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Degree-of-Freedom Evaluation of Six-Port Antenna Arrays in a Rich Scattering Environment

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Abstract—It has been proposed that six co-located antennas, namely three electric and three magnetic dipoles, can offer up to a six-fold capacity increase in wireless channels, relative to that of single antennas. In other words, six degrees of freedom (DOFs) can be supported by co-located six-port transmit and receive antenna arrays. However, due to the complexity in designing and measuring such a six-port antenna, to our knowledge, no experimental verification has yet been successfully performed. In this paper, the six DOFs hypothesis is experimentally verified at the 300 MHz band. The experiment involved the design and fabrication of two six-port arrays, and MIMO channel measurements in a rich scattering environment with these arrays.

I. INTRODUCTION

The use of two polarization states of plane waves has been known to introduce two degrees of freedom (DOFs) in a wireless communication channel. However, an additional three-fold increase in channel capacity in a rich scattering environment is proposed in [1] by the use of six distinguishable electric and magnetic polarization states. Co-located, orthogonally polarized electric and magnetic dipoles are postulated to achieve the six DOFs in the context of MIMO systems. Nevertheless, the study in [1] only experimentally demonstrates three DOFs by means of tri-polarized half-wave ($\lambda/2$) sleeve dipoles, rather than the postulated six-fold increase. The pioneering work in [1] is followed up by a number of theoretical studies on the number of available DOFs [2]–[5], which give further insights into the topic. On the other hand, significant attention is given towards the design of compact and/or co-located antenna arrays with good DOF characteristics, *e.g.*, [6]–[12]. Nevertheless, to our knowledge, no experiment has been performed to verify the six polarization DOFs hypothesis in [1].

In this paper, two six-port antenna arrays are designed and fabricated in order to investigate the number of DOFs in measured MIMO channels. In particular, one of the two arrays is made compact, in order to co-locate the antenna elements and to constrain spatial DOFs. The latter requirement is to ensure that the obtained DOFs may be attributed to polarization and angle diversities [5], rather than spatial diversity. This compact array is used on the receive (RX) end. In contrast, the other six-port array, which is used as a reference on the transmit (TX) end, is significantly larger and intentionally designed to afford six DOFs from spatial, polarization and

Fig. 1. Six-port arrays.

angle diversities. Thus, the focus is on whether the compact six-port RX array can support six DOFs in the given setup. The antenna elements of both prototypes are designed to resemble the desired characteristics of the fundamental electric and magnetic dipoles. In order to simplify the construction of the multiport antenna structures, as well as to utilize our MIMO channel measurement equipment, the arrays are designed for a relatively low frequency of 377 MHz. Using the two arrays, 6×6 MIMO channels are measured in a RF shielded laboratory, which is inherently a rich scattering environment.

The remainder of the paper is organized as follows. Section II presents the characteristics of the TX and RX antenna arrays. In Section III, the MIMO channel measurement campaign is described in detail. In Section IV, the number of DOFs of the measured MIMO channel is discussed. Section V concludes the paper.

II. SIX-PORT ARRAY CHARACTERISTICS

A. Reference TX Array

The reference TX antenna array is designed by means of half-wave dipoles and Alford loops [13]. Fig. 1(a) shows a picture of the prototype. In order to obtain the desired magnetic dipole characteristics without the use of a small loop, the Alford loop is chosen to achieve uniform current distribution along the loop wire. Three Alford loops (Ports 4-6) are placed perpendicularly to one another as tri-polarized magnetic dipoles, which complement the three electric dipoles (Ports 1-3). Each of the six antennas is equipped with a

Fig. 2. Measured S parameters of the reference TX array and the compact RX array.

Fig. 3. Measured gain patterns of the reference TX array, $G_{TX,\phi}(\phi, \theta)$.

Fig. 4. Measured gain patterns of the reference TX array, $G_{TX,\theta}(\phi, \theta)$.

quarter-wave balun, in order to mitigate cable influence. The TX array is designed to fit into a cube with sides of 0.75λ .

The measured S parameters of the TX array are given in Figs. 2(a) and (b). The reflection coefficients show that the bandwidth of the dipoles is larger than that of the loops. As a result, the array bandwidth is mainly determined by the bandwidth of the loops, and it is around 13.6 MHz at the -6 dB level. Good isolation of more than 20 dB can be

achieved between all pairs of antenna ports. In particular, the co-polarized antenna pairs of electric and magnetic dipoles exhibit very low mutual coupling around the resonant frequency, as can be observed from S_{41} , S_{52} and S_{63} in Fig. 2(b). The S parameters that are not shown exhibit similar behavior due to the symmetrical structure of the array.

When measuring the TX array in the SATIMO Stargate 64 chamber [14], a coaxial cable is connected to the port being

The 6×6 channel transfer functions between the TX/RX antennas were measured based on the “switched array” principle [16] using the Medav RUSK Lund wideband channel sounder, which was stationed outside the lab. The ROF system was used for connecting between each port of the compact RX array and the RF switch. The measurements were performed using 65 subcarrier signals over a 20 MHz bandwidth centered at 377 MHz. However, we only used the measured data over a 6 MHz bandwidth (*i.e.*, 374 MHz – 380 MHz) for this study, which produces 21 frequency samples. A block of 400 consecutive snapshots was obtained for each measurement position (with a given TX/RX array orientation). The measured channel matrices obtained from the consecutive snapshots are used in post processing to enhance the signal-to-noise ratio (SNR) of the measurement and to estimate the noise power. As a result, the achieved post processing SNR is on average 30 dB throughout the measurements.

Fig. 6. Capacity of measured MIMO channels.

IV. NUMBER OF DOFS

One simple approach to characterize the DOFs of a multiport array is to calculate the correlation between all pairs of antenna radiation patterns. At the center frequency, the correlation is found to be less than 0.13 for the TX array, and it is less than 0.32 for the RX array. The correlation is higher for the RX array due to its compactness. Although this correlation is generally considered low enough to ensure good diversity gain (and hence DOF capability), channel capacity as calculated from the measured channels can provide a more concise indication of the number of DOFs in MIMO channels.

Fig. 6 compares the measured channel capacity with that of independent and identically distributed (IID) Rayleigh MIMO channels. Particularly, in Fig. 6(a), the cumulative distribution function (CDF) of the measured channel capacity is evaluated at 20 dB SNR. The CDF can be seen to very closely follow that of the 6×6 IID Rayleigh channels. Indeed, the envelope of the measured channels is Rayleigh distributed, because a rich scattering environment is ensured inside the RF shielded lab. Furthermore, since the compact array is used at one end, it is confirmed that good performance can be achieved when the array is contained in a small spatial volume of $0.24\lambda \times 0.24\lambda \times 0.24\lambda$. Therefore, the experiment results verify that the six DOFs (as postulated in [1]) can indeed be achieved in a propagation channel with rich scattering, even when compact arrays with co-located elements are used.

V. CONCLUSIONS

In this paper, two six-port antenna arrays are designed by means of tri-polarized antenna pairs of electric and magnetic dipoles. In particular, the RX array is compact and has co-located antenna elements. Experimental results of the MIMO channel measurements performed in a RF shielded laboratory verify that six DOFs are attained by a compact array in a rich scattering environment.

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