi Antenna Systems (MAS). This subject has received considerable research interest over the past couple of years. Compared to a traditional single antenna to antenna transmission, it has increased capacity, spectral efficiency and robustness, as presented in [1].

The 4^{th} Generation (4G) mobile network technology sets out to satisfy the demand for higher data rate in mobile terminals. It uses MIMO technologies to achieve download rates up to 100 Mbit/s. Among the challenges faced by this technology is the limited space available in today's handheld devices which is less than $\lambda/4$ for the lower bands used in Long Term Evolution (LTE). Therefore the antennas are electrically close to each other and present a high coupling between the elements [2]. Mutual coupling between antennas degrades the efficiency as well as the capacity of the MIMO system, as shown in [3] and [4].

Among the existing methods to decouple closely spaced antennas for a mobile phone is the use of the orthogonality of antenna array's eigenmodes to achieve decoupling as discussed in [5]. For a symmetric antenna system, it has been shown in [5] that the eigenmodes can be excited by couplers. To obtain the eigenmodes, hybrid-couplers have been successfully used either as microstrip-based rate-race hybrid as in [6],[7] and [8], or as branch-line hybrid coupler as in [5]and [9]. They are not a solution for low frequencies in hand-held devices because of the considerable space needed. Therefore, in LTE terminals, an equivalent coupler composed of lumped components can be implemented as in [9].

This paper makes an analysis on practical issues of implementing a passive component network for port decoupling in MIMO systems that use frequency lower than 1 GHz. The method of using a hybrid coupler with lumped components is improved. The rest of the paper is composed of three sections. In the first section, the test scenario is presented. The following section contains the discussions of the proposed method and the results obtained with it. The last section concludes the paper.

II. SIMULATION PARAMETERS

The antenna structure used in this paper consists of two meander line monopole antennas with the size 52x19x1 mm^3, as shown in figure 1. It is a small, low-cost, and low-profile antenna printed directly on a Printed Circuit Board (PCB), standard FR4 of size 110x52x1 mm^3, for easy integration and simple manufacturing. It has been simulated using the Finite Difference Time Domain (FDTD) method with the cell size of 1 mm. The patch in the middle must be grounded, therefore a double sided PCB is needed, as it can be seen in figure 2. The sides of the PCB are covered with conductive material so that the two ground planes are connected. The middle patch is grounded via hole as the top of the ground plane, the part that is just under the antenna.

In the design process of a MIMO antenna the following parameters must receive special consideration : total efficiency, near-field coupling and envelope correlation coefficient. The efficiency can be calculated with equation 1 [2], where η_{rad} is the radiation efficiency taking into account the conductive and dielectric losses, while the envelope correlation coefficient can be obtained from equation 2.

$$\eta_{total1} = \eta_{rad1} * (1 - |S_{11}|^2 - |S_{21}|^2) \tag{1}$$

$$\rho_e = \frac{|\int_0^{\pi}\int_0^{2\pi}[\overrightarrow{F}_1(\theta,\phi) \bullet \overrightarrow{F}_2] d\phi \sin\theta d\theta|^2}{\int_0^{\pi}\int_0^{2\pi} |\overrightarrow{F}_1(\theta,\phi)|^2 d\phi \sin\theta d\theta \int_0^{\pi}\int_0^{2\pi} |\overrightarrow{F}_2(\theta,\phi)|^2 d\phi \sin\theta d\theta} \tag{2}$$

where • denotes the Hermitian product and $\overrightarrow{F}_i(\theta, \phi)$ is the radiation pattern when port i is excited [4]. Furthermore, the envelope correlation can be calculated from the scattering parameters of the antenna using equation 3 under the assumption of lossless antennas and uniform distribution incoming angle of the power or angle of arrival (AoA) [10].

$$\rho_e = \frac{|S_{11}^* S_{21} + S_{21}^* S_{22}|^2}{(1 - |S_{11}|^2 + |S_{21}|^2)(1 - |S_{22}|^2 - |S_{12}|^2)} \tag{3}$$

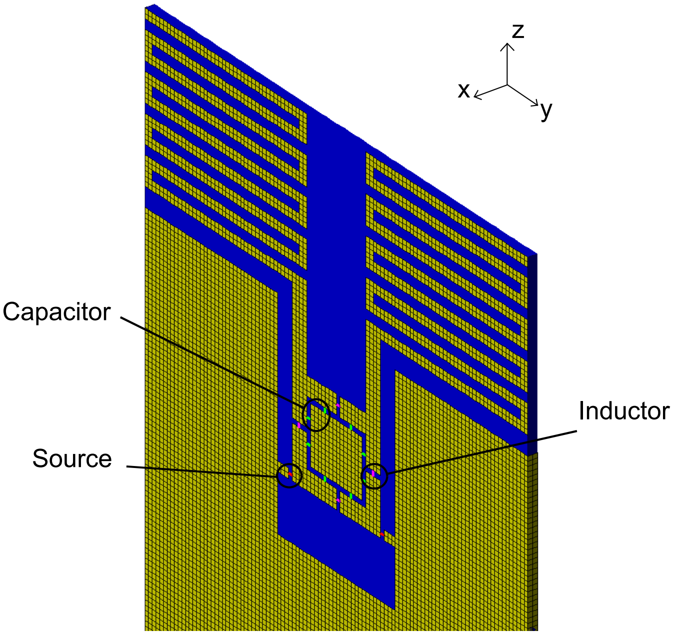

Fig. 1. Numerical model of the antenna array, front side view, where the red lines represent the feed point, the green lines capacitors and magenta inductors. The patch in the middle of the network is grounded and the cell is size 0.5mm.

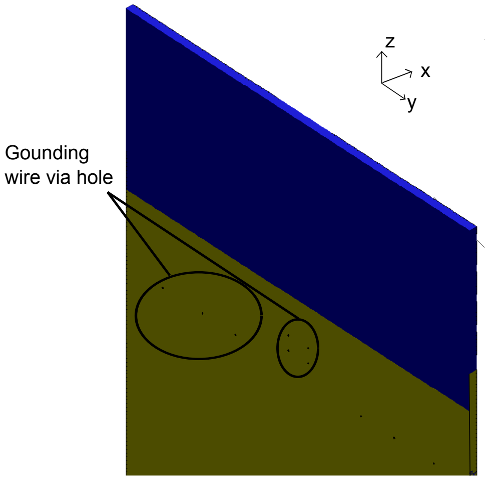

Fig. 2. The back side of antenna array. The wires that connect the top and bottom ground plate are highlighted. the cell is size 0.5 mm.

III. RESULTS AND DISCUSSIONS

Simulations of the structure from figure 1 without the decoupling network, just the radiating elements, for a cell size of 0.5 mm give the results plotted in figure 3. Compared with the measured results of the prototype there is a difference between resonance frequencies as can be seen in figure 3. In order to accurately simulate a structure with meandering such as the one in question, a very small cell size must be used to limit the errors of the approximations in the FDTD algorithm. As a consequence of computing limitations, the simulations are limited to a cell size of 0.5 mm. Furthermore, the influence of the measuring set-up on the antenna parameters has not been simulated.

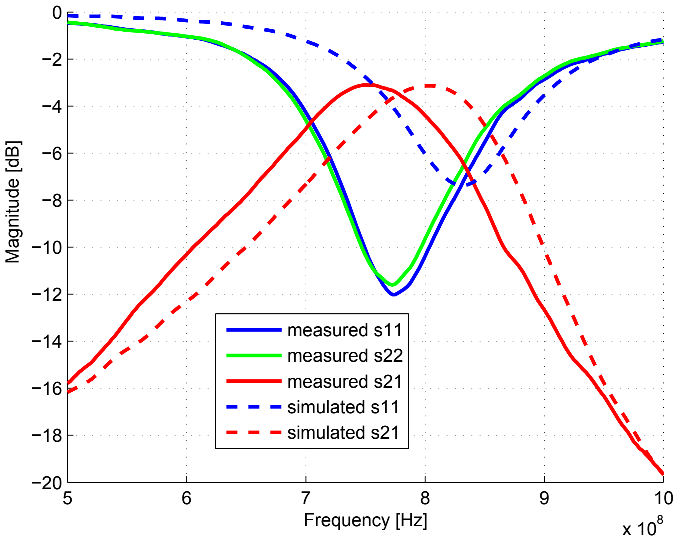

Fig. 3. Simulation results for 0.5 mm cell size compared with measurements of just the antennas without the decoupling network. Simulated S_{11} and S_{22} are identical and only the second is plotted.

In order to increase the efficiency and to reduce the correlation of the two antennas, a hybrid coupler can be used. It can be implemented with lumped components by using four equivalent π networks instead of a quarter of a wave long branchlines. The coupler's π networks, two capacitors and a inductor, are calculated with the following equations:

$$L_i = \frac{Z_i}{2\pi f} \tag{4}$$

$$C_i = \frac{1}{2\pi Z_i f} \tag{5}$$

where Z_i is equal to 35.35 Ω between the feed point and each of the antennas (C1 and L1) and 50 Ω between the two antennas and between the two feed points(C2 and L2).

For the coupler with the values of C_1=5.8 pF, C_2=4.1 pF, L_1=7.3 nH and L_2=10.3 nH and 50 Ω terminations, the S parameters from figure 4 are obtained. Ports 1 and 2 are the feeding ports and Ports 3 and 4 are the ports that lead to the antennas. If the impedance of the antenna's ports is not 50 Ω then S11 and S21, which correspond to the self matching and decoupling, are not in the same frequency band, as shown in figure 5. The reason behind this is that the coupler is no longer terminated with 50 Ω impedance when the output ports of the coupler are connected to the input antenna ports. The new output impedance is complex due to the fact that the input impedance of the antenna is a function of the impendence seen at the other antenna port. In other words, because the mutual coupling prevents it to been seen as a classic termination, when the antenna array is connected to the output ports of the coupler, an equivalent two port network is placed. It is not anymore a classical terminations for which the coupler was designed.

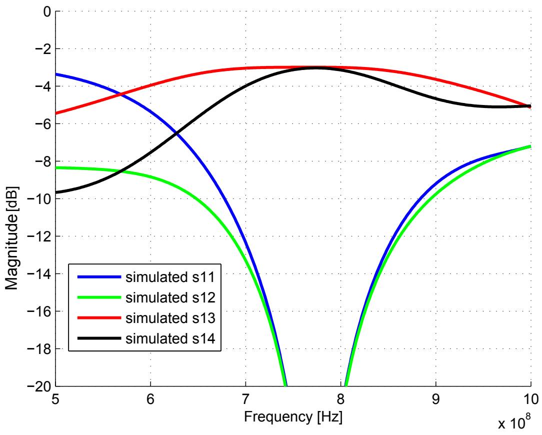

Fig. 4. The S parameters of the hybrid coupler when the ports are terminated on 50 Ω.

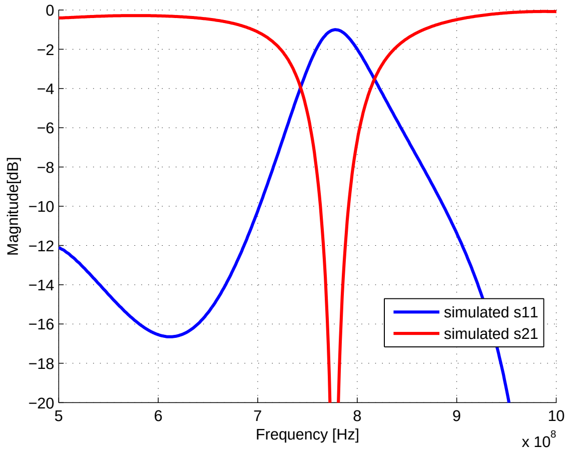

Fig. 5. The S parameters of the hybrid coupler when the antenna structure is connected to the output ports 3 and 4.

In [9] it has been shown that when the coupler is terminated with the antenna array, a matching network is required in order for the decoupling frequency to coincide with the port's self matching. For this paper, an analytical approach has been used to solve the impedance of the equivalent transmission lines as a function of antenna's input impedance. They have been calculated by using the even and the odd mode of the combined system (the antenna plus the coupler). The equations found for optimizing the values of the components needed in order to have matched and decoupled antennas at the same frequency for any antenna impedance are difficult to solve analytically and for some antenna impedance it has complex solutions. A parametric study using numerical methods is preferred. Multiple simulation have been run to find acceptable values for the characteristic impedance of the quarter-wave transmission lines in order to have a good level of matching and isolation of the input ports.

After the values of the components used in the coupler are obtained, existing components are chosen. They are C1=8.2pF, L1=4.7nH, C2=3.3pF and L2=5.7nH. Also, an analysis of the network's sensitivity to the components' tolerances has been done. It has been observed that the network is robust to variations of the nominal value in the frequency band of interest. These values, simulated in the antenna setup from figure 1, produce the S-parameters which are similar to the measured ones, plotted in figure 6.

The proposed coupler acts as a matching network that is jointly optimized for minimum envelope correlation and maximum matching efficiency, as described in [2]. From analysis and through simulation it was found that it is possible to eliminate the matching network by adapting the values of the coupler's components to specific antennas.

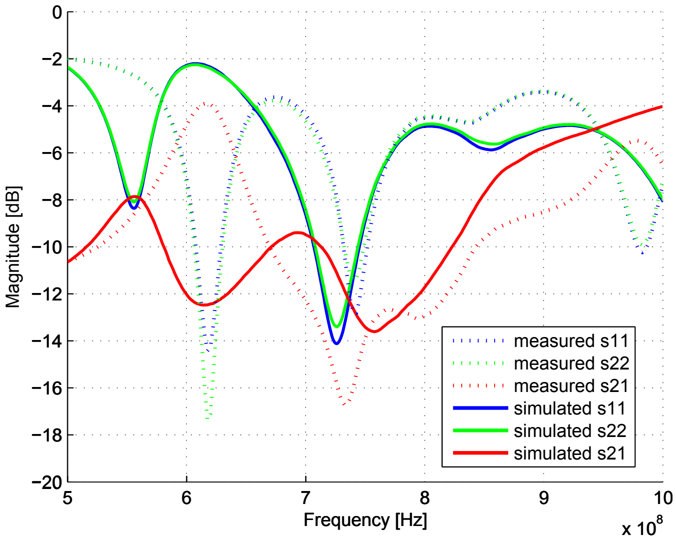

Fig. 6. The measured and simulated S parameters of the coupler when the components are calculated considering the antenna impedance.

Because the matching network is eliminated and the response of the coupler is wider, the bandwidth of the system has doubled both in matching (-6 dB bandwidth of 42 MHz compared to less than 20 MHz in [9]) and in isolation (-10 dB bandwidth of 120 MHz). These results are consistent with the findings of [2], where it was found that the decoupling networks reduce efficiency bandwidth of the antenna system.

At 742 MHz, the measured total efficiency for the antenna with the S parameters shown in figure 6 is -6 dB's. The components used in the prototype have average quality factors (Q) values , 100 for the capacitors and around 20 for the inductors. The radiation efficiency of the antenna accounting for the dielectric and conductive losses in the radiating element, has been calculated from measurements to be -2.8 dB's. The network has a loss of 3.2dB's which is a little higher than the simulated one which is 2.6 dB's. This can be explained by the errors in the manufacturing process. If inductors with a Q of 54 are used, the simulated efficiency of the coupler is -1.08 dB's.

The efficiency of the coupler is low but can be easily improved by using better quality components. Thus, any increase in efficiency due to improved S parameters is canceled by the coupler's lossy components, especially the coils. At 742 MHz, the far field gain patterns which are plotted in figure 7 confirm that the orthogonal radiation modes are excited, similar to beamforming. For these radiation patterns, the far-field envelope correlation coefficient is 0.02 compared to 0.52 in the case with out coupler.

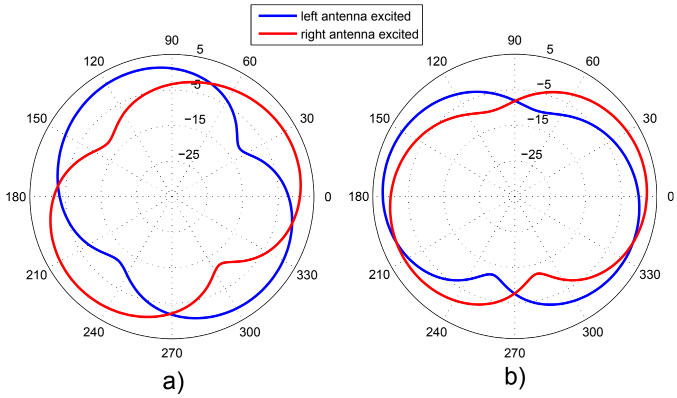

Fig. 7. The simulated radiation patterns of the antenna in the YZ plane and in dB's without hybrid coupler at 781 MHz(a) and with hybrid coupler at 742 MHz(b).

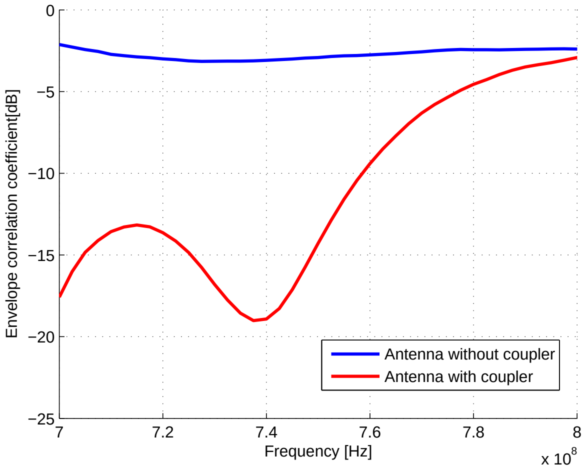

Fig. 8. The envelope correlation coefficient calculated from the measured S parameters using equation 3.

IV. CONCLUSIONS

By using a hybrid coupler, as the one shown in this paper, it is possible to decouple closely spaced antennas on a small ground plane even at sub GHz frequencies.

In this paper it has been shown that the use of a matching network for the hybrid coupler is not necessary if the antenna impedance is taken into consideration.

An increase in bandwidth has been noticed and because there are fewer lossy components, there is an extra gain in efficiency. Still, the coupler is not efficient enough to have inexpensive circuit elements with low Q.

The free-space radiation patterns of the two antennas indicate that the coupler excites the eigenmodes of the antenna systems, resulting in a low envelope correlation.

The hybrid coupler offers a solution to the mutual coupling of the antennas. Nevertheless, its efficiency must be improved in order for this method to be considered a strong candidate for future applications.

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