A Decorrelated Closely Spaced Array of Four Slot Antennas Backed with SIW Cavities for MIMO Communications

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Abstract— **An array of four slot antennas backed with substrate integrated waveguide (SIW) cavities is presented for application to multiple input multiple output (MIMO) systems. Two 0.18λ spaced antennas are decorrelated by the use of a rat race hybrid. An investigation based on simulations and measurements has been carried out. The impedance matching and the radiation characteristics of these structures were studied using the Finite Difference Time Domain (FDTD) technique. The array performance is judged by considering the correlation coefficients between the elements and the MIMO channel capacity.**

I. Introduction

MIMO communications systems promise overcoming the limits of single-input single-output (SISO) systems with their ability of providing high data rates without need for extra bandwidth [1]. However it is a challenge to realize these systems in small sized mobile units. When the antennas are spaced less than 0.5λ, they face severe mutual coupling which degrades the efficiency. It also results in high correlation coefficient between the closely spaced antennas decreasing the performance of the MIMO system [2]-[3]. In order to decorrelate such antennas, some techniques were proposed in [4]-[6]. However no practical results for capacity enhancement have been given. The technique of inserting a rat race hybrid to an array of slot antennas backed by conventional cavities was presented by the authors in [7]. In this paper these results are extended and compared with measured antenna data.

Cavity backed slot (CBS) antennas were first studied in [8] to the best of the author's knowledge. After that, the topic is very well covered in the literature. However much of the previous work done on CBS antennas only consider deep cavities which are not suitable for use on small mobile terminals. In this paper, slot antennas backed by shallow SIW cavities are considered. SIW technique is first proposed in [9] and since then, it has been applied to many microwave devices including waveguide slot antennas [10]. It has many advantages but primary aim of the use of SIW in this research is to improve the antenna performance in terms of manufacturing repeatability.

Two 0.18λ spaced slots are decorrelated by a rat race hybrid and the performance of the four element array with and without the rat race hybrid is presented in terms of correlation coefficients and MIMO channel capacity for different scenarios.

In section II, design of the four element array and the rat race hybrid is presented. The enhancement due to the hybrid is demonstrated in section III. And the paper concludes with section IV.

II. Design Procedure

A. CBS Array

The array is constructed on two RT/Duroid 5880 substrates with a thickness of 1.575mm each. The slots are fed by stripline feeds which are located off central for matching purposes. The lowest slot resonance which is defined by the slot length is theoretically at 5.17GHz and, in practice, at 5.2 GHz. The cavity's lowest resonance is calculated to be at 9.5GHz assuming that the cavity is fully closed. Since this lowest cavity resonance is far away from the slot resonance, the cavity dimensions have only a small effect on operating frequency.

Dimensions labelled in Figure 1 are as follows: CL= 40mm, CW= 11mm, SL= 29mm, $2 \leq s \leq 4$mm, d= 0.55mm. Virtual walls are used to form the SIW cavity following on from the authors' previous investigations [12]. As mentioned before, the cavity does not have a big effect on the antenna resonance; its purpose is to confine the radiation from slot to one direction. That is why the virtual wall parameters namely "s" and "d" are not as strict as given in the literature as shown in [12].

Measured and simulated S11 and S21 plots of the array are in good agreement, as can be seen in Figure 2. Measured and simulated coupling at 5.2 GHz are -7.569dB and -6.07dB respectively. Coupling is expected to be high since A1 and A2 are only 0.18λ spaced. The other two elements, A3 and A4 are 0.88λ apart from each other and their polarisations are perpendicular to A1 and A2 which results in low coupling with the other elements. For this reason, only A1 and A2 need to be decorrelated and will be the focus of discussion for the rest of the paper.

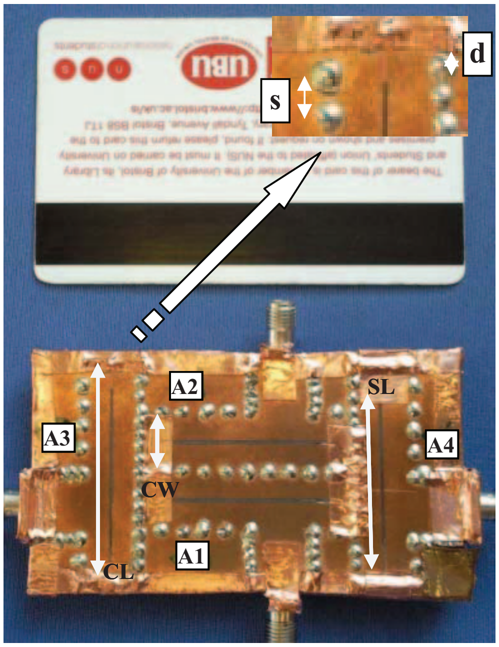

Figure 1 4 element array, where CL: cavity length, CW: cavity width, SL: slot length, s: shorting pin separation, d: shorting pin diameter

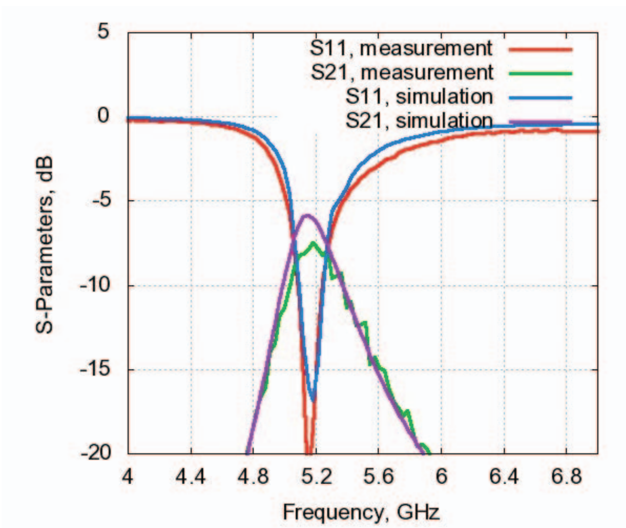

Figure 2 Measured and Simulated S-Parameters of the array before decorrelation

B. *Rat-Race Hybrid*

A stripline rat race hybrid designed to operate at 5.2GHz will be used to decorrelate the closely spaced antennas as proposed in [11]. It is manufactured using another two layers of RT/Duroid 5880 of which first layer can be seen in Figure 3. Figure 4 shows the measured S-Parameters of the manufactured hybrid. The 4 layers of Duroid, 2 being the array layers, and 2 being the hybrid layers are sticked to each other forming a final structure with dimensions of 6.3mm x 8cm x 6cm as seen in Figure 5. A1 and A2 are connected to isolated 2nd port (H2) and the 4th port (H4) of the hybrid by means of two 0.55mm diameter shorting pins. When the structure is excited from the H1 which refers to P1 in the final structure in Figure 5, the signals arriving at A1 and A2 are out of phase. When the H3 (P2 in the final structure) is excited signals with the same amplitude and phase arrive at A1 and A2. This theoretically should form difference and a sum patterns respectively.

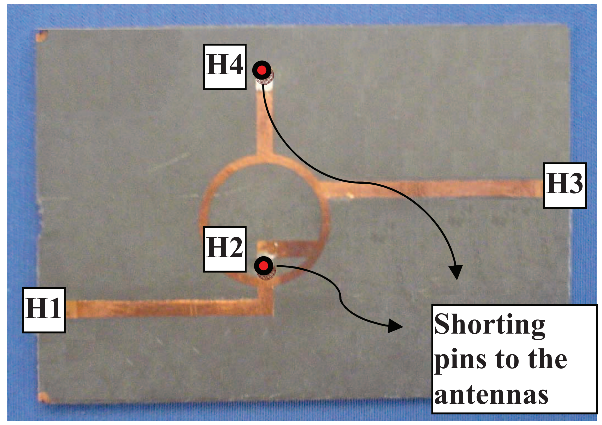

Figure 3 The rat race hybrid

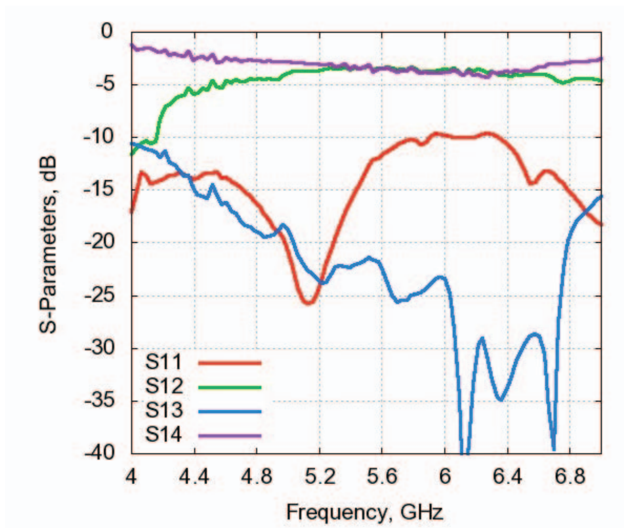

Figure 4 Measured S-Parameters of the Hybrid

III. RESULTS

The effects of the hybrid on the overall performance of the antenna are presented in terms of different parameters such as coupling coefficient, radiation patterns, correlations and MIMO channel capacity. Coupling coefficient between the two closely spaced elements is plotted in Figure 6 before and after the insertion of the hybrid. Simulations predict that S21 after decorrelation at 5.2 GHz is reduced to -19.9dB. Although the improvement which was achieved in practice is not as great as this, nevertheless the measurements show that the coupling has been reduced to -11.7dB.

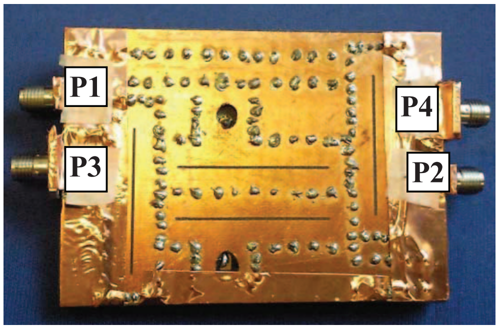

Figure 5 Decorrelated Array

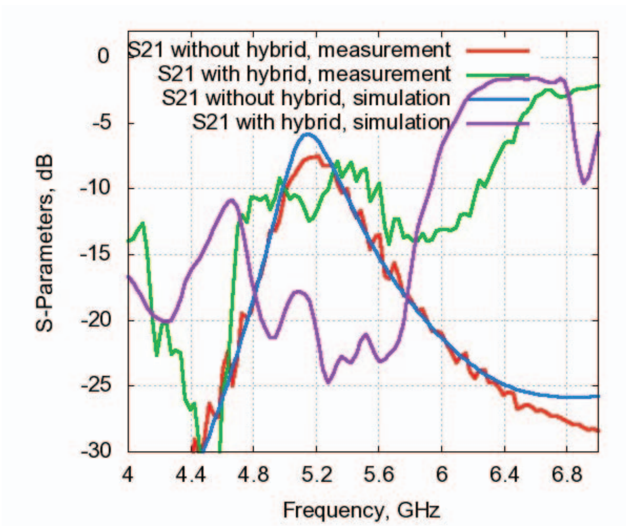

Figure 6 Simulated coupling between the closely spaced antenna elements

Figure 7a and Figure 7b show measured radiation patterns of A1 and A2 respectively when the remaining antennas are terminated by matched loads. Figure 7c and Figure 7d show the radiation patterns after the insertion of the hybrid when driven by P1 and P2 respectively. The radiation patterns were measured in an 8m long anechoic chamber at 5.2 GHz. The array was mounted on a rectangular ground plane of 20 by 20cm (considering the difficulty in measuring electrically small antennas). The data is displayed with the level at the centre of the plot -40dB relative to that at the outside. Figure 7a and 7b show that due to mutual coupling, the beam is squinted at an angle of θ= ±60. Sum and difference patterns can be observed in Figure 7c and 7d. These radiation pattern data are used to calculate the correlation between the antennas as seen in Table 1. Both the measurements and the simulations show that the correlation is decreased.

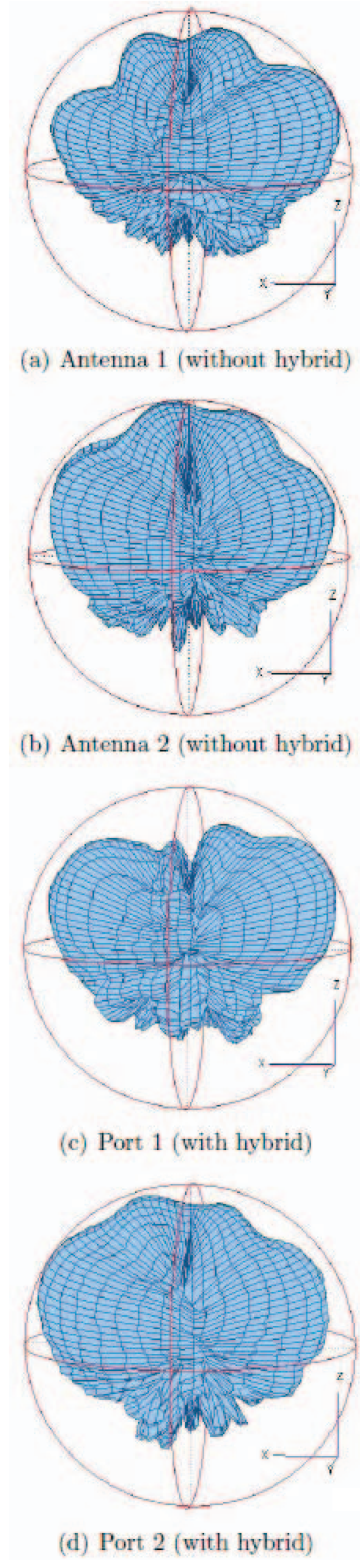

Figure 7 Comparison of measured and simulated radiation patterns of two closely spaced antennas

TABLE I
CORRELATIONS BETWEEN THE CLOSELY SPACED ANTENNA ELEMENTS

	Correlation coefficient	
	Measurements	Simulations
Antennas without hybrid	**0.583**	**0.318**
Antennas with hybrid	**0.306**	**0.197**

The MIMO channel was simulated using a summation of paths such that the total received signal was the superposition of a number of plane waves. The H matrix which characterised the transmission from transmit antenna array to the receive antenna array is given by equation (1) where θi, φi, θd, φd are the azimuth and elevation angles of departure and incidence. The maximum capacity is then calculated using the channel matrix with equation (2). The data for the channels were obtained in two ways: artificial channel and measured outdoor channel. Artificial channel was generated using a specified statistical distribution. All angles were uniformly distributed; path lengths were normally distributed with a mean of 2km and standard deviation of 200m. Secondly a real outdoor channel data was measured at Bristol by our colleagues in the Wireless group of the Centre for Communications Research.

$$H_{ij} = \sum_k A_k e^{j\psi_k} G_{tx}(\theta d_j, \varphi d_j) G_{rx}(\theta i_i, \varphi i_i) \quad (1)$$

$$C = \log_2 (I + \rho^2 H \overline{H^T}) \quad (2)$$

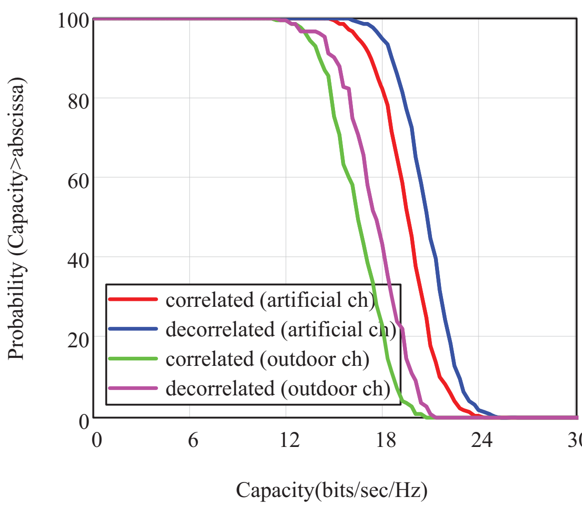

Figure 8 Capacity plots for selected arrays and channel models

Capacities for artificial and measured outdoor channels are calculated with the transmitted power kept constant before and after the insertion of the hybrid. Figure 8 shows that the 4x4 MIMO channel capacity increases as the correlation between the two closely spaced antennas decreases. The artificial channel has a better performance as it is the one closer to the ideal condition. Note that 1000 samples of the artificial channel were generated whereas only 120 samples of the measured data were available.

IV. CONCLUSIONS

A study of an array of four slot antennas backed by SIW cavities of which two closely spaced elements are decorrelated using a rat race hybrid is presented. The effect of the rat race hybrid on correlation and MIMO channel capacity is investigated. Measurements and FDTD analysis have both shown that when the hybrid is included, the correlation coefficient between the closely spaced elements (calculated using 3D radiation patterns) is greatly reduced. Capacity calculations have been performed using artificial channel data and measured outdoor channel data. It has been shown that the MIMO performance of the array is improved by the use of the hybrid at the cost of only a 3.15mm increase in the height of the structure. Finally a compact, light weight and efficient array is reached.

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