Measurements on Indoor Channel Characteristics Using Wideband MIMO Antennas

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***Abstract*—In this paper, we design two wideband compact MIMO antennas, and utilize them for experiments on indoor channel characteristic measurements. One of the antennas is a three-port orthogonally polarized, and the other is a six-port formed into a cube. The antennas operate at center frequency of 2.6 GHz and support a bandwidth of over 400 MHz. Isolation between the ports of the antennas are kept under -18 dB. Using these antennas, we measure the channel characteristics of the indoor environment, and analyze the performance of the antennas. As a result, high data rate capacity can be achieved with the proposed compact antennas, making them applicable in MIMO wireless communications.**

***Index Terms*—MIMO systems, polarization, antenna arrays, indoor radio communication.**

I. Introduction

Multi-Input Multi-Output (MIMO) transmission scheme recently is one of the key solutions for the next generation of wireless communication systems. In MIMO systems, antenna issues such as element radiation pattern, array configuration, element polarization, mutual coupling, and array size are essential points affecting on the performances of the systems [1], [2]. In the last few years, many types of compact and multiple orthogonal polarization antennas for MIMO have been introduced [3]- [8]. However, several drawbacks still remain to be addressed, namely, high mutual coupling, narrow bandwidth and bulky in size. Almost all of the related designs only investigate three-port orthogonal polarization antennas. Furthermore, the mutual couplings between elements, and operating bandwidth of the antennas are relatively limited. In [4]- [6], the worst mutual coupling is about -15 dB; whereas the relative bandwidth for voltage standing wave ratio (VSWR) less than 2 is as narrow as 2% in [4], 4% in [5], 5% in [6], and 8.6% in [7], [8].

Additionally, quite many experiments on MIMO channels are conducted with narrowband antennas [9]- [12], which are carried in time domain at only the center frequency of a narrow bandwidth. In [13], Lukama presented an analysis of MIMO performance with general three-branch polarization diversity but there was no specified compact antenna being mentioned. Wideband MIMO issues within real compact antennas still require much attention.

In this work, we firstly propose two wideband compact MIMO antennas, which offer a relative bandwidth of over 16%, and keep within mutual couplings under -18 dB. Furthermore, we utilize the proposed wideband MIMO antennas to characterize wideband MIMO channels in several measurements in indoor environment with line-of-sight (LOS) condition. Measured data are processed after some discussion of measurement issues, such as signal levels or capacity computation. The impact of the compact antennas and individual antenna's configuration on channel capacity is emphasized with detailed discussions.

II. Antenna Designs

In this section, we firstly show the designs of two wideband compact MIMO antennas, which aim to achieve low mutual couplings, and a wide bandwidth within a compact size. The 3-D electromagnetic simulator, Ansoft's HFSS, is used to simulate the designs.

A. Three-port Antenna

Elementary in our compact antenna designs are printed dipoles which have two arms lying at two sides of the substrate. This sort of antenna has been briefly considered in [14]; however, its bandwidth is still a significant problem due to balun-feeding issues. To solve this problem, we introduce a simple but effective balun to feed the dipole. The balun is structured by gradually reducing the grounding apparatus from the connector side to the feeding point as shown in Figs. 1(a) and 1(b). This type of balun is similar to the cutaway balun which is only applied to coaxial cable [15], but in our case the balun does not require a long transforming balun as in a coaxial cable.

In order to reduce the size of elements while maximizing the length of the dipole, the first two elements, named dipole 1 and dipole 2, have arms lying along the diagonal of the substrate. The third, named dipole 3, is a rectangularly printed dipole. Dipole 3 separates the others into two sides so that the overall antenna has an "H" shape as illustrated in Fig. 1. In order to fix the three elements, a glue is used.

The substrate size of dipoles 1 and 2 is 40 mm × 40 mm × 1.6 mm, and 50 mm × 40 mm × 1.6 mm for dipole 3. The lengths of their arms equal to 23.5 mm, 24.5 mm, and 19 mm respectively for center frequency of 2.5 GHz. Here, due to the mutual couplings between the dipoles, the length of their arms are not the same.

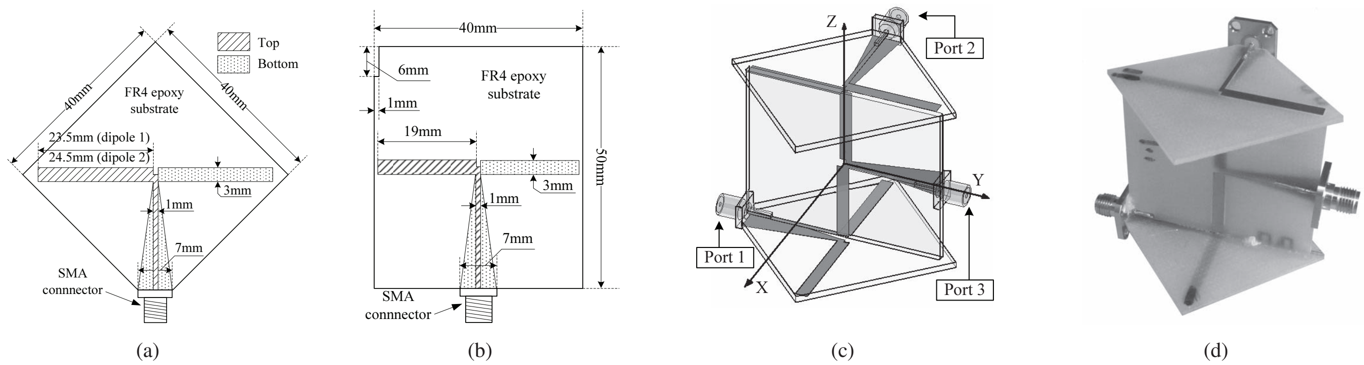

Fig. 1. Three-port orthogonal polarization antenna: (a) dipole 1, 2; (b) dipole 3; (c) the 3-D view; (d) the practical antenna.

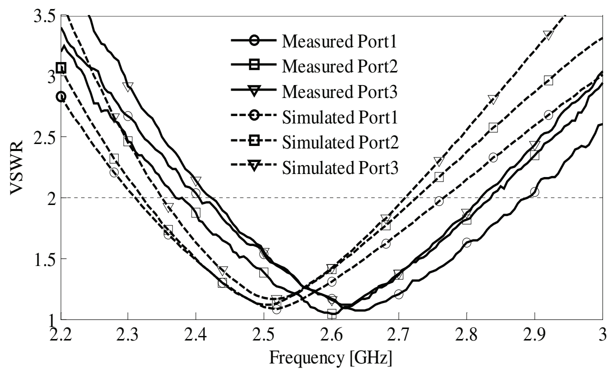

Fig. 2. The VSWR characteristics of the three-port antenna

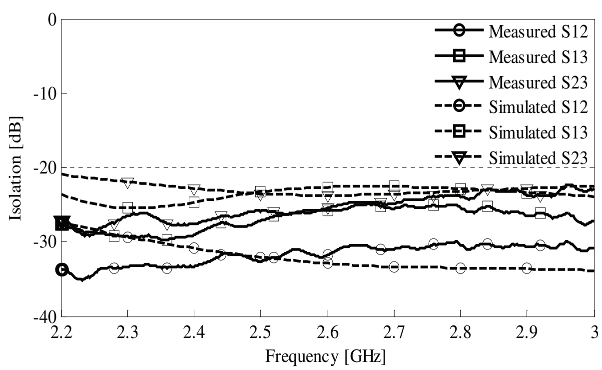

Fig. 3. The inter-port isolations of the three-port antenna

Figs. 2 and 3 show the VSWR and mutual coupling (inter-port isolation) characteristics of the three-port MIMO antenna. The bandwidth of three dipoles is relatively wide, over 400 MHz for VSWR less than 2.0 (center frequency of 2.5 GHz). It can be seen from Fig. 2 that the measured data almost agree with the simulated results for broadband characteristics with a small discrepancy from its centre frequency (2.5 GHz for simulated and 2.6 GHz for measured). Mutual couplings are smaller than -20 dB between ports 1, 2 and 3 over the entire frequency band, making them working independently in MIMO applications.

B. Six-port Antenna

In [3], a MIMO cube - a compact MIMO antenna - is presented and discussed in theory, showing a possible huge capacity. However, the theoretical capacity was calculated without considering the practical issues such as mutual coupling, the matching of the dipoles, or the difficulty of forming the cube. In this part, we will propose a practical cube of six printed dipoles that has low mutual couplings, good matching, wide bandwidth, and simple design. The cube-six-port antenna also resonates at 2.5 GHz in simulations. Two of the six elements and the configuration of the cube-six-port antenna are illustrated in Fig. 4. Elements 1, 2 and 3, illustrated in Fig. 4(a), are similar whereas elements 4, 5 and 6, shown in Fig. 4(b), are made to be the mirrored image of elements 1, 2, 3 in order to achieve low mutual couplings between the elements. For each element, the length of arm is 21.5 mm, whereas the size is 56 mm × 56 mm × 1.6 mm. Overall, the cube has the volume of 56 mm × 56 mm × 56 mm.

The cube's simulated and measured VSWR are shown in Fig. 5. The cube offers a bandwidth of approximately 500 MHz for VSWR less than 2.0; which accounts for over 16% of the relative bandwidth. All VSWR curves are almost the same because of the symmetric design. Simulation and measurement are in good agreement for broadband characteristics with a small discrepancy from its centre frequency.

Fig. 6 illustrates the inter-port isolation between ports of the cube. Because the cube is symmetric, the isolation characteristics can be divided into the following groups.

- The first group: isolations between relatively close and orthogonal ports, including 1-2, 1-3, 2-3, 4-5, 4-6, 5-6. The isolation of this group is represented by S12.
- The second group: isolations between same polarization ports, including 1-4, 2-5, 3-6. The isolation of this group is represented by S14.
- The third group: isolations between relatively far and orthogonal ports, including 1-5, 1-6, 2-4, 2-6, 3-4, 3-5. The isolation of this group is represented by S15.

It can be seen that mutual couplings are kept under -18 dB, which support independent operations of the elements in MIMO applications.

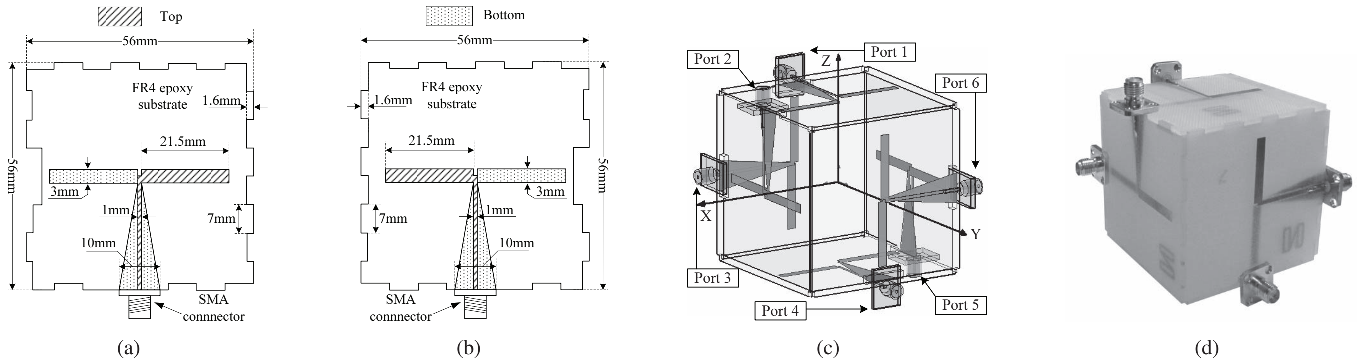

Fig. 4. The cube-six-port antenna: (a) dipoles 1, 2 and 3; (b) dipoles 4, 5 and 6; (c) the 3-D view; (d) the practical cube.

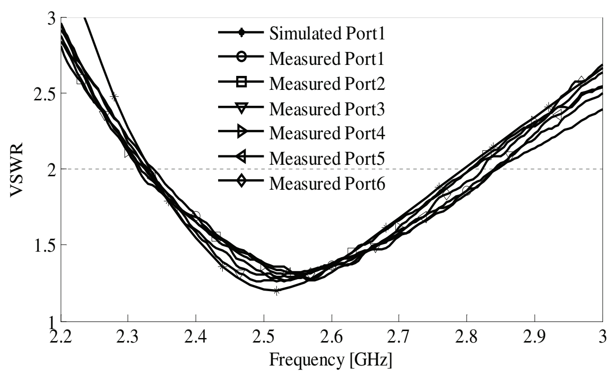

Fig. 5. The VSWR characteristics of the cube

TABLE I
ANTENNA CONFIGURATION IN MIMO EXPERIMENTS

MIMO scheme (Tx-Rx)	Spacing (d)	Polarization (Tx-Rx)
Com6 × Com6	Fixed	3O - 3O
Com3 × Com6	Fixed	3O - 3O
Com3 × Com3	Fixed	3O - 3O
Ind6V × Ind6V	$0.5\lambda_0$	V - V
Ind3V × Ind6V	$0.5\lambda_0$	V - V
Ind3V × Ind3V	$0.5\lambda_0$	V - V
Ind3V × Ind3H	$0.5\lambda_0$	V - H
Ind1V × Ind1V	-	V - V

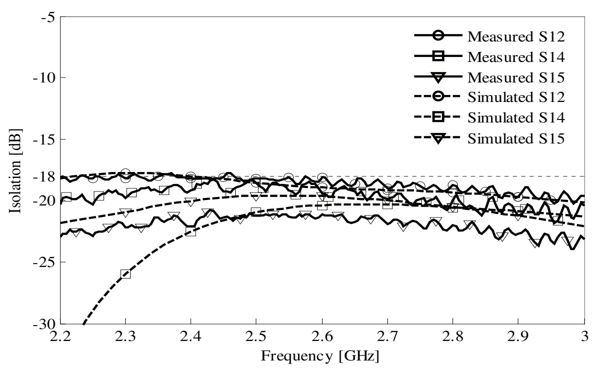

Fig. 6. The inter-port isolations of the cube

III. MIMO Experimental Setups

In this section, we will utilize our proposed MIMO antennas in experiments to examine how they actually work in a system. To deal with wideband antennas, we divided the band into a number of smaller bandwidth. It allows us to compute the average channel capacity for a wideband. Also, we measured MIMO channels within different antenna configurations, and then compare the effect of each antenna configuration.

Measurements are conducted inside an indoor environment where the multipath-rich condition is not fulfilled. A four-port vector network analyzer (VNA) is used to measure the channel characteristics. Three ports of VNA are occupied to connect to transmitter antennas, whereas the other port of VNA is connected alternatively to receiver antennas via a coaxial switch. In the 6 × 6 MIMO case, we used two coaxial switches to select respective transmiter and receiver pairs. In these experiments, all the other system's parameters, such as the array's position in the chamber and output power of the vector network analyzer, are kept unchanged. Frequency sweep in this measurement ranges from 2.45 GHz to 2.85 GHz (in the bandwidth of antennas). Data were saved with 20001 samples in the entire frequency range.

Indoor experiments were taken in a small room in the second floor of an eight-story building. The size of experiment room is 6.5 m × 3.6 m × 2.5 m (Length × Width × Height). In order to reduce the reflected paths, we kept the room empty except the antenna and cable systems. The layout of the experimental room and a photograph of it are presented in Fig. 7. Antennas are set at 1m-height from the floor of the experimental room, and configurations varied as illustrated in table I, where ”V” standards for vertically polarized linear antenna array, and ”H” standards for horizontally polarized linear antenna array. For example, the Ind6V configuration means the linear antenna array, which consists of 6 individual elements polarized vertically. These arrays are used to compare with the proposed compact MIMO antennas.

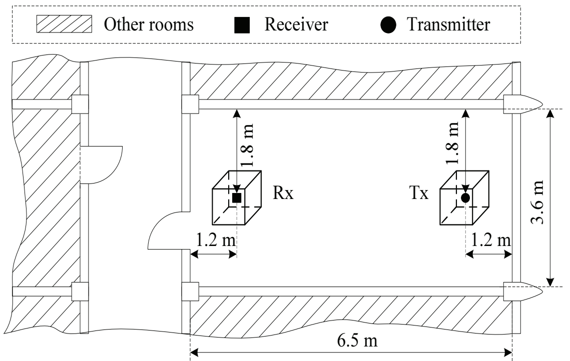

Fig. 7. Layout of the indoor experiment room.

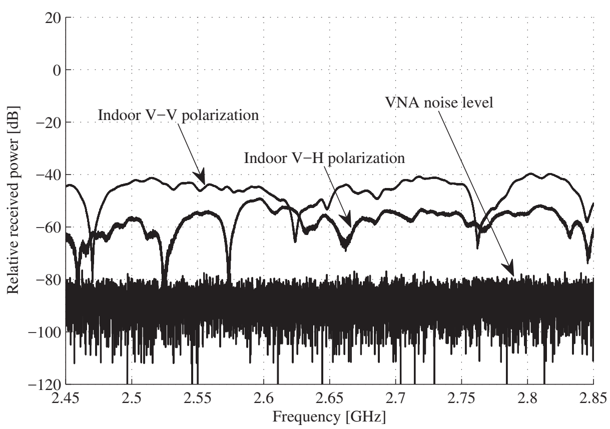

Fig. 8. Typical received signals

IV. Channel characteristics

The channel matrix $\mathbf{H}(f)$ of a MIMO system which has N_t transmitter antennas and N_r receiver antennas is given by:

$$\mathbf{H}(f) = \begin{bmatrix} h_{11}(f) & \cdots & h_{1N_t}(f) \\ \vdots & \ddots & \vdots \\ h_{N_r1}(f) & \cdots & h_{N_rN_t}(f) \end{bmatrix} \quad (1)$$

where $h_{rt}(f)$ represents for the frequency dependent path gain between the t^{th} transmitter and r^{th} receiver antennas ($1 \leq r \leq N_r$ and $1 \leq t \leq N_t$). The eigenvalues of the channel, λ_i (i = 1, 2,..., $\min\{N_r, N_t\}$) sequenced in descending order of value, are calculated from the correlation matrix $\mathbf{HH^H}$ where $(.)^{\mathbf{H}}$ is Hermitian operator.

Channel characteristics in different antenna configurations will be examined in received signal levels and the cumulative distribution functions (CDF) of eigenvalues. Comparisons of CDFs of eigenvalues of measurement data for the 6 × 6, 3 × 6 and 3 × 3 MIMO systems after the normalization are highlighted.

Fig. 8 illustrates typical received signal levels in different polarizations. These signals are obtained when setting the transmitter antenna to vertical polarization; whereas the receiver antenna has vertical and horizontal polarizations in succession. In indoor environment, received signal levels in polarizations are clearly different due to high cross polarization discrimination (XPD) value (of about 13dB in our experiments).

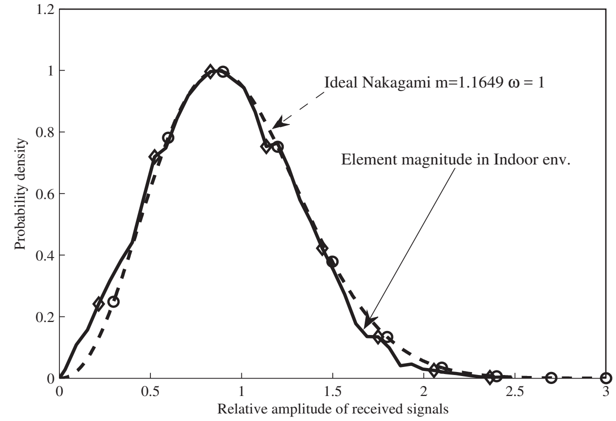

Fig. 9. PDFs for the magnitude of normalized received signals

The marginal probability density funtions (PDFs) for the magnitude of normalized received signals are also computed. Fig. 9 shows the obtained PDFs for "Ind6V × Ind6V" configuration in the considered environment. The PDF for normalized received signals in the indoor environment is compared with the ideal Nakagami-m distribution [16] with parameters $m = 1.6149$ and $\omega = 1$, which are determined from the measured results.

As soon as the channel matrix is determined by the measured data, eigenvalues can be obtained from singular value decomposition of the matrix. The CDFs of measured eigenvalues in the indoor environment are plotted in Fig. 10 respectively. Here, we can see that respective eigenvalues λ_1, λ_2 and λ_3 in the 6 × 6 MIMO are greater than those in 3 × 6 and 3 × 3 MIMO. Those values in 3 × 3 MIMO are the smallest among these MIMO systems. This is because MIMO systems rely on the environment to produce uncorrelated signals at the receive antennas. If the number of transmitting antennas is unchanged, and the number of receiving antennas is increased, the probability that uncorrelated signals can reach to the receiver will increase. Therefore, among MIMO systems having the same number of transmitting antennas, whichever has more receiving antennas will have higher eigenvalues, and hence increasing throughput.

V. Channel Capacity

Channel capacity is one of the most important parameters in MIMO research. The channel capacity can be calculated from eigenvalues based on the water filling solution [1], [17]. We will now examine the difference between systems using tri-polarization antennas and the single polarization array, and the averaged channel capacities in different number of antennas.

A. The effect of polarization

Polarization is one of the most important factors which affect channel capacity. In our experiments, we measured 3

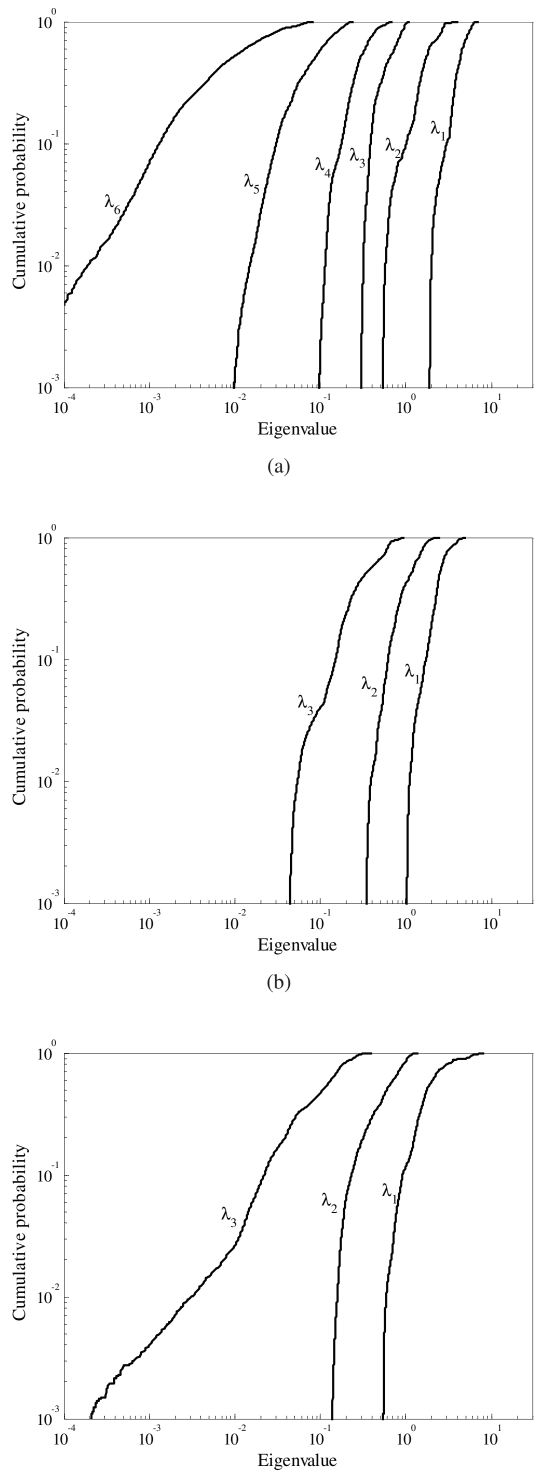

Fig. 10. The CDFs of normalized eigenvalues for MIMO systems with compact antenna configurations in the indoor environment: (a) Com6 × Com6; (b) Com3 × Com6; (c) Com3 × Com3.

× 3 MIMO systems when successively using co-polarization and cross-polarization, named "Ind3V × Ind3V" and "Ind3V × Ind3H" (spacing $0.5\lambda_0$) respectively, in the transmiter and receiver. Besides, a "Com3 × Com3" MIMO system which

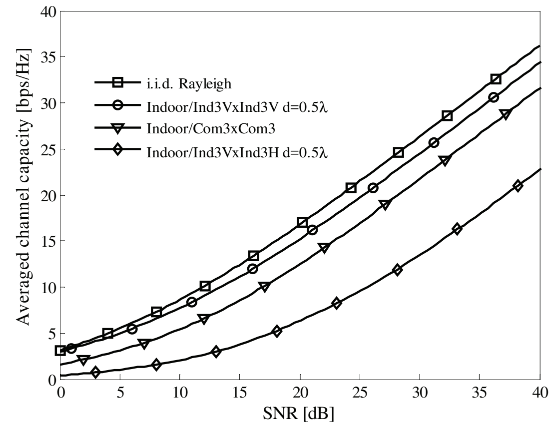

Fig. 11. Averaged channel capacity for different polarization diversities.

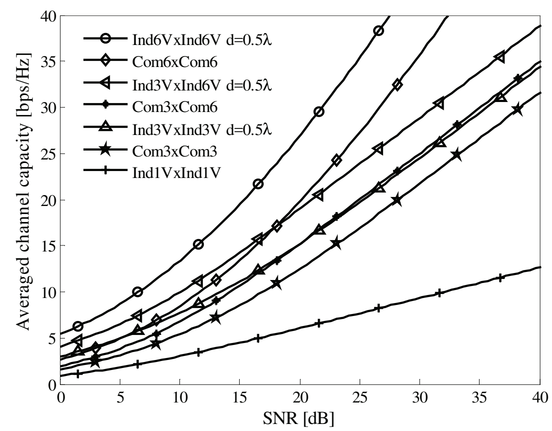

Fig. 12. Averaged channel capacity for different antenna number.

employed the three-port orthogonal polarization antennas is also measured. Channel capacities for these systems are presented in Fig. 11.

In the co-polarization system, the received signal level is higher than that in the cross-polarization system, mainly due to XPD in the environment [2]. Therefore, it results in higher channel capacity as shown in Fig. 11. Channel capacity in the compact MIMO system is greater than that in the cross-polarization system, but lower than that of the co-polarization system. The gap between channel capacities of these systems depends on different environments.

B. The effect of the number of antennas

To explore channel capacity in systems which employed the proposed compact antennas, we measured "Com6 × Com6", "Com3 × Com6" and "Com3 × Com3" MIMO systems. In order to compare with conventional single polarization systems, MIMO systems with 6 × 6, 3 × 6, 3 × 3 and 1 × 1 individual vertical polarized dipoles (linear antenna arrays), are also measured. The channel capacities of these systems are shown in Fig. 12 in considered environment. As can be seen from the figure, the compact MIMO systems provide high channel capacities. The highest capacities in these systems can be achieved from the implementation of the six-port MIMO antenna. Also, channel capacity of "Com3 × Com6" MIMO is much higher than that of "Com3 × Com3" MIMO. These measured data demonstrated that the proposed compact antennas work very well in MIMO systems and promise to achieve high data rate capacities in real applications.

VI. Conclusion

This paper has presented investigations of two novel, wideband compact antennas for MIMO wireless communications. One has three orthogonal polarizations, whereas the other is a cube-form six-port antenna which inherits both polarization and space diversities. These antennas achieved a bandwidth over 16% at the centre frequency of 2.6 GHz. Mutual couplings between ports of the antennas are very low. They are smaller than -20 dB and -18 dB for three-port and cube-six-port antennas respectively. The size of them is only 40 mm × 40 mm × 40 mm for three-port antenna and 56 mm × 56 mm × 56 mm for the six-port antenna.

We also presented the results of measurements on MIMO systems in indoor environment. Measured data were processed in order to examine the channel characteristics such as received signal level or the CDFs of eigenvalues. The effects of the compact antennas' and array antennas' configuration on channel capacity were investigated. High capacity can be achieved from the MIMO systems, which employed the proposed compact MIMO antennas, showing that the antennas are promising for practical applications.

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