Progress In Electromagnetics Research, PIER 65, 27–40, 2006

EFFECT OF MUTUAL COUPLING ON CAPACITY OF MIMO WIRELESS CHANNELS IN HIGH SNR SCENARIO

A. A. Abouda and S. G. Häggman

Helsinki University of Technology
P.O. Box 3000, FIN-02015 HUT, Finland

Abstract—Theoretical results on the effect of antenna mutual coupling (MC) on capacity of multiple-input multiple-output (MIMO) wireless channels are presented in this paper with particular emphasis on the case of high signal to noise ratio (SNR) scenario. Two cases are considered, 1- channel capacity variations due to MC effect on correlation properties and target average receive SNR and 2- channel capacity variations due to MC effect on correlation properties at fixed average receive SNR. It is shown that the effect of MC on MIMO channel capacity can be positive or negative depending on the propagation environment spatial correlation properties and the characteristics of the transmitter and receiver MC matrices. Conditions where MC has positive and negative effects on MIMO channel capacity in the two considered cases are identified. Numerical results for half wavelength dipole antenna supporting the theoretical observations are presented.

1. INTRODUCTION

Utilizing the available spatial domain efficiently by using multi-element antennas (MEA) has shown to be a promising direction to cope with the increasing demands for high data rate wireless communications in a practical way. Adaptive antenna and space diversity are two tangible technologies that are enjoying the use of MEA. Deploying MEA at both ends creates a multiple-input multiple-output (MIMO) system that has shown astonishing increase in spectral efficiency and significant improvement in signal detection [1, 2]. However, the promising advantages of MIMO systems over traditional single antenna systems depend on different parameters. Propagation environment, antenna array geometry and antenna element properties are among these parameters.

The impact of propagation environment and antenna array geometry on the performance of MEA wireless communications systems have been extensively investigated, e.g., [3, 4]. On the other hand, the influence of antenna element properties has been less considered. Usually antenna element properties are either excluded or ideal isotropic antenna elements are assumed for modeling and studying the performance of MEA wireless systems. Mutual coupling (MC) phenomena that appears when the antenna elements are closely spaced is one of the parameters that strongly affect the performance of these systems. The effect of MC in adaptive antenna array systems has been extensively investigated and well understood, e.g., [5]. In adaptive antenna array context, the MEA array is used to direct the antenna array beam towards a desired user and null the undesirable ones. The presence of MC between antenna elements results in deviation in the antenna array beam, therefore, algorithms for eliminating MC effects in adaptive antenna array systems are used, e.g., [6]. In spatial diversity systems the MEA is used to create replica of the desired signal to improve its detection in fading environments. The presence of MC may increase or decrease the correlation between antenna elements and consequently reduces or improves the effectiveness of spatial diversity techniques [7]. However, in MIMO system context the effect of MC is less understood. Research results have drawn different conclusions concerning this effect. In [8, 9] it is shown that the presence of MC between antenna elements has a negative impact on the capacity of MIMO wireless channels. On the other hand, in [10, 11] it is shown that the presence of MC between antenna elements is a desirable phenomena to increase channel capacity through what is known as pattern diversity.

This paper presents theoretical and numerical results on the effect of MC on capacity of MIMO wireless channels with particular emphasis on the case of high SNR scenario where the MIMO channel capacity formula can be decomposed into individual quantities that can be studied independently. Two cases are considered, 1- channel capacity variations due to MC effect on correlation properties and target average receive SNR and 2- channel capacity variations due to MC effect on correlation properties at fixed average receive SNR. We show that there is no contradiction between the reported results in literature since MC may have a positive or negative impact depending on the propagation environment spatial correlation properties and the characteristics of the receiver and transmitter MC matrices. Conditions where MC has positive and negative effects on MIMO channel capacity in the two considered cases are identified. We support our theoretical observations by numerical results for half wavelength dipole antenna.

The rest of this paper is organized as follows: System model description is given in Section 2. The MIMO channel capacity including two ends antenna systems is given in Section 3. Numerical results for half wavelength dipole antenna are presented in Section 4. Our conclusions are drawn in Section 5.

2. SYSTEM MODEL

In order to account for antenna system effects, antenna system parameters should be incorporated into the MIMO system model. One common way to do that is by means of impedance matrices. The transmitter and receiver antenna impedances in addition to the feeding and loading impedances effectively represent the antenna system parameters. It should be noticed that the concept of impedance matrix, devised originally for lumped circuit elements, presents some difficulties when applied directly to wave propagation problems [12]. However, useful insights into the MIMO system performance is gained using this approach.

We consider a narrowband MIMO wireless communication system with N_t transmit antennas and N_r receive antennas. The system employs spatial multiplexing signaling scheme where different transmit antenna element is fed with different stream of data. Taking into account both the transmitter and receiver antenna systems, the input-output relation of the MIMO wireless communication system, schematically shown in Fig. 1, can be obtained by utilizing the concepts of impedance matrix representation of linear networks [13]. In transmission mode the role of an antenna is to convert an applied voltage signal or injected current signal into electromagnetic field. Using simple circuit theory analysis, the terminal voltage at each transmit antenna can be written as [12, 13]:

$$\mathbf{V}_t = \mathbf{Z}_t(\mathbf{Z}_t + \mathbf{Z}_F)^{-1}\mathbf{V}_t^{oc} \tag{1}$$

where $\mathbf{Z}_t \in C^{N_t,N_t}$ is the transmitter mutual impedance matrix, $\mathbf{Z}_F \in C^{N_t,N_t}$ is the feeding impedance matrix and $\mathbf{V}_t^{oc} \in C^{N_t,1}$ is the applied open circuit voltages at each transmit antenna. Since no channel knowledge at the transmitter side is assumed, uniform power allocation strategy is employed. Under this power allocation the transmitter open circuit voltages covariance matrix can be written as:

$$\mathbf{R}_{\mathbf{V}_t^{oc}} = E\{\mathbf{V}_t^{oc}\mathbf{V}_t^{oc*}\} = \frac{\sigma_t^2}{N_t}\mathbf{I}_{N_t} \tag{2}$$

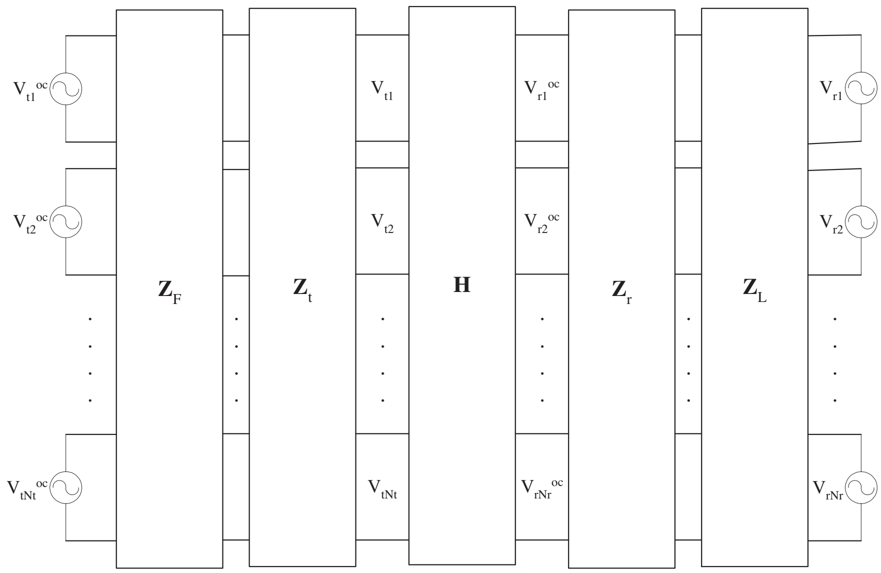

Figure 1. Schematic block diagram of MIMO wireless communication system including two ends antenna systems.

where $(.)^*$ denotes Hermitian transposition, σ_t^2 is the total transmitter signal power and $\mathbf{I}_{N_t}$ denotes identity matrix of size $N_t \times N_t$.

In reception mode the same antenna has an opposite role. It is used to convert an incident electromagnetic filed to an induced voltage or current signal. Similarly, at the receiver side the terminal voltages at each receive antenna can be written as [12, 13]:

$$\mathbf{V}_r = \mathbf{Z}_L(\mathbf{Z}_L + \mathbf{Z}_r)^{-1}\mathbf{V}_r^{oc} + \mathbf{V}_n \tag{3}$$

where $\mathbf{Z}_r \in C^{N_r,N_r}$ is the receiver mutual impedance matrix, $\mathbf{Z}_L \in C^{N_r,N_r}$ is the loading impedance matrix, $\mathbf{V}_r^{oc} \in C^{N_r,1}$ is the open circuit voltage at each receive antenna and $\mathbf{V}_n \in C^{N_r,1}$ is the thermal noise voltage at each receive antenna with covariance matrix:

$$\mathbf{R}_{\mathbf{V}_n} = E\{\mathbf{V}_n\mathbf{V}_n^*\} = \sigma_n^2\mathbf{I}_{N_r} \tag{4}$$

and σ_n^2 is the noise power at each receive antenna. The feeding and loading impedance matrices represent the feeding and loading networks in the transmitter and receiver ends, respectively. They both depend on the antenna impedance matching at each end. For maximum power delivery the feeding and loading impedance matrices are matched to the transmitter and receiver mutual impedance matrices, respectively, i.e., $\mathbf{Z}_F = \mathbf{Z}_t^*$ and $\mathbf{Z}_L = \mathbf{Z}_r^*$ [12].

The transmitter terminal voltages and the receiver open circuit voltages are related through the channel matrix as follows:

$$\mathbf{V}_r^{oc} = \mathbf{H}\mathbf{V}_t \tag{5}$$

where $\mathbf{H} \in C^{N_r,N_t}$ is the narrowband channel matrix normalized such that $\frac{1}{N_r N_t} \parallel \mathbf{H} \parallel_F^2 = 1$, where $\parallel . \parallel_F$ denotes matrix Frobenius norm. Normalization is performed in order to set the channel matrix average power to unity. Substituting for the receiver open circuit voltages from (5) and the transmitter terminal voltages from (1) into (3) we can obtain the following relation:

$$\begin{aligned} \mathbf{V}_r &= \underbrace{\mathbf{Z}_L(\mathbf{Z}_L + \mathbf{Z}_r)^{-1}}_{\mathbf{C}_r} \mathbf{H} \underbrace{\mathbf{Z}_t(\mathbf{Z}_t + \mathbf{Z}_F)^{-1}}_{\mathbf{C}_t} \mathbf{V}_t^{oc} + \mathbf{V}_n \\ &= \mathbf{C}_r \mathbf{H} \mathbf{C}_t \mathbf{V}_t^{oc} + \mathbf{V}_n \end{aligned} \tag{6}$$

where $\mathbf{C}_r \in C^{N_r,N_r}$ and $\mathbf{C}_t \in C^{N_t,N_t}$ are the receiver and transmitter MC matrices, respectively. It can be clearly seen that the effect of the transmitter and receiver antenna systems on the MIMO wireless communication system model is effectively represented by the two ends MC matrices that depend on the two ends mutual impedance matrices and the feeding and loading impedances. It is worthy to notice that the two ends MC impedances depend on the array geometry, antenna type, inter-element spacing and also near field scatterers [14]. They can be practically quantified using two approaches, numerical methods and measurement methods [12]. However, the later approach is less practical due to its complexity and high cost while the numerical methods can give very sufficient accuracy if all the affecting parameters are included.

Now the covariance matrix of the receiver terminal voltages can be written as:

$$\mathbf{R}_{\mathbf{v}_r} = E\{\mathbf{V}_r \mathbf{V}_r^*\} = \frac{\sigma_t^2}{N_t} \mathbf{C}_r \mathbf{H} \mathbf{C}_t \mathbf{C}_t^* \mathbf{H}^* \mathbf{C}_r^* + \sigma_n^2 \mathbf{I}_{N_r} \tag{7}$$

3. CHANNEL CAPACITY

The error free spectral efficiency represents the maximum achievable capacity by a communication system over a given channel realization and power constraint. In MIMO systems, channel capacity is a common performance measure that maps a channel realization to a non negative scalar whose relative magnitude indicates channel quality. The capacity of the MIMO wireless communication system described above, including two ends antenna systems, is defined as [15]:

$$c = \max_{f(\mathbf{V}_t^{oc})} I(\mathbf{V}_t^{oc}; \mathbf{V}_r, \mathbf{H}) \tag{8}$$

where $I(\mathbf{V}_t^{oc}; \mathbf{V}_r, \mathbf{H})$ is the mutual information between the transmitter open circuit voltages, the receiver terminal voltages and the channel matrix, respectively, and $f(\mathbf{V}_t^{oc})$ is the probability distribution function of the transmitter open circuit voltages. Under perfect channel state information at the receiver side the mutual information between these quantities can be written as:

$$I(\mathbf{V}_t^{oc}; \mathbf{V}_r, \mathbf{H}) = H(\mathbf{V}_r) - H(\mathbf{V}_r | \mathbf{V}_t^{oc}) \tag{9}$$

where $H(\mathbf{V}_r)$ is the entropy of the receiver terminal voltages and $H(\mathbf{V}_r | \mathbf{V}_t^{oc})$ is the conditional entropy of the receiver terminal voltages given knowledge of the transmitter open circuit voltages. Since the transmitter open circuit voltages are independent on the receiver thermal noise voltages, (9) simplifies to:

$$I(\mathbf{V}_t^{oc}; \mathbf{V}_r, \mathbf{H}) = H(\mathbf{V}_r) - H(\mathbf{V}_n) \tag{10}$$

Therefore, maximizing the mutual information $I(\mathbf{V}_t^{oc}; \mathbf{V}_r, \mathbf{H})$ is reduced to maximizing the entropy of the transmitter open circuit voltages. In order to maximize the channel capacity, the distribution of the receiver terminal voltages should be zero mean circularly symmetric complex Gaussian (ZMCSCG) [16]. This in turn implies that the distribution of the transmitter open circuit voltages should be also ZMCSCG. Under this condition the entropies of the receiver terminal voltages and the receiver thermal noise voltages can be written as [15]:

$$H(\mathbf{V}_r) = \log_2(\det(\pi e \mathbf{R}_{\mathbf{V}_r})) \tag{11}$$

$$H(\mathbf{V}_n) = \log_2(\det(\pi e \mathbf{R}_{\mathbf{V}_n})) \tag{12}$$

Substituting into (8) we can obtain:

$$c = \log_2 \det(\mathbf{I}_{N_r} + \frac{\rho}{N_t} \mathbf{C}_r \mathbf{H} \mathbf{C}_t \mathbf{C}_t^* \mathbf{H}^* \mathbf{C}_r^*) \tag{13}$$

where $\rho = \frac{\sigma_t^2}{\sigma_n^2}$ is the average receive SNR. (13) is the widely known channel capacity formula of MIMO wireless channel but it also includes the two ends antenna systems. Considering the case of high average receive SNR scenario where the deployment of MIMO technology can offer its significant advantages, the channel capacity in (13) can be approximated as:

$$\hat{c} \approx \log_2 \det(\frac{\rho}{N_t} \mathbf{C}_r \mathbf{H} \mathbf{C}_t \mathbf{C}_t^* \mathbf{H}^* \mathbf{C}_r^*) \tag{14}$$

The channel capacity formula in (14) represents the effect of MC on MIMO channel capacity in a high average receive SNR scenario. It can be seen that MC affect both the channel correlation properties and the target average receive SNR. In order to evaluate the channel capacity variations due to changes in correlation properties at a fixed average receive SNR the new channel matrix, including the two ends MC matrices, should be properly normalized. In the following subsections we consider two cases: 1- channel capacity variations due to MC effect on correlation properties and target average receive SNR, 2- channel capacity variations due to MC effect on correlation properties at fixed average receive SNR.

3.1. Channel Capacity Variations due to MC Effect on Correlation Properties and Target Average Receive SNR

The channel capacity variations due to MC in (14) are due to changes in the channel correlation properties and the average receive SNR. Consider the case that $N_t = N_r = N$ and assuming that the channel correlation matrix without coupling effects and the two ends MC matrices are all full rank matrices, (14) can be decomposed as follows:

$$\hat{c}_{mc} = \log_2 \det(\frac{\rho}{N} \mathbf{H}\mathbf{H}^*) + \log_2 \det(\mathbf{C}_r \mathbf{C}_r^*) + \log_2 \det(\mathbf{C}_t \mathbf{C}_t^*) \tag{15}$$

which can be further written as:

$$\hat{c}_{mc} = \sum_{i=1}^{N} \log_2(\frac{\rho}{N} \lambda_i(\mathbf{H}\mathbf{H}^*)) + \sum_{i=1}^{N} \log_2(\lambda_i(\mathbf{C}_r \mathbf{C}_r^*)) + \sum_{i=1}^{N} \log_2(\lambda_i(\mathbf{C}_t \mathbf{C}_t^*)) \tag{16}$$

where $\lambda_i(\mathbf{H}\mathbf{H}^*)$, $\lambda_i(\mathbf{C}_r \mathbf{C}_r^*)$ and $\lambda_i(\mathbf{C}_t \mathbf{C}_t^*)$ are the i-th eigenvalues of the channel correlation matrix, the receiver MC correlation matrix and the transmitter MC correlation matrix, respectively. It can be noticed that while the first term in (16), $\sum_{i=1}^{N} \log_2(\frac{\rho}{N} \lambda_i(\mathbf{H}\mathbf{H}^*)) = \hat{c}_{iso}$, represents the channel capacity at high average receive SNR with isotropic MEA at both ends, the second two terms represent the effect of the two ends MC matrices. In the light of (16) one can observe that the effect of MC on the channel capacity do not depend on the propagation environment in a high average receive SNR scenario and only depends on the two ends coupling matrices. It is obvious that different coupling matrices will result in different effect on the channel capacity, therefore, the following result is obtained:

Proposition 1: In a high average receive SNR scenario, if normalization is not performed after including the two ends MC effect, an improvement in the channel capacity over the case of isotropic MEA is obtained due to coupling effect if and only if $\beta_1 = \prod_{i=1}^{N} \lambda_i(\mathbf{C}_r\mathbf{C}_r^*)\lambda_i(\mathbf{C}_t\mathbf{C}_t^*) > 1$.

The above result states that in order for the coupling effect to have a positive impact on the channel capacity, the product of the eigenvalues of the two ends MC correlation matrices should be large than one. When the product of these eigenvalues is less than one the effect of MC on the channel capacity will be negative.

3.2. Channel Capacity Variations due to MC Effect on Correlation Properties at Fixed Average Receive SNR

In order to keep the average receive SNR fixed to a target value and consider only channel capacity variations due changes in correlation properties, normalization should be performed after including the two ends coupling effect. In this case the channel capacity in (14) can be written, including the two ends coupling matrices, for $N_t = N_r = N$ as:

$$\hat{c}_{mc,n} \approx \log_2 \det(\frac{\rho}{N}\frac{1}{\alpha^2}\mathbf{C}_r\mathbf{H}\mathbf{C}_t\mathbf{C}_t^*\mathbf{H}^*\mathbf{C}_r^*) \tag{17}$$

where $\alpha^2 = \frac{1}{N^2} \parallel \mathbf{C}_r\mathbf{H}\mathbf{C}_t \parallel_F^2$ is a normalization factor to compensate for the power variations due to including the two ends coupling matrices. Normalization ensures that the channel capacity with MC effect is calculated at fixed average receive SNR, i.e. $\frac{1}{N^2} \parallel \frac{\mathbf{C}_r\mathbf{H}\mathbf{C}_t}{\alpha} \parallel_F^2 = 1$. It should be noticed that in this case the variations in the channel capacity are due to changes in correlation properties and not due to power changes. Similarly, assuming that the channel correlation matrix and the two ends MC matrices are all full rank matrices, (17) can be decomposed as follows:

$$\begin{aligned} \hat{c}_{mc,n} &= \sum_{i=1}^{N} \log_2(\frac{\rho}{N}\lambda_i(\mathbf{H}\mathbf{H}^*)) + \\ &\quad \sum_{i=1}^{N} \log_2 \frac{\lambda_i(\mathbf{C}_r\mathbf{C}_r^*)\lambda_i(\mathbf{C}_t\mathbf{C}_t^*)}{\frac{1}{N^2}\sum_{i=1}^{N}\lambda_i(\mathbf{C}_r\mathbf{H}\mathbf{C}_t\mathbf{C}_t^*\mathbf{H}^*\mathbf{C}_r^*)} \end{aligned} \tag{18}$$

where $\lambda_i(\mathbf{C}_r\mathbf{H}\mathbf{C}_t\mathbf{C}_t^*\mathbf{H}^*\mathbf{C}_r^*)$ is the i-th eigenvalue of the channel correlation matrix including two ends coupling effects. Again the first term in (18) represents the channel capacity at a high average receive SNR with isotropic MEA at both ends and the second term represents channel capacity variations due to changes in correlation properties. In this case the effect of MC depends on both the propagation environment correlation properties and the MC matrices, therefore, the following result is obtained:

Proposition 2: In a high average receive SNR scenario, if normalization is performed after including the two ends MC effect, an improvement in the channel capacity over the case of isotropic MEA is obtained due to coupling effect if and only if $\beta_2 = \frac{\prod_{i=1}^{N} \lambda_i(\mathbf{C}_r\mathbf{C}_r^*)\lambda_i(\mathbf{C}_t\mathbf{C}_t^*)}{[\frac{1}{N^2}\sum_{i=1}^{N} \lambda_i(\mathbf{C}_r\mathbf{H}\mathbf{C}_t\mathbf{C}_t^*\mathbf{H}^*\mathbf{C}_r^*)]^N} > 1$.

It is clear that at different propagation environments the same coupling matrix may have different effects on the channel capacity.

4. NUMERICAL RESULTS

In this section we present numerical results supporting the above theoretical observations. We consider a 2×2 MIMO wireless communication system operating at 2 GHz carrier frequency in a rich scattering environment where the elements of the channel matrix can be modeled as independent identical distributed (iid) zero mean complex Gaussian random variables. We neglect the transmitter MC effect and account only for the receiver MC. This is a typical case of download scenario where in the base station (BS) side the antenna elements can be largely spaced. In the mobile station (MS) side an uniform linear MEA array with 0.5λ dipole elements is considered where λ is the wavelength. The receiver MC matrices are calculated at different inter-element spacing numerically [17] under matched load condition. It is well known that changing the inter-element spacing affect both the angular spread information and the MC matrix. However, in order to study the effect of MC on the channel capacity under specific propagation environment spatial correlation properties it is assumed that the inter-element spacing affects only the MC matrix but not the angular spread information. In order to account for the angular spread changes due to the propagation environment, the Kronecker stochastic MIMO radio channel model is used [18] with a specific spatial receiver correlation value.

Fig. 2 shows the term β_1 at different inter-element spacing. It can be noticed that the condition in proposition 1 is fulfilled at inter-element spacing less than 0.17λ where β_1 is higher than 1. This reveals that inter-element spacing less than 0.17λ results in capacity increase relative to the case when no coupling is present. The effect of MC on the channel capacity at 20 dB SNR is shown in Fig. 3 in terms of the

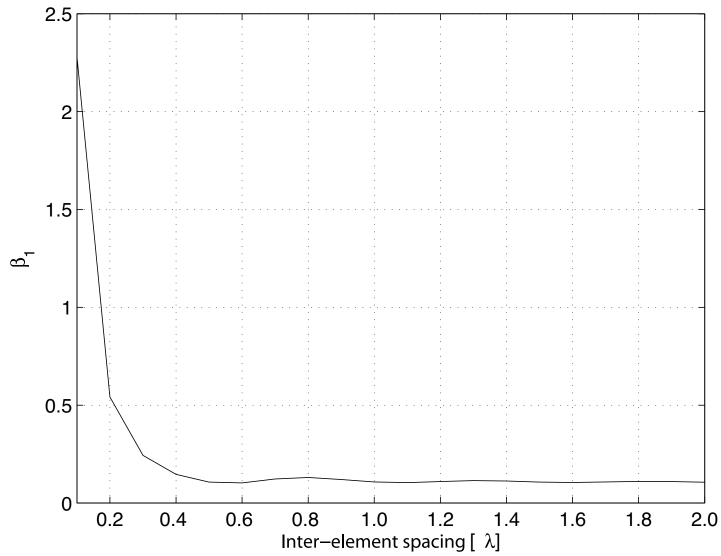

Figure 2. β_1 at different inter-element spacing for half wavelength dipole MEA.

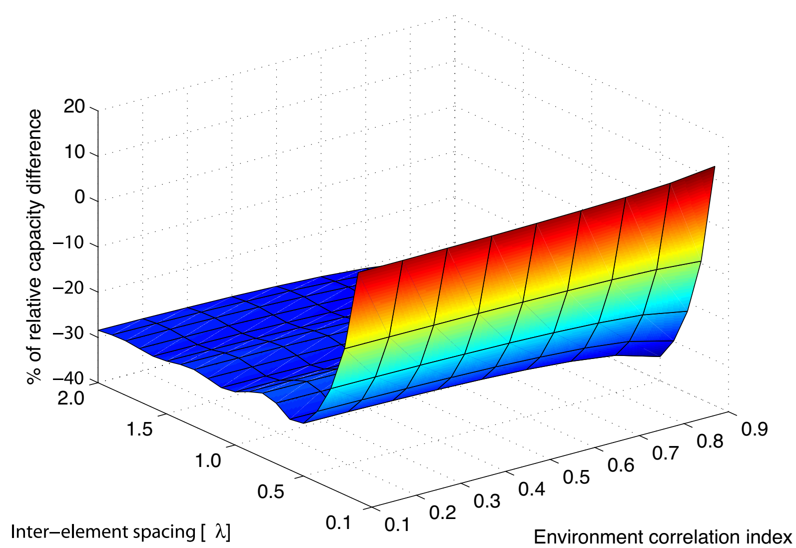

Figure 3. Channel capacity variations due to MC effect on correlation properties and target average receive SNR for half wavelength dipole MEA.

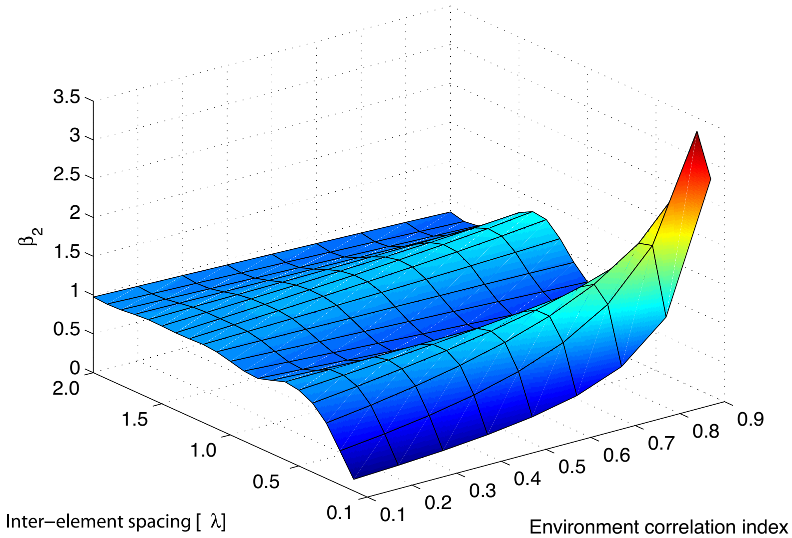

Figure 4. β_2 at different correlation values and inter-element spacings for half wavelength dipole MEA.

percentage of relative mean capacity difference, i.e. $100 \times E\{\frac{c_{mc}-c_{iso}}{c_{iso}}\}$, where $E\{.\}$ denotes expectation. In this case, coupling affects both the target average receive SNR and the channel correlation properties. It can be noticed that regardless to the propagation environment correlation properties, MC results in capacity increase relative to the case when coupling effect is absent at inter-element spacing less than 0.17λ. This is simply because with very small inter-element spacing, $<0.17\lambda$, relatively high energy is coupled to the closely spaced element which results in average receive SNR higher than the target value. When the inter-element spacing is increased higher than 0.17λ the negative impact of MC on the channel capacity becomes evident. At large inter-element spacing, $>0.5\lambda$, the effect of MC on the channel correlation properties becomes negligible and only the impact of MC on the average receive SNR remains. With very large inter-element spacing the effect of MC on the channel capacity is still clear and the relative capacity difference does not go to zero because the power variations due to MC are not compensated.

Fig. 4 shows the term β_2 at different inter-element spacing and different propagation environment correlation values. It can be noticed that in this case the effect of MC depends also on the propagation environment correlation properties. The condition in proposition 2 is fulfilled in some propagation environments and at some inter-element

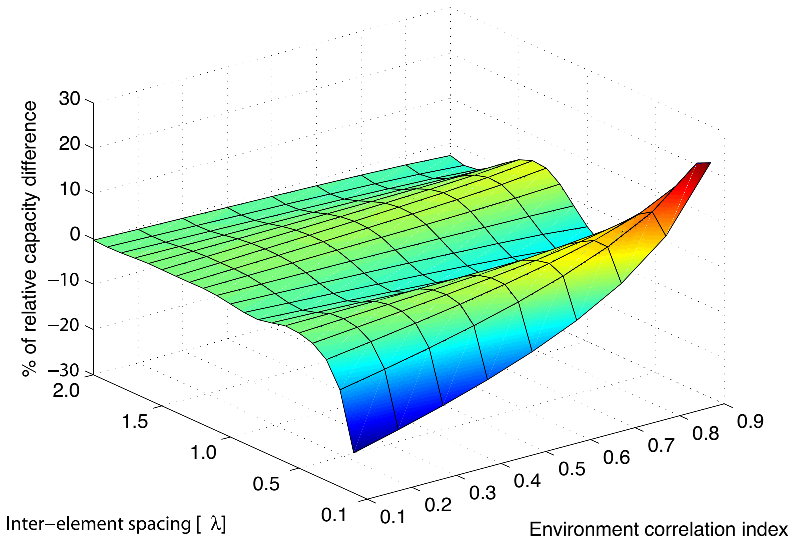

Figure 5. Channel capacity variations due to MC effect on correlation properties at fixed average receive SNR for half wavelength dipole MEA.

spacings. For instance at 0.2λ inter-element spacing and propagation environment with correlation index higher than 0.6, $\beta_2 > 1$ and one expect positive effect on the MIMO channel capacity due to MC. Fig. 5 shows the effect of MC on the channel capacity at 20 dB average receive SNR in terms of the percentage of relative mean capacity difference, i.e., $100 \times E\{\frac{c_{mc,n}-c_{iso}}{c_{iso}}\}$. We can clearly see that the effect of MC at highly correlated propagation environment and at inter-element spacing less than 0.5λ results in relative capacity increase. This relative increase ranges from 0.46% to 21.85%. However, in low correlated propagation environment the effect of MC on the channel capacity is negative. One can notice that inter-element spacing larger than 0.5λ is sufficient to reduce the effect of MC and results in decorrelated paths. This result is online with the common understanding in literature.

5. CONCLUSIONS

We have shown that both the propagation environment spatial correlation properties and the characteristics of the MC matrices determine the impact of MC on the capacity of MIMO wireless channels. Considering channel capacity variations due to MC effects on both correlation properties and average receive SNR, channel capacity variations depend only on the two ends MC matrices. However, studying channel capacity variations due to MC effects on correlation properties at fixed average receive SNR reveals that the presence of MC in highly correlated propagation environment may have decorrelation impact and consequently positive effect on the channel capacity. On the other hand, the presence of MC in low correlation propagation environment may have negative impact on the channel capacity due to extra correlation effect.

REFERENCES

1. Foschini, G. J. and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Commun.*, Vol. 6, No. 3, 311–335, 1998.
2. Telatar, I. E., "Capacity of multi-antenna Gaussian channels," *European Trans. Tel.*, Vol. 10, No. 6, 585–595, 1999.
3. Forenza, A. and R. W. Heath, Jr., "Impact of antenna geometry on MIMO communication in indoor clustred channels," *Proc. of IEEE Antennas and Propagation Symposium*, Vol. 2, 1700–1703, 2004.
4. Abouda, A. A., H. M. El-Sallabi, and S. G. Häggman, "Effect of antenna array geometry and ULA azimuthal orientation on MIMO channel properties in urban city street grid," *Progress In Electromagnetics Research*, PIER 64, 257–278, 2006.
5. Gupta, I. J. and A. A. Ksienski, "Effect of mutual coupling on the performance of adaptive arrays," *IEEE Trans. on Antennas and Propagation*, Vol. 31, No. 5, 785–791, 1989.
6. Steyskal, H. and J. S. Herd, "Mutual coupling compensation in small array antennas," *IEEE Trans. on Antennas and Propagation*, Vol. 38, No. 12, 1971–1975, 1990.
7. Lee, W. C. Y., "Mutual coupling effect on maximum ratio diversity combiners and application to mobile radio," *IEEE Trans. on Communications Technology.*, Vol. 18, No. 6, 779–791, 1970.
8. Fletcher, P. M., M. Dean, and A. R. Nix, "Mutual coupling in multi-element array antennas and its influence on MIMO channel capacity," *IEE Electronics letters*, Vol. 39, No. 4, 342–344, 2003.
9. Skafidas, E. and R. J. Evans, "Antenna effects on the capacity of MIMO communications systems in Rayleigh channels," *Proc. of IEEE Personal Indoor and Mobile Radio Communications, PIMRC04*, Vol. 1, 617–621, 2004.
10. McNamara, D. P., M. A. Beach, and P. N. Flescher,

"Experimental investigation into the impact of mutual coupling on MIMO communication systems," *Proc. of Int. Symp. on Wireless Personal Multimedia Communications, WPMC01*, Vol. 1, 169–173, Sep. 2001.

11. Borja, C., A. Algans, M. Royo, J. Anguera, and C. Puente, "Impact of the antenna technology and the antenna parameters on the performance of MIMO systems," *Proc. of IEEE Antennas and Propagation Symposium, APS03*, Vol. 2, 507–510, 2003.
12. Godara, L. C., *Handbook of Antennas in Wireless Communications*, 888, CRC Press, 2002.
13. Haus, H. A. and R. B. Adler, *Circuit Theory of Linear Noisy Networks*, 79, John Wiley and Sons, Inc., 1959.
14. Özdemir, M. K., H. Arslan, and E. Arvas, "Mutual coupling effect in multi-antenna wireless communication systems," *Proc. of IEEE Global Telecommunications Conference, GLOBECOM03*, Vol. 2, 829–833, 2003.
15. Cover, T. M. and J. A. Thomas, *Elements of Information Theory*, 542, John Wiley and Sons, Inc., 1991.
16. Neeser, F. and J. Massey, "Proper complex random processes with applications to information theory," *IEEE Trans. on Information Theory*, Vol. 39, No. 4, 1293–1302, 1993.
17. Kraus, J. D. and R. J. Marhefka, *Antennas for All Applications*, 938, McGram-Hill, 2002.
18. Pederson, K. I., J. B. Anderson, J. P. Kermoal, and P. Mogensen, "A stochastic multiple-input multiple-output radio channel model for evaluation of space-time coding algorithms," *Proc. of IEEE Conference on Vechular Technology, VTC*, Vol. 2, 893–897, 2000.