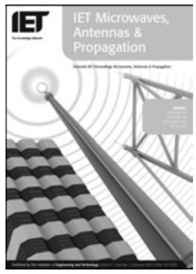
Published in IET Microwaves, Antennas & Propagation
Received on 16th October 2007
Revised on 11th January 2008
doi: 10.1049/iet-map:20070242



ISSN 1751-8725

Dual-monopole array backed by a reflector for antenna diversity/MIMO systems

H.T. Hui[1] *T.C. Tiong*[2]

[1]*Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576, Singapore*
[2]*School of Information Technology and Electrical Engineering, The University of Queensland, St Lucia, QLD 4072, Australia*
E-mail: elehht@nus.edu.sg

Abstract: A dual-monopole array backed by a plane reflector is designed and rigorously analysed to provide information on the installations and applications of monopole arrays mounted on a wall or ceiling for antenna diversity/multiple-input and multiple-output (MIMO) operations. The optimum design of the array is determined through computer simulation. On the basis of the experimental measurements and theoretical investigations in a typical rich multipath environment, the authors found that both the diversity gain and the average MIMO capacity of the array are almost unaffected by the distance of the array from the reflector if the distance is greater than $\sim 0.16\lambda$. On the other hand, both the diversity gain and the average MIMO capacity are significantly reduced once the separation between the monopoles is less than $\sim 0.2\lambda$. The findings have reference values for the design of monopole arrays in diversity/MIMO systems

1 Introduction

Monopole arrays are frequently used in multi-antenna communications such as in diversity and MIMO arrays. In a rich multipath signal environment, monopole antennas provide an omni-directional radiation pattern, which can fully capture the multipath signals. Their simple structure and ease of installation also contribute to their wide-spread use. Notwithstanding these advantages, monopole arrays are seldom installed in an empty space. More often, monopole arrays are found near some mounting objects or supporting structures (in addition to the ground plane). These may include mounting walls or ceilings in indoor or outdoor environments, human hands or bodies of the users and machine parts or structures upon which they are installed. When monopole arrays are placed near other objects, conducting or dielectric, their radiation characteristics are affected and modified. Studies on the effect of the human body on a single monopole have been carried out before by many researchers, for example [1, 2]. Studies on the effect of a finite ground plane size on the operation of monopole arrays have also been seen before, for example [3]. However, studies on the effect of nearby reflecting objects on the operation of monopole arrays are not so common [4]. In this paper, we will carry out a rigorous investigation of the effect of a large reflecting plane on the operation of a diversity/MIMO dual-monopole array. The reflecting plane, termed the reflector, is placed in close proximity to the monopole array and this arrangement can simulate the situation of a monopole array mounted on a wall or ceiling if the wall or ceiling has a good conducting characteristic. This situation is very common in today's wireless communication environments, for example the base-station antenna array of a wireless local area network (WLAN) mounted in a conference hall, in an exhibition centre, or inside a library. The objective of this study is to characterise the performance of this array for use in diversity operation or in MIMO systems. Particularly, we want to find out the diversity gain and the MIMO capacity of this array. Our study will also determine the optimum design of a diversity/MIMO array with the effect of a nearby reflecting object taken into account. The results from this study will have a reference value for the design of diversity/MIMO arrays in a practical situation. Both experimental and simulation results will be presented.

2 Array design

The dual-monopole array is designed and shown in Fig. 1. It is a conventional monopole array backed by a large conducting reflecting plane (the reflector), which is joined to the ground plane of the monopoles. The introduction of the reflector is to simulate the presence of a reflecting wall in close proximity to the array. The ground plane is to model the scattering effect of the casing of the base station. A rather common practical situation for this application of monopole arrays is shown in Fig. 2, which shows a base station of a WLAN system. To simulate the reflecting wall, the size of the reflector should be substantially larger than the monopole size to reduce backward radiation. It is to be determined together with other antenna parameters in the following array design.

The design of the array is aided by computer-simulation software FEKO [5] with an aim to optimise the array dimensions for a good impedance match at the operation frequency. Fig. 3 shows the simulation results on the return loss L of monopole #1 with antenna separation d between the two monopoles when $s = 0.2\lambda$. The dimensions of the reflector and the ground plane have been determined from the consideration of a number of factors such as the amount of backward radiation reduction and the grounding effect that can be obtained, the possibility of obtaining simulation results in a reasonable time, and the difficulty in the handling of the prototype. They are $a = b = 2.5\lambda$ and $c = 0.3\lambda$. The length of the monopoles is 0.23λ and their radius is 0.3 mm. The length and the radius of the monopoles were obtained from the optimisation design of a single monopole over a large ground plane but without a reflector. This was a compromising step to avoid the complicated repetitive procedures of optimising the monopole dimensions for each reflector size, each antenna separation d, or each array and reflector separation s. Fig. 3 shows that the optimum antenna separation is about 0.5λ. In Fig. 4, the variation of the return loss of monopole #1 with the distance s between the monopole array and reflector is shown when $d = 0.4\lambda$. It shows an optimum choice of s is $\sim 0.2\lambda$. Combining the results in Figs. 3 and

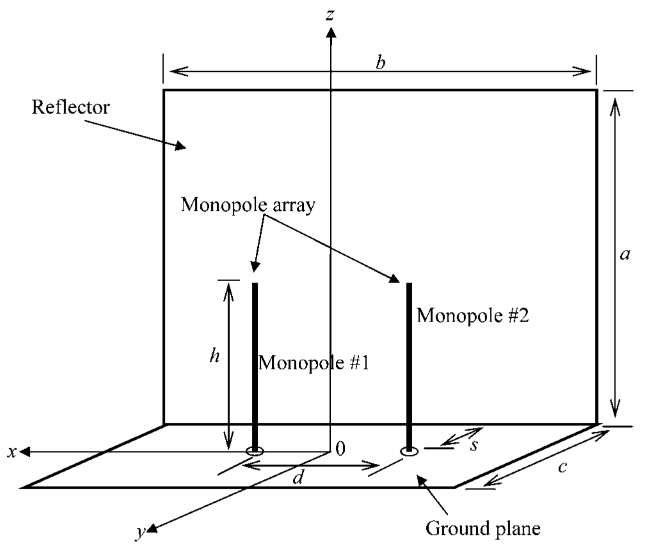


Figure 1 *Dual-monopole array backed by a conducting reflector*

Figure 2 *Dual-monopole array mounted close to a reflecting wall in a WLAN base station*

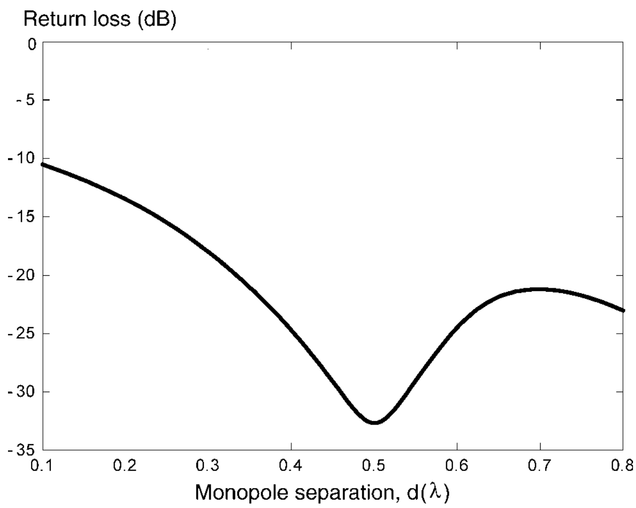


Figure 3 *Variation of the return loss L of monopole #1 with separation d between the two monopoles when $s = 0.2\lambda$*

Other dimensions of the array are $a = b = 2.5\lambda$ and $c = 0.3\lambda$

IET Microw. Antennas Propag., 2008, Vol. 2, No. 4, pp. 383–388
doi: 10.1049/iet-map:20070242

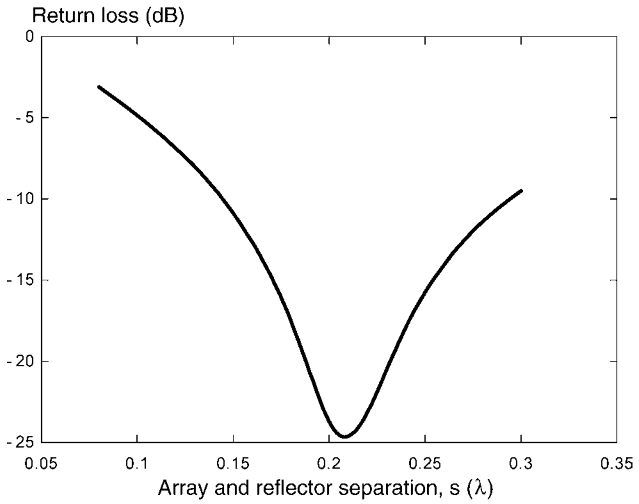


Figure 4 *Variation of the return loss L of monopole #1 with the distance s between the monopole array and reflector when d = 0.4λ*

4, we fabricated a prototype array with $d = 0.4\lambda$, $s = 0.2\lambda$, $a = b = 2.5\lambda$ and $c = 0.3\lambda$. The measured and calculated return loss of monopole #1 is shown in Fig. 5. It can be seen that a good match is attained at around 2.4 GHz.

3 Results on diversity gain and MIMO capacity

Both the diversity gain and the MIMO capacity depend on the signal correlation of the array [6, 7]. The signal correlation between the two monopoles in the array can be calculated from their radiation patterns using the following formula [6, 8]

$$\rho_e = \frac{\left|\int\int\left(\mathrm{XPD}E_{\theta 1}E_{\theta 2}^{*}P_\theta + E_{\phi 1}E_{\phi 2}^{*}P_\phi\right)\mathrm{d}\Omega\right|^2}{\int\int\left(\mathrm{XPD}E_{\theta 1}E_{\theta 1}^{*}P_\theta + E_{\phi 1}E_{\phi 1}^{*}P_\phi\right)\mathrm{d}\Omega \int\int\left(\mathrm{XPD}E_{\theta 2}E_{\theta 2}^{*}P_\theta + E_{\phi 2}E_{\phi 2}^{*}P_\phi\right)\mathrm{d}\Omega} \quad (1)$$

where $E_{\theta k}$ and $E_{\phi k}$ $(k = 1, 2)$ are, respectively, the θ and ϕ components of the electric field radiation patterns and P_θ and P_ϕ are, respectively, the θ and ϕ components of the probability distribution functions of the incoming wave. The parameter XPD is the cross-polarisation discrimination ratio [6]. For the purpose of illustration, both P_θ and P_ϕ are assumed to be uniform along the horizontal direction (the ϕ variation) and Gaussian along the vertical direction (the θ variation). The uniformity of the incoming waves from the horizontal direction is the well known Clarke's Model [9]. The Gaussian variation of the incoming wave along the vertical direction can model both urban and suburban signal environments [10]. For the Gaussian variation, a mean of $\theta = 90^\circ$ and a variance of 24° are chosen [10]. The value of XPD is fixed at one which means both horizontal and vertical polarisation waves are equally likely. Note that this set of values are selected as a typical case to illustrate the performance of the array over a rich-multipath environment and does not mean that the array works only under these conditions. Actually the formula in (1) is a general one, which can be applied to any specific signal environment by modifying the distributions P_θ and P_ϕ once they are known for that signal environment. The loading effect, the mutual coupling and the gain of the antennas are all taken into account in (1) through the radiation patterns $E_{\theta k}$ and $E_{\phi k}$ (also known as the coupled element patterns [11]). The radiation patterns of the two monopoles have been obtained by measurement

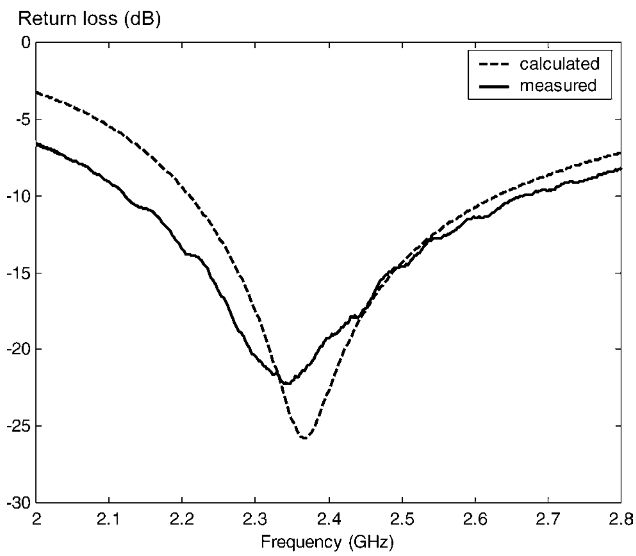


Figure 5 *Measured and calculated return loss of monopole #1 with d = 0.4λ and s = 0.2λ*

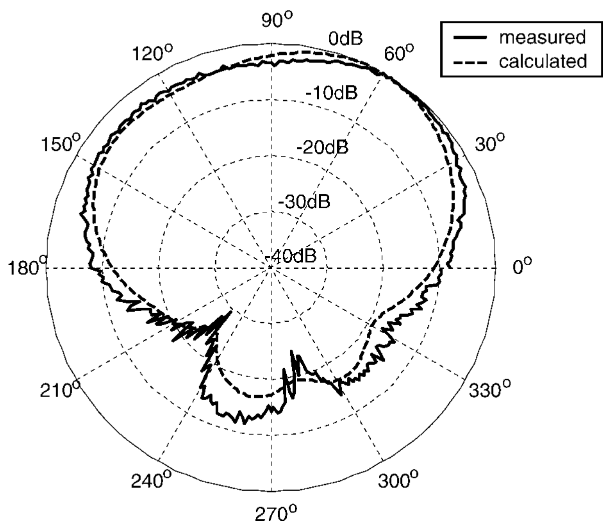


Figure 6 *Measured and calculated azimuth radiation patterns of E_θ for monopole #1 over the horizontal plane ($0^\circ \le \phi \le 360^\circ$ and $\theta = \pi/2$) with $d = 0.4\lambda$, $s = 0.2\lambda$ and frequency = 2.4 GHz*

and calculation and $E_{\theta 1}$ for monopole #1 is shown in Fig. 6. It can be seen that the backward radiation is about 20 dB lesser than the forward radiation, indicating the size of the reflector designed in Section 2 is effective of blocking most of the backward radiation. The radiation patterns of monopole #2 are almost the mirror images of those of monopole #1 and not shown here for brevity. In using (1) to calculate the envelope correlation coefficient for the array, multipath signals come from the half space $0^\circ \leq \phi, \theta \leq 180^\circ$ only and this is the range for the integrations in (1).

Fig. 7 shows the variation of the envelope correlation coefficient ρ_e with separation d between the two monopoles when $s = 0.2\lambda$. The envelope correlation coefficient for the same two monopoles but without the reflector (obtained using the method in [12]) is also shown for comparison. It can be seen that the variation of the envelope correlation coefficient is quite similar to that of two monopoles without the reflector, especially for $d = 0.1\lambda$ to $d = 0.3\lambda$. This observation can be explained by the fact that the radiation pattern in Fig. 6 over the range $0^\circ \leq \phi \leq 180^\circ$ is similar (except for the small regions very close to the reflector) to the corresponding radiation pattern in the same region of the array without the reflector (shown in Fig. 8). We further found that the radiation pattern for E_ϕ has a magnitude at least 4 dB below that of E_θ. This shows that the contribution of E_ϕ to the integrals in (1) is much less than that of E_θ. This explains why the envelope correlation coefficient is similar to that of the array without the reflector. Fig. 9 shows the variation of the envelope correlation coefficient with the distance s between the monopole array and reflector when $d = 0.4\lambda$. It is interesting to note that the envelope correlation coefficient decreases monotonically with increasing distance of the array from the reflector and the decrease of ρ_e is very significant over the range of distance shown in the figure. This decrease in correlation can be attributed to a larger

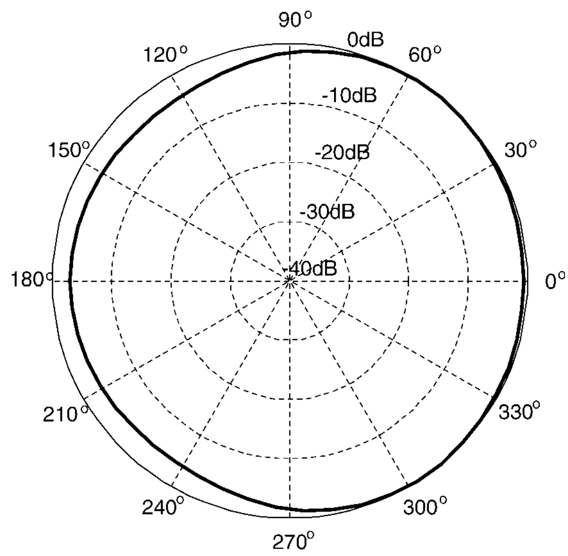


Figure 8 *Corresponding azimuth radiation pattern to Fig. 6 for the same monopole array but without the reflector*

angular spread of the multipath signals with an increasing separation s between the array and reflector.

When the envelope correlation coefficient is known, the signal received by the array can be modelled by generating two correlated Gaussian random variables with their correlation given by the square of the envelope correlation coefficient [13]. The diversity gain G of the array is then obtained by finding the difference between the values of the signal-to-noise ratio (SNR) for a single antenna and that for the array at a certain level of the cumulative distribution functions (CDFs), for example, 0.01 [13, p. 327]. For this array, the signals from the two antennas are assumed to be combined by the optimum maximum-ratio combiner. Fig. 10 shows the variation of the diversity gain G with separation d between the two monopoles when

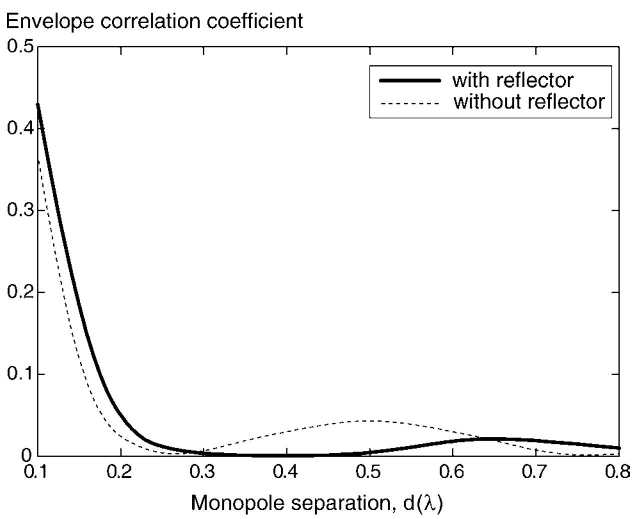


Figure 7 *Variation of the envelope correlation coefficient ρ_e with separation d between the two monopoles when $s = 0.2\lambda$*

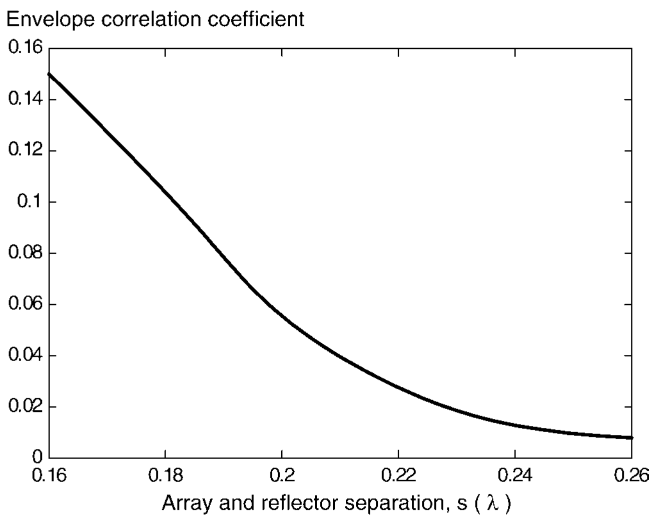


Figure 9 *Variation of the envelope correlation coefficient ρ_e with the distance s between the monopole array and reflector when $d = 0.4\lambda$*

doi: 10.1049/iet-map:20070242

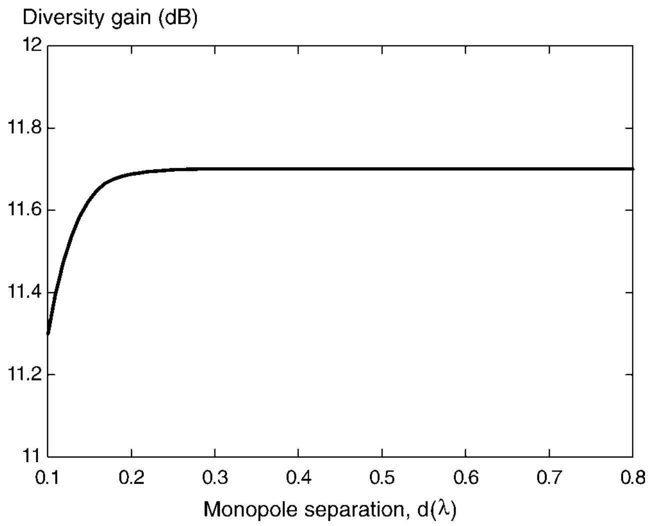


Figure 10 *Variation of the diversity gain G with separation d between the two monopoles when s = 0.2λ*

Diversity gain is obtained at the level of 0.01 of the CDFs of the instantaneous SNRs

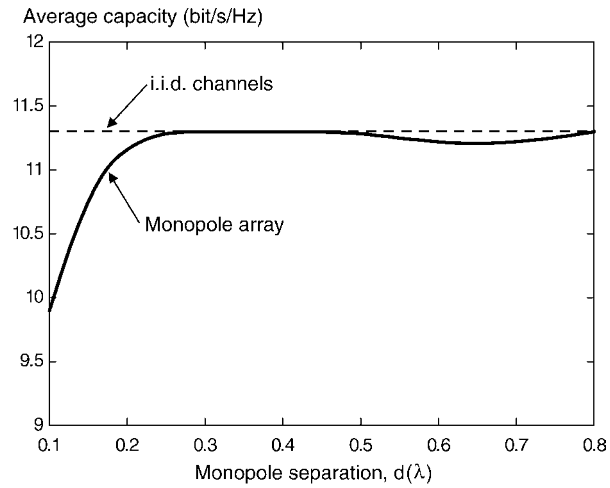


Figure 11 *Variation of the average capacity EC of a 2 × 2 MIMO systems with separation d between the two monopoles when s = 0.2 λ and SNR = 20 dB for each receiving monopole*

$s = 0.2\lambda$. The diversity gain is obtained at 0.01 of the CDFs of the instantaneous SNRs. It can be seen that the effect of monopole separation on the diversity gain is strong only when the separation is less than $\sim 0.2\lambda$. This corresponds to the rapid increase of the envelope correlation coefficient in Fig. 7 when monopole separation is less than 0.2λ. We have also investigated the effect of array separation s from the reflector on the diversity gain and found that this dependence is very weak over the range $0.16\lambda \leq s \leq 0.26\lambda$ when the monopole separation is fixed at $d = 0.4\lambda$.

To use this array in an MIMO system, our interest is to find out the channel capacity which this array can provide. We study a 2 × 2 MIMO system using this array as both the transmitting and receiving arrays. Using the values of the envelope correlation coefficient at different monopole separations (Fig. 7) and different array and reflector separations (Fig. 9), we can generate the correlated channel matrix $\boldsymbol{H}$ with the method in [14]. The channel capacity [15] of the MIMO system C is then a random number, but we can find its average value $E\{C\}$. Fig. 11 shows the change of the average capacity $E\{C\}$ with monopole separation d when $s = 0.2\lambda$ and SNR = 20 dB for each receiving monopole. Compared with the case of identically and independently distributed (i.i.d) channels, it reveals that the average capacity of the MIMO system is affected by the monopole separation only when d is less than $\sim 0.2\lambda$. This observation is very similar to the behaviour of the diversity gain in Fig. 10, but in general the average capacity seems to be more strongly affected by the monopole separation. In fact, the graph of the average capacity is very similar to the graph of the envelope correlation coefficient when it is inverted. In Fig. 12, the variation of the average capacity with array separation from the reflector is studied. It can be seen that the dependence on s is a weak one, similar to the case of the diversity gain. But the average capacity tends to decrease when s is smaller. The capacity is seen to be more sensitive to the decrease of s than the diversity gain. However, it should be pointed out that the array should not be placed too close to the reflector because this will lead to a serious mismatch of the monopoles (see the return loss in Fig. 4), and the power received by the array will be significantly reduced.

Combining the results on diversity gain and MIMO capacity, it can be seen that the design of some of the existing monopole arrays for diversity/MIMO systems (e.g. the one in Fig. 2) can be substantially modified without a significant effect on the system performance. For example,

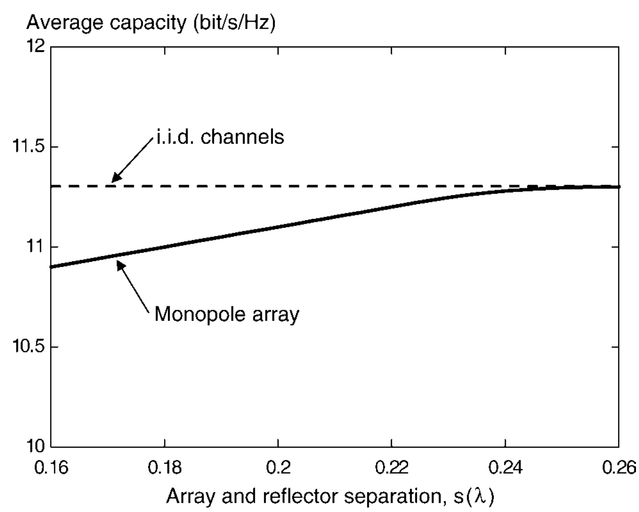


Figure 12 *Variation of the average capacity EC of a 2 × 2 MIMO systems with the distance s between the monopole array and reflector when d = 0.4λ and SNR = 20 dB for each receiving monopole*

the monopole elements can be placed at a smaller separation ($\sim 0.2\lambda$) to reduce the overall size of the base station while keeping the effect on the system performance to a minimum. Note that this conclusion is based on the array model in Fig. 1 and the Clarke's model for the multipath signals. How close this array model is to the real situation is still another question for investigation.

4 Conclusions

A dual-monopole array backed by a plane reflector has been designed and studied to provide information on practical installations and applications of monopole arrays mounted on a wall or ceiling for antenna diversity/MIMO operations. Our study has been focused on the determination of optimum monopole separation and the distance of the array from the reflector, and the resulting diversity gain and MIMO capacity that can be obtained. On the basis of the experimental measurements and theoretical investigations in a typical rich-multipath environment with a Clarke's signal model assumption on the horizontal plane, we found that both the diversity gain and the average MIMO capacity of the array are almost unaffected by the distance of the array from the reflector if that distance is greater than $\sim 0.16\lambda$. On the other hand, both the diversity gain and the average MIMO capacity are significantly reduced once the separation between the monopoles is less than $\sim 0.2\lambda$. We believe our findings have a reference value for the design of monopole arrays in diversity/MIMO systems.

5 References

[1] ISKANDER M.F., YUN Z., QUINTERO-ILLERA R.: 'Polarization and human body effects on the microwave absorption in a human head exposed to radiation from handheld devices', *IEEE Trans. Microw. Theory Tech.*, 2000, **48**, (11), pp. 1979–1987

[2] WANG J., FUJIWARA O.: 'Comparison and evaluation of electromagnetic absorption characteristics in realistic human head models of adult and children for 900-MHz mobile telephones', *IEEE Trans. Microw. Theory Tech.*, 2003, **51**, (3), pp. 966–971

[3] YUAN H., HIRASAWA K., ZHANG Y.: 'The mutual coupling and diffraction effects on the performance of a CMA adaptive array', *IEEE Trans. Veh. Technol.*, 1998, **47**, (3), pp. 728–736

[4] DOMINGUEZ H., RAIZER A., CARPES W.P.JR.: 'Electromagnetic fields radiated by a cellular phone in close proximity to metallic walls', *IEEE Trans. Magn.*, 2002, **38**, (2), pp. 793–793

[5] Available at: http://www.feko.info/

[6] VAUGHAN R.G., ANDERSEN J.B.: 'Antenna diversity in mobile communication', *IEEE Trans. Veh. Technol.*, 1987, **36**, pp. 149–172

[7] KILDAL P.S., ROSENGREN K.: 'Correlation and capacity of MIMO systems and mutual coupling, radiation efficiency, and diversity gain of their antennas: simulations and measurements in a reverberation chamber', *IEEE Commun. Mag.*, 2004, **42**, (12), pp. 104–112

[8] DOUGLAS M.G., OKONIEWSKI M., STUCHLY M.A.: 'A planar diversity antenna for handheld PCS devices', *IEEE Trans. Veh. Technol.*, 1998, **47**, pp. 747–754

[9] CLARKE R.H.: 'A statistical theory of mobile-radio receptions', *Bell Syst. Tech. J.*, 1968, **47**, pp. 957–1000

[10] EBINE Y., YAMADA Y.: 'A vehicular-mounted vertical space diversity antenna for a land mobile radio', *IEEE Trans. Veh. Technol.*, 1991, **40**, (2), pp. 420–425

[11] KELLY D.F., STUTZMAN W.L.: 'Array antenna pattern modeling methods that include mutual coupling effects', *IEEE Trans. Antennas Propag.*, 1993, **41**, pp. 1625–1632

[12] HUI H.T., OWYONG W.T., TOH K.B.: 'Signal correlation between two normal-mode helical antennas for diversity reception in a multipath environment', *IEEE Trans. Antennas Propag.*, 2004, **52**, (2), pp. 572–577

[13] JAKES W.C.: 'Microwave mobile communications' (Wiley, New York, 1974)

[14] WALLANCE J.W., JENSEN M.A.: 'Modeling the indoor MIMO wireless channel', *IEEE Trans. Antennas Propag.*, 2002, **50**, (5), pp. 591–599

[15] FOSCHINI G.J., GANS M.J.: 'On limits of wireless communications in a fading environment when using multiple antennas', *Wirel. Pers. Commun.*, 1998, **6**, pp. 311–335

doi: 10.1049/iet-map:20070242