Implementation of Polarized Antenna Array for Six Degrees of Freedom

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***Abstract*— Nowadays multiple-input multiple-output (MIMO) technology is applied commonly in wireless communications to increase reliability and capacity. However, multiple-antenna array needs large space to reduce the correlation among antenna elements. In this paper, we propose antenna array with six ports in cube whose side length is less than 0.67 wavelength in simulation and 0.93 wavelength in implementation, and show that the proposed polarized antenna achieves six degrees of freedom (DOFs).**

***Keywords*— Polarized Antenna, Degree-of-Freedom, Channel Matrix, CST simulation, GNUradio**

I. INTRODUCTION

In recent years, wireless traffic increases rapidly in mobile communication systems due to the explosive growth of mobile devices (e.g. smartphones, tablets) and the demands of high quality content; according to [7], global mobile data traffic is expected to grow to 6.3 exabytes per month by 2015 which is 26 times the capacity in 2010. This trend will result in saturation of traffic in mobile communication systems in the near future.

In order to increase channel capacity, recent works have paid attention to many technologies for next generation communication systems. Multiple-input multiple-output (MIMO) technology is one of the typical solutions to achieve capacity gain. However, due to the constraint of the spacing of the antenna elements, this technology has limitation to improve channel capacity in the next generation communication systems especially for small cell with small size antenna. Hence, co-located orthogonally polarized antenna based system, which was proposed by Andrews *et al.* [1], has appeared to be a space-effective alternative of MIMO technology. They found that six independent channels can be obtained with six orthogonal elements of the electric and magnetic dipoles located at a single point in rich scattering environments.

After the Andrews' seminal work [1], some studies have been done on how to design polarized antenna and evaluate the performance of polarized antenna system in real environment. Oestges *et al.* [2] presented an analytical model of dual-polarized MIMO transmissions and addressed the potential benefits of dual-polarized antenna system. Svantesson *et al*. [3] provided an analytical framework for assessing the use of all six electric and magnetic polarizations proposed by Andrews [1]. However, these works [2, 3] only focus on analytically modeling the polarized channel without any concern for the design of polarized antenna. In [4, 5], the authors proposed designs for three electric polarized antenna and evaluate diversity performance. Their experimental performance results showed that the antenna elements have a mutual coupling of less than -18dB between elements and the channel capacity can be increased as much as three times in rich scattering environment. Tian *et al*. [6] implemented six co-located antennas with three electric and three magnetic dipoles and have shown that six degrees of freedom (DOFs) can be obtained.

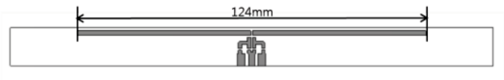
In this paper, we design polarized antenna composed of six antenna elements in 0.67 wavelength cube in simulation and 0.93 wavelength cube in implementation. We show polarized antenna with six antenna elements can achieve the multiplexing gain 5.9 at 25 to 30dB signal-to noise (SNR) by simulation and implementation.

II. ANTENNA DESIGN BASED ON CST SIMULATION

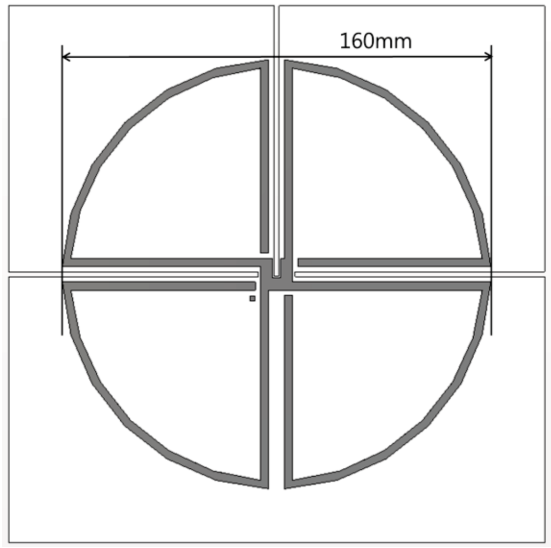
Polarized antenna is composed of orthogonal 3 electric dipoles and 3 magnetic dipoles. Antennas specifications are as follows:

- Dipole antenna length (electric dipole) : 124mm
- Loop antenna diameter (magnetic dipole) : 160mm
- Center frequency of antennas : 1GHz

Fig. 1 (a) shows dipole antenna structure. Fig. 1 (b) is the structure of Kandoian loop with four sectors where linear components are canceled by complementary current flows. This loop antenna is bigger in size than the circular loop antenna, but its design is easy to integrate multiple antennas in a small volume.



(a) Dipole antenna structure



(b) Kandoian loop antenna structure

Fig. 1 Designed antenna elements

The proposed six dimensional antenna is shown in Fig. 2 The total size is 200mm x 200mm x 200mm (0.67 wavelength), but the distance among ports is only 100mm x 100mm x 100mm (0.34 wavelength), especially 15mm between dipole antennas (0.05 wavelength). It has very low interference among dipole antennas and among Kandoian loop antennas, but frequency shift in dipole antennas has occurred. Thus, we reduce the length of dipole antenna to 112mm to adjust center frequency.

Elnour *et al.* [8] proposed two orthogonal Kandoian loops. In a similar manner, we make three orthogonal Kandoian loops. However, three antennas may interfere with each other. To solve this problem, we have designed a semi-cubic structure with 3 Kandoian loop antennas as in Fig. 2. This structure has the following advantages; interference among Kandoian loops is very small (below 15 dB), and there is cavity in center of cube so other antennas (dipole antennas in this case) can be placed in it.

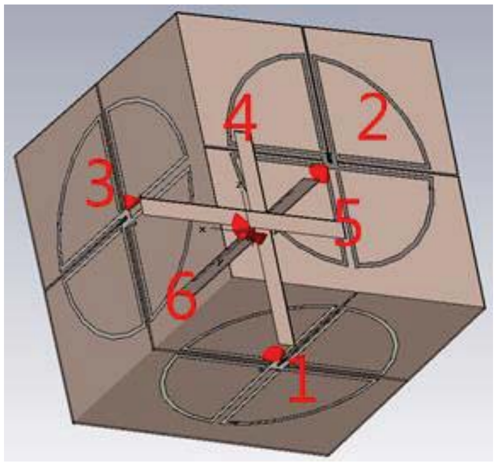
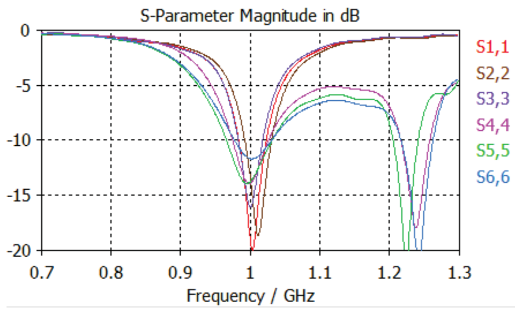
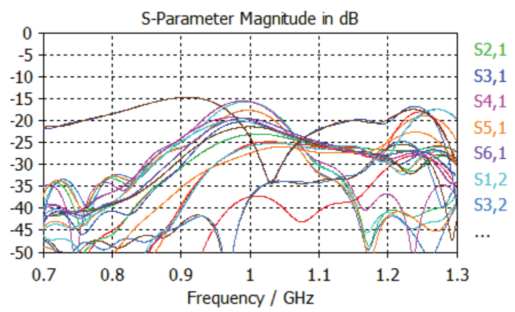


Fig. 2 Designed antenna array with six ports

Microwave CST is 3D electro-magnetic simulator commonly used to design antenna or antenna array. This program generates input signals at input ports and calculates output signals at output ports. It can also be used to obtain the channel matrix between transceiver and receiver. Fig. 3 shows the CST simulation results for integrated antenna radiation characteristics and interference among antennas. Reflection coefficient of antenna is shown in Fig. 3 (a) and S parameter between antennas is shown in Fig. 3 (b). All antennas radiate electromagnetic waves at 1GHz (below -12dB), and interference between antennas are low (below -15dB). The bandwidth of designed structure is 26MHz.



(a) Reflection coefficient



(b) S parameters between antennas

Fig. 3 Radiation characteristics and interference between antennas

For this antenna array, we evaluate channel matrix H. This measurement environment is shown in Fig. 4. Transmitter and receiver have the same antenna array and the distance is 1m (33.3 wavelengths). We consider both line-of-sight (LOS) environment and non-LOS environment. For the non-LOS environment, we put some scatter material for multi-path fading environment. Note that non-LOS assumption is common in indoor environment. Conductor planes are used as the scatter material in the simulator.

Channel matrix H is obtained with the following procedure in CST simulation.

- Place two polarized antennas at 1m distance.
- Use transient solver to have S-parameters among transceivers and receivers at 1GHz frequency.
- Obtain complex channel matrix H using the amplitude and phase of S-parameter
- Compensate amplitude of S-parameter with transmission path loss (29 dB is used for compensation and this value is determined by path loss)

Ergodic capacity is expectation of the instantaneous channel capacity in ergodic channel environment. The ergodic capacity in MIMO is estimated as follows:

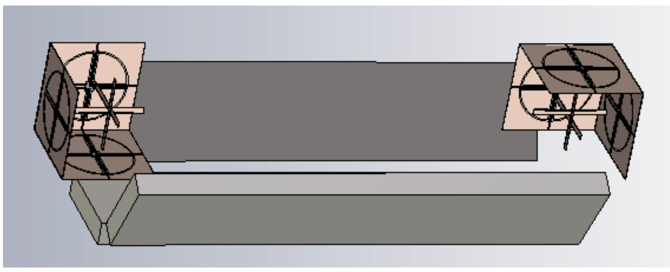
$$C = \log_2 \det\left(I + \frac{SNR}{n} HH^H\right) \qquad (1)$$

where n is the number of antenna arrays in the transmitter. At high SNR, C can be approximated as:

$$C \sim \mathrm{Rank}(H) \times \log_2 SNR \qquad (2)$$

In SNR versus capacity curve, the slope at high SNR shows rank of H matrix. Thus, the rank of H can be regarded as DOFs of the proposed antenna array relative to single-input single-output (SISO) transmission. Fig. 5 shows the capacity of six port antenna as SNR increases. In pure LOS environment, we can obtain only 2 DOFs, but the slope is 4.21 at 30dB SNR. It is because dielectric of antenna may become scattering material, that is, the environment is not pure LOS. In non-LOS environment, the slope is 5.91 at 30dB SNR.

(a) LOS environment



(b) Non-LOS environment

Fig. 4 Simulation structure for LOS and non-LOS environments

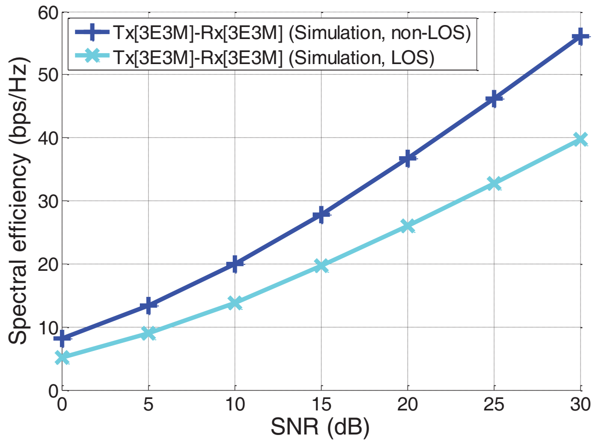


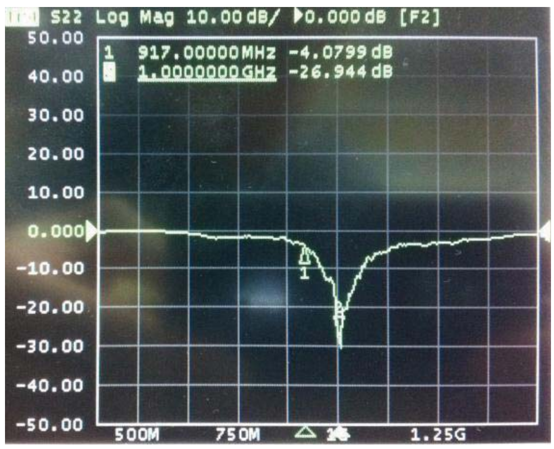
Fig. 5 Capacity of six ports antenna as SNR increases

III. IMPLEMENTATION OF POLARIZED ANTENNA

A. Antenna implementation with six polarization

Fabricated dipole antenna and its characteristic are shown in Fig. 6. In Fig. 6 (a), the length of fabricated dipole is slightly longer than that used at simulation to adjust frequency, and balun with lumped elements is placed at port to match impedance at 50 Ohm. It resonates at frequency 1GHz as in Fig. 6 (b).

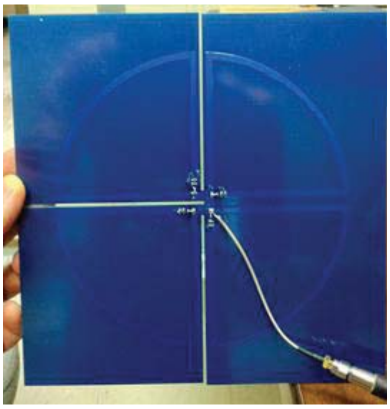
(a) Fabricated dipole antenna



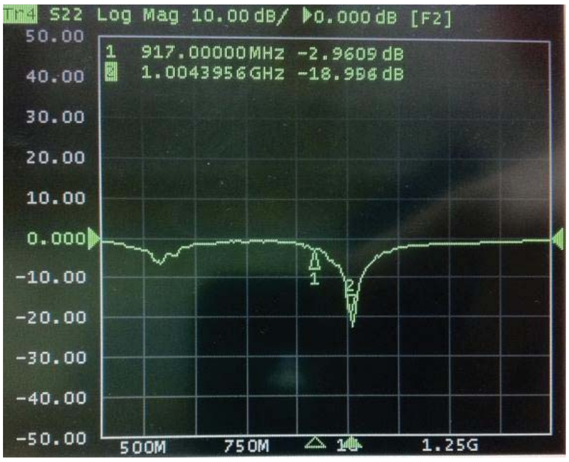
(b) Reflection coefficient

Fig. 6 Fabricated dipole antenna

Designed Kandoian loop is shown in Fig. 7 (a). Kandoian loop shows good radiation in 1GHz frequency in Fig. 7 (b), and integrated form also has low interference among antennas.



(a) Fabricated Kandoian loop



(b) Reflection coefficient

Fig. 7 Fabricated Kandoian loop antenna

In simulation, 3 dipole antennas' ports can be located very closely, but in real fabrication this structure shows high interference (~10dB) between antennas and distortion of center frequency. Alternative antenna array is designed as in Fig. 8. This polarized antenna array structure is bigger in size and the maximum distance between ports is 222mm (0.74 wavelength), and all antennas are in the cube whose side length is less than 280mm (0.97 wavelength).

B. Measurement of Spatial Multiplexing Gain

GNUradio is well known software development toolkit to process radio signals. We can implement baseband processing in the PC environment. USRP2 board is RF/IF processing hardware device to support GNUradio. To measure capacity of antenna array, same antenna array design is used in transmitter and receiver. The way to estimate channel matrix is shown in the following:

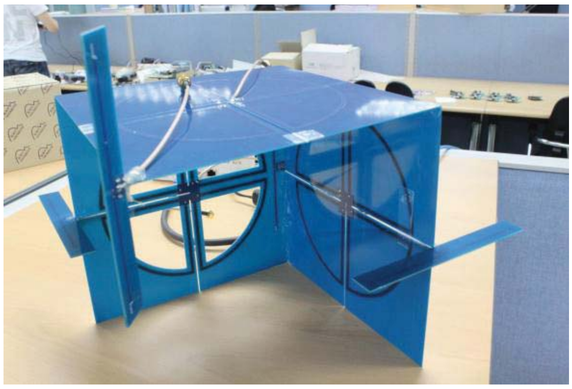


Fig. 8 Fabricated six ports antenna array

- Make a frame structure with preamble at the head of the frame to distinguish signal.
- Measure power of pilot signal and delay to evaluate channel matrix and phase delay.

We estimate capacity of designed polarized antenna using the channel matrix. Single carrier frequency 1GHz is used for transmission, and all experiments are done in indoor environment with rich scattering.

Figure 9 shows ergodic capacity when transmitter (TX) and receiver (RX) consist of polarized antenna arrays. Measurement results are compared with simulation results, where 3E denotes 3 electric dipoles and 3M denotes 3 magnetic dipoles.

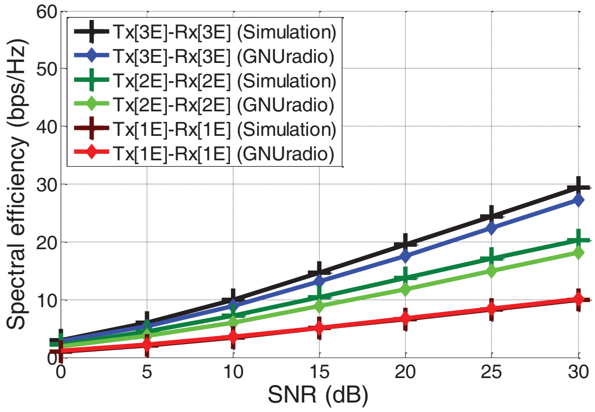
In Fig. 9 (a) and (b), electrical dipoles and magnetic dipoles are used, respectively, where spectral efficiencies are compared as SNR increases with different number of antenna arrays. Comparing these two results, loop antennas give similar capacity dipole antennas. And we observe that simulation results match well with the experimental results.

Table I compares the multiplexing gain which is estimated from the slope between SNR 25dB and 30dB. The experimental results achieved by GNUradio and fabricated polarized antenna is compared with simulation results, and its approximation error is lower than 5%.

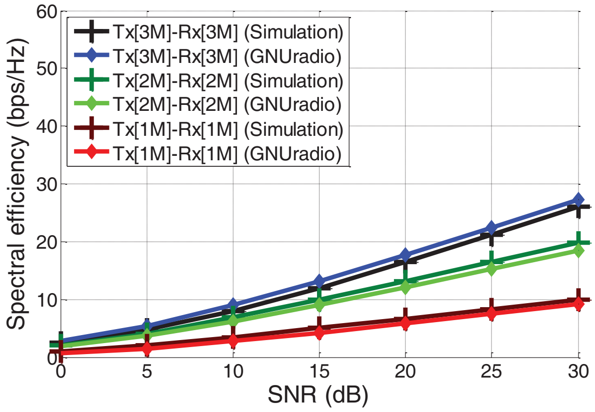
Fig. 10 shows the capacity for the six polarized antenna array. In the experimental results with GNUradio, the slope at 30dB SNR is 5.86. In the simulation results, the slopes at 30dB SNR for LOS and non-LOS environments are 4.21 and 5.91, respectively.

IV. CONCLUSIONS

In this paper, six polarized antenna array is proposed and we use CST simulation to verify antenna structure. We fabricated six port antenna array, and measure channel matrix to obtain DOFs by using GNUradio in indoor environment. We have achieved six DOFs in indoor environment with the six polarized antenna array. It remains for the future work to obtain the DOFs of more than 6 in a small space.



(a) Capacity of dipole antennas



(b) Capacity of Kandoian loop antennas

Fig. 9 Ergodic capacity of antenna array

Table I

MULTIPLEXING GAIN COMPARISON

Polarized antenna	1E	2E	3E	1M	2M	3M
CST Simulation	1.0	2.0	3.0	1.0	2.0	3.0
GNUradio	1.0	1.9	2.9	1.0	1.9	2.9

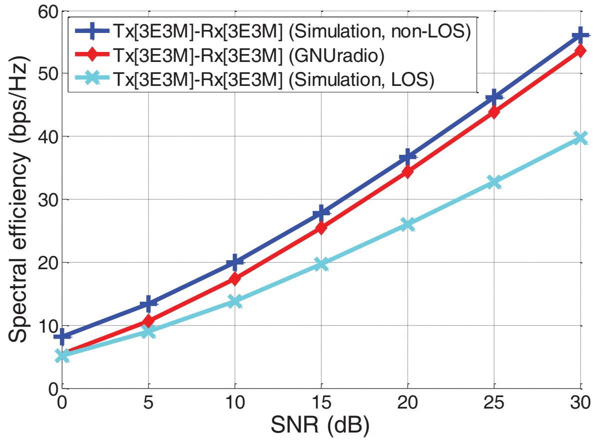


Fig. 10 Capacity of six polarized antenna array

ACKNOWLEDGMENT

This research was supported by the KCC(Korea Communications Commission), Korea, under the R&D program supervised by the KCA(Korea Communications Agency) (KCA-2011-11913-04001)

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