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

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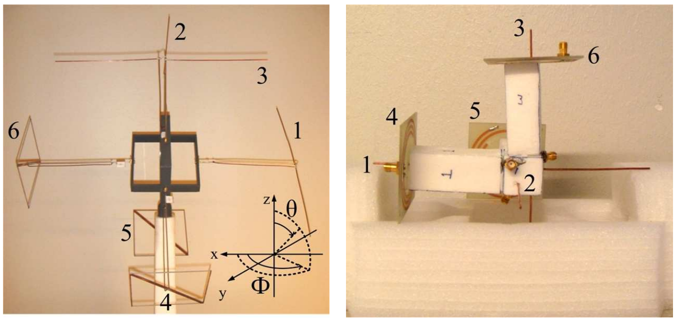
***Abstract*—It has been proposed that six co-located antennas, namely three electric and three magnetic dipoles, can offer up to a six-fold capacity increase in wireless channels, relative to that of single antennas. In other words, six degrees of freedom (DOFs) can be supported by co-located six-port 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.**



(a) Reference TX array (b) Compact RX array

Fig. 1. Six-port 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 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.

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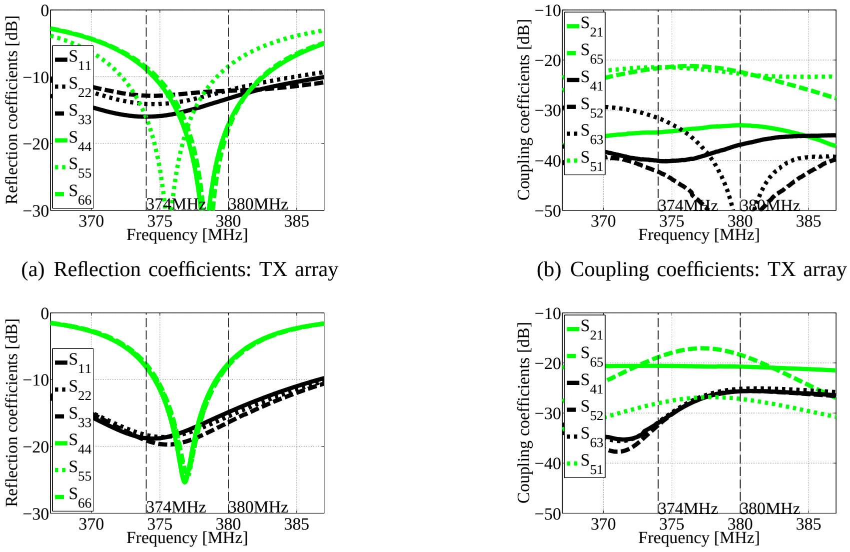
II. Six-port Array Characteristics

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



(a) Reflection coefficients: TX array

(b) Coupling coefficients: TX array

(c) Reflection coefficients: RX array

(d) Coupling coefficients: RX array

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

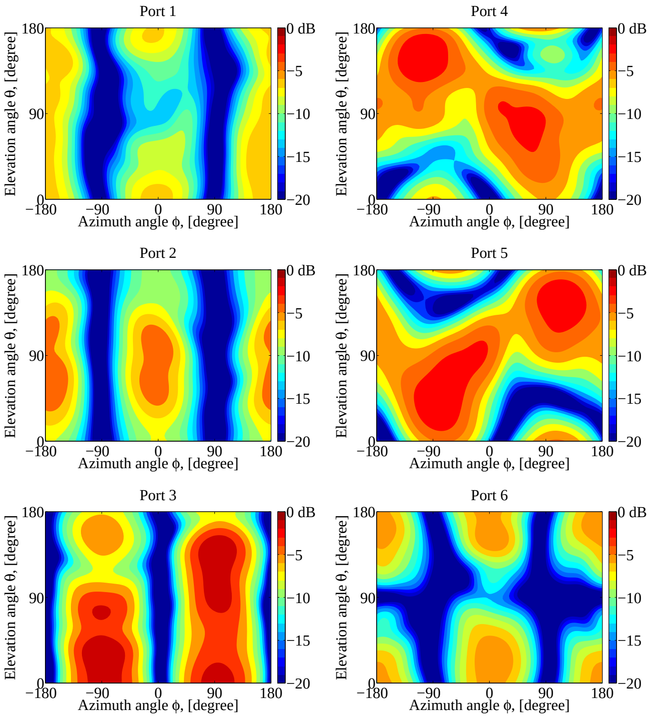


Fig. 3. Measured gain patterns of the reference TX array, $G_{\mathrm{TX},\phi}(\phi,\theta)$.

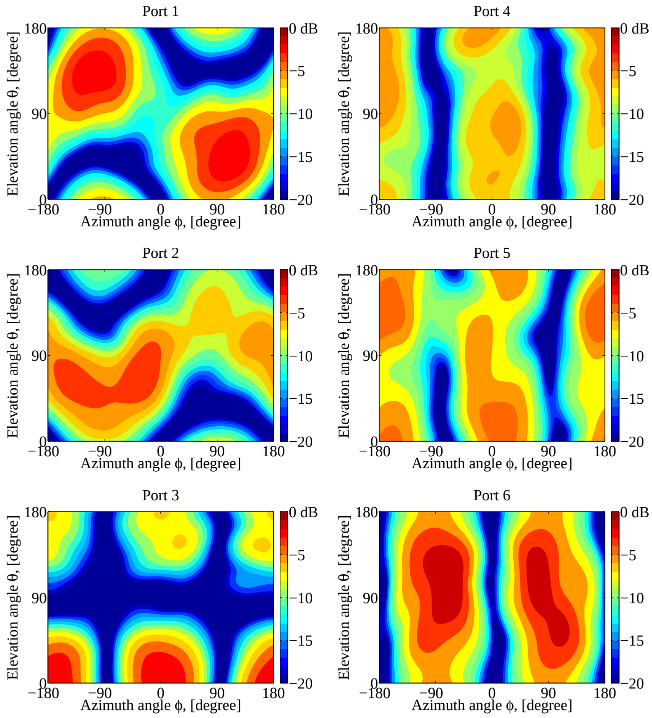


Fig. 4. Measured gain patterns of the reference TX array, $G_{\mathrm{TX},\theta}(\phi,\theta)$.

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 $13.6\,\mathrm{MHz}$ at the $-6\,\mathrm{dB}$ level. Good isolation of more than $20\,\mathrm{dB}$ 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 couping 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 measured, whereas the other five ports are terminated in $50\,\Omega$ loads. For over $10\,\mathrm{MHz}$ bandwidth, the average total efficiency is measured as $88.4\%(-0.5\,\mathrm{dB})$ and $60.9\%(-2.1\,\mathrm{dB})$, for the electric and magnetic dipoles of the array, respectively. The measured gain patterns of the TX array for the ϕ- and θ-polarized components are illustrated in Figs. 3 and 4, where the coordinate system of the measurement is given in Fig. 1(a). The gain patterns shown are normalized, such that the peak total gain is $0\,\mathrm{dB}$. It can be seen that, in addition to polarization diversity which is observed between the electric and magnetic dipoles, angle diversity is also achieved.

B. Compact RX Array

In order to demonstrate that six DOFs are achievable by orthogonally polarized, electric and magnetic dipoles in a co-located manner, electrically smaller antennas are designed for the RX array than for the TX array. After studying dipoles with different lengths, a compromise is made between performance and length. Quarter-wave dipoles with the length of $200\,\mathrm{mm}$ can be matched to $50\,\Omega$ using a simple L-network of a serial inductor together with a shunt capacitor. For the magnetic dipoles, electrically small planar split ring resonator (SRR) antenna [15] is considered.

Fig. 1(b) shows the compact RX array. Three quarter-wave dipoles (Ports 1-3) are placed perpendicularly to one another and are co-located to the center of the array structure. Three complementary magnetic dipoles (Ports 4-6) made by the planar SRR antennas are also perpendicular to one another and are placed at one of the ends of each of the dipoles in order to avoid strong mutual coupling. The maximum dimension of the array is determined by the quarter-wave dipoles, whose length can be reduced slightly in the presence of the SRR antennas, due to their proximity to the substrate material. The size of the fabricated RX array is $0.24\lambda \times 0.24\lambda \times 0.24\lambda$.

Due to the use of electrically compact antennas, special attention is paid to the connecting RF coaxial cables. In the S-parameter measurements, coaxial cables integrated with wideband RF ferrite beads are used to minimize their influence on the antennas. In the radiation pattern measurements, a custom-developed radio-over-fiber (ROF) system is employed.

The measured S parameters are shown in Figs. 2(c) and (d). The magnetic dipoles realized by the SRR antennas exhibit a much smaller bandwidth ($8\,\mathrm{MHz}$ at the $-6\,\mathrm{dB}$ level) relative to that of the electric dipoles. Due to compactness of the RX array, the isolation is slightly worse than the case of the TX array, especially between the loops. Nevertheless, a minimum isolation of $17\,\mathrm{dB}$ can still be achieved.

Using the ROF system, the SATIMO measurement system is calibrated with respect to a reference wideband horn antenna whose efficiency is over 90%. For over $10\,\mathrm{MHz}$ bandwidth, the average total efficiency of the RX array is approximately $25\%(-6.0\,\mathrm{dB})$ for both the electric and magnetic dipoles. The relatively low efficiency can be explained by the use of lossy lumped elements in the matching circuits of the quarter-wave dipoles, as well as the use of lossy FR4 substrate in making the SRR antennas. The measured gain patterns of the RX array are not shown here for the sake of conciseness. As in the case of TX array, angle and polarization diversities have been observed in the patterns of the RX array.

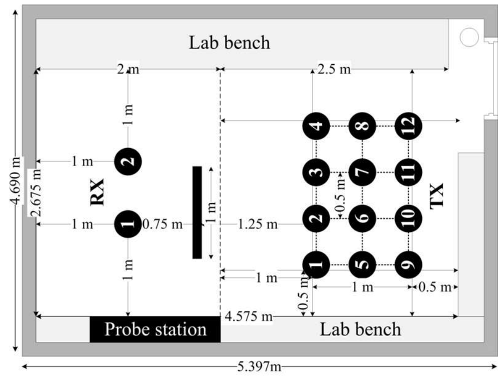
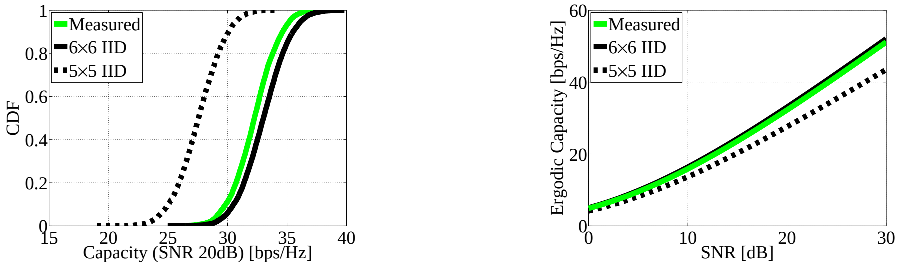


Fig. 5. Floor map of the lab and the setup in the measurement campaign.

III. Measurement Campaign

In order to verify the number of DOFs experimentally, a MIMO channel measurement campaign was conducted in a RF shielded laboratory (see Fig. 5). The dimensions of the lab are $5.40\,\mathrm{m}$ (length) $\times$ $4.69\,\mathrm{m}$ (width) $\times$ $2.51\,\mathrm{m}$ (height). There were many lab equipment and other office furniture in the lab at the time of measurement (not shown in Fig. 5). In order to ensure that there is no dominant path in the rich scattering environment, a big metal plate is used to block the Line-of-Sight (LOS) between the TX and RX arrays. Each antenna array is mounted on top of a trolley, at a height of $0.8\,\mathrm{m}$. The two trolleys were stationed at different measurement locations inside the lab, as shown in Fig. 5. In total, 2 RX positions together with 12 TX positions were measured in order to obtain good fading statistics. Adjacent TX measurement positions were $0.5\,\mathrm{m}$ (*i.e.*, more than $\lambda/2$) apart from each other. In addition, 4 different orientations of 90° angular separation were utilized at each TX (also RX) measurement position, which resulted in total of 384 $(2 \times 4 \times 12 \times 4)$ unique measurements.

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 $20\,\mathrm{MHz}$ bandwidth centered at $377\,\mathrm{MHz}$. However, we only used the measured data over a $6\,\mathrm{MHz}$ bandwidth (*i.e.*, $374\,\mathrm{MHz} - 380\,\mathrm{MHz}$) 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 $30\,\mathrm{dB}$ throughout the measurements.



(a) Capacity distribution

(b) Ergodic capacity

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 $20\,\mathrm{dB}$ 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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References

[1] R. A. Andrews, P. P. Mitra, and R. deCarvalho, “Tripling the capacity of wireless communications using electromagnetic polarization,” *Nature*, vol. 409, pp. 316 – 318, Jan. 2001.

[2] A. Poon, R. Brodersen, and D. Tse, “Degrees of freedom in multiple-antenna channels: a signal space approach,” *IEEE Trans. Inf. Theory*, vol. 51, no. 2, pp. 523 – 536, Feb. 2005.

[3] M. Migliore, “On the role of the number of degrees of freedom of the field in MIMO channels,” *IEEE Trans. Antennas Propag.*, vol. 54, no. 2, pp. 620 – 628, Feb. 2006.

[4] M. Gustafsson and S. Nordebo, “Characterization of MIMO antennas using spherical vector waves,” *IEEE Trans. Antennas Propag.*, vol. 54, no. 9, pp. 2679 –2682, Sept. 2006.

[5] T. Svantesson, M. Jensen, and J. Wallace, “Analysis of electromagnetic field polarizations in multiantenna systems,” *IEEE Trans. Wireless Commun.*, vol. 3, no. 2, pp. 641 – 646, Mar. 2004.

[6] B. Getu and J. Andersen, “The MIMO cube - a compact MIMO antenna,” *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 1136 – 1141, May 2005.

[7] D. Stancil, A. Berson, J. Van’t Hof, R. Negi, S. Sheth, and P. Patel, “Doubling wireless channel capacity using co-polarised, co-located electric and magnetic dipoles,” *Electron. Lett.*, vol. 38, no. 14, pp. 746 –747, July 2002.

[8] G. Gupta, B. Hughes, and G. Lazzi, “On the degrees of freedom in linear array systems with tri-polarized antennas,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 7, pp. 2458 –2462, July 2008.

[9] A. Konanur, K. Gosalia, S. Krishnamurthy, B. Hughes, and G. Lazzi, “Increasing wireless channel capacity through MIMO systems employing co-located antennas,” *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 6, pp. 1837 – 1844, June 2005.

[10] C.-Y. Chiu, J.-B. Yan, R. Murch, J. Yun, and R. Vaughan, “Design and implementation of a compact 6-port antenna,” *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 767 –770, Dec. 2009.

[11] R. Tian, V. Plicanic, B. K. Lau, and Z. Ying, “A compact six-port dielectric resonator antenna array: MIMO channel measurements and performance analysis,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1369 –1379, Apr. 2010.

[12] C.-Y. Chiu, J.-B. Yan, and R. Murch, “24-port and 36-port antenna cubes suitable for MIMO wireless communications,” *IEEE Trans. Antennas Propag.*, vol. 56, no. 4, pp. 1170 –1176, Apr. 2008.

[13] A. Alford and A. Kandoian, “Ultra-high frequency loop antennae,” *Electrical Communication*, vol. 18, pp. 255 – 265, 1940.

[14] “SATIMO Homepage,” *http://www.satimo.fr*.

[15] O. Kim, “Low-Q electrically small spherical magnetic dipole antennas,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 7, pp. 2210 –2217, July 2010.

[16] R. Thoma, D. Hampicke, A. Richter, G. Sommerkorn, A. Schneider, U. Trautwein, and W. Wirnitzer, “Identification of time-variant directional mobile radio channels,” *IEEE Trans. Instrum. Meas.*, vol. 49, no. 2, pp. 357–364, Apr. 2000.