Performance of Non Co-phase EGC Diversity Technique with Multiple Antennas on Limited Space

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ABSTRACT

The Equal Gain Combining (EGC) diversity technique is generally known to have a performance close to an optimal Maximal Ratio Combining (MRC) technique while being less complex for realization. Hence, the implementation of EGC in practice is of interest; however the implementation of EGC diversity is cumbersome due to additional circuitry required for making a co-phase signal in each branch. As a result, it is interesting to investigate whether non co-phase EGC diversity is able to provide an acceptable performance while keeping much greater simplicity with only marginally inferior as compared to co-phase method. This paper studies performance of non co-phase EGC diversity through the problem of limited space on WLAN terminal. This is because the diversity technique in real application cannot determine antenna spacing as large as required in theory. Therefore, it is impossible to avoid the effect of antenna correlation due to limited space. Also in this paper, the measurements of WLAN signals are undertaken in order to justify the use of proposed system. The results reveal that non co-phase EGC diversity provides a benefit on enhancing signal strengths where its performance depends on number of antennas and type of fading channels.

Keywords: Antenna Diversity, Equal Gain Combining (EGC), Correlation, AWGN and Rician Fading Channels

1. INTRODUCTION

The Antenna diversity with multiple antennas is a well known technique to improve performance in fading channel for wireless systems. This technique includes maximal ratio combining (MRC), equal gain combining (EGC), and selection diversity (SC) [1]. Maximal ratio combining (MRC) is often referred to as optimum combining [2] because it yields the highest signal-to-noise ratio at the output when compared to all other combining techniques. However, the EGC receiver performance is superior to SC performance and only marginally inferior as compared to MRC. A great number of practical diversity systems can be found in the literature [3-6] with appropriate description and analysis. In practice, EGC technique provides performance comparable to the MRC receiver but with greater simplicity. Hence, it is interesting to choose EGC diversity for implementing in wireless systems.

EGC is the simplest diversity technique in which the outputs of different diversity branches are first co-phased and weighted equally before being summed to give the resultant output [7-9]. The weights are all set to one with the requirement that the channel gains are approximately constant. This is usually achieved by using an automatic gain controller (AGC) in the system [10]. Some practical applications of EGC include the use of regenerative circuits to co-phase the received carriers. However, implementation of EGC diversity is cumbersome due to the additional circuitry required in order to co-phase the signal in each branch. Consequently, it is interesting to reduce co-phase method of EGC diversity for implementing this technique. The literature on non co-phased antenna diversity branches is meager despite its importance from both practical and theoretical viewpoints which this technique has never been reported. Therefore, the first contribution of this paper is to analyze the performance of non co-phase EGC diversity via analytical and simulated results. Then the use of non co-phase EGC diversity in real application has been investigated. In this paper, the use of diversity in an indoor WLAN system is on focus. One problem on designing multiple antennas for WLAN terminal is having a limited space as the dimension of wireless terminal is bounded by the trend of smaller size. This causes an undesired correlation to antenna branches and degrades the theoretical performance. The literature on correlated diversity branches is quite a few and amongst the initial works of gain combining schemes, Pierce and Stein [11] studied the BER for MRC and EGC for BPSK modulation in a correlated Rayleigh fading channel and showed that an increase

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in correlation had adverse effects on the BER of the system. The correlation between the signal branches is a function of the spacing antennas. Therefore, the problem to space multiple antennas on limited space is necessary to be considered. This problem deals with the correlation between each antenna which can greatly affect the performance of wireless system reported in the literatures [12-18]. In [13-14], the practical implementations of spatial diversity at the mobile handsets are usually restricted to second order diversity with closely spaced antennas that result in correlation between the diversity branches. As explained in [15], the correlation between the branch envelopes in spatial diversity systems is a function of the spacing between the antennas. However, assumption avoiding correlations cannot be accepted in practice because the size of user terminal is so small that multiple antennas on this limited space are unfortunately correlated. Thus, performance of EGC diversity technique with multiple antennas on limited space is of interest both practical and theoretical viewpoints. In [19], the authors of this paper had been initially investigated the performance of EGC diversity technique by considering the problem of multiple antennas on limited space. The simulation results reveal the significant differences observed if neglecting or including the antenna correlations. From all simulation results, the effect of correlated signals due to limited space is seriously significant in AWGN channel but not Rayleigh channel. However, the real propagation channel of indoor WLAN system is different from either AWGN or Rayleigh fading channel. Thus, the measuring observation is required to validate the use of EGC diversity technique. This paper presents the measurement results of non co-phase EGC diversity applying on the same problem reported in [19]. This is considered as another paper contribution to verify the proposed system in use of real application.

The remainder of paper is organized as follows. Section 2 provides the details of EGC diversity and its antenna correlation. The analytical attempt of non co-phase EGC is given in Section 3. In Section 4, the differences between non co-phase and co-phase EGC techniques are examined and then the performance comparison of both EGC techniques in presence of Rician and AWGN fading channels is presented in Section 5. Afterward, the performance investigation of non co-phase EGC diversity technique is presented by considering the problem of multiple antennas on limited space. The effect of correlated fading on the non co-phase EGC diversity of antenna systems where more than two antennas are used is now discussed. In addition, the measured results are undertaken to justify the simulation results. Finally, Section 6 presents the conclusions of this paper.

2. SYSTEM MODEL

2.1 EGC diversity

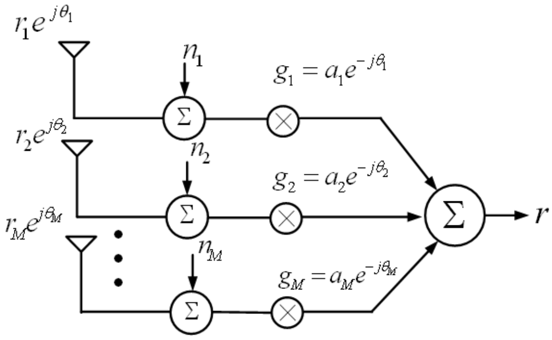

Fig.1: *EGC diversity technique*

EGC diversity is known to combine the signals from multiple diversity branches. The signal output of the combiner is the direct sum of the received signals, which a co-phase signal on each branch is performed and then it is combined with equal weighting in each branch of receivers. Fig. 1 illustrates a configuration of EGC diversity technique.

The signal output of the combiner is the direct sum of the received signals with weighting $g_i = a_i e^{-j\theta}$ on the i th antenna branch. For EGC diversity, the amplitude of weighting is equally set to 1 for all branches. Hence, the combined signal is expressed as

$$r = \sum_{i=1}^{M} r_i \tag{1}$$

where M is the total number of diversity antenna branches. Assuming a mean noise power equal to N for each branch, the total noise power $\boldsymbol{N}$ at the combiner's output is written by

$$\boldsymbol{N} = N \sum_{i=1}^{M} a_i^2 \tag{2}$$

Consequently, the output Signal to Noise Ratio (SNR : γ) is given as

$$\gamma = \frac{r^2/2}{\boldsymbol{N}} = \frac{r^2}{2NM} \tag{3}$$

The combined output r is a sum of M Rayleigh variables. Let $P(r)$ be the probability density function of r. Therefore, the probability density function $P_{EGC}(\gamma)$ of output EGC SNR γ can be found as

$$P_{EGC}(\gamma)|d\gamma| = p(r)|d(r)| \tag{4}$$

By replacing (3) into (4), then

$$\begin{aligned} P_{EGC}(\gamma) &= NM\frac{P(r)}{r} \\ &= NM\frac{P(\sqrt{2\gamma NM})}{\sqrt{2\gamma NM}} \end{aligned} \tag{5}$$

The problem of finding this distribution is a classically old one, going back even to Lord Rayleigh, but has never been solved in terms of tabulated functions for $M \geq 3$. The question is how to find $p(r)$. For the case where $M = 2$, the problem can be easily tackled as follows. The joint distribution of two signals is derived [1, 4.37] as

$$p(r_1, r_2) = \frac{r_1 r_2}{\sigma^4(1-\rho^2)} \exp\left[-\frac{r_1^2 + r_2^2}{2\sigma^2(1-\rho^2)}\right] I_0\left(\frac{r_1 r_2 \rho}{\sigma^2(1-\rho^2)}\right) \quad (6)$$

where $I_0(x)$ is the modified Bessel function of zero order.
and

$$\rho^2 = \frac{\mu_1^2 + \mu_2^2}{\sigma^2} \quad (7)$$

where μ_1, μ_2 are the mean signals of two branches and σ^2 is the variance of two signals. If both signals are independent,then $\mu_1 = \mu_2 = \rho = 0$and $I_0(0) = 1$

$$p(r_1, r_2) = \frac{r_1 r_2}{\sigma^4} \exp\left[-\frac{r_1^2 + r_2^2}{2\sigma^2}\right] \quad (8)$$

Assuming $r = r_1 + r_2$ or $r_2 = r - r_1$. Then

$$\begin{aligned} p(r) &= \int_0^r p(r_1, r_2)|_{r_2 = r - r_1} dr_1 \\ &= \int_0^r p(r_1, r - r_1) dr_1 \end{aligned} \quad (9)$$

Such an integral can be solved in term of $p(r)$ and using this result into (9), the final probability density function is given by

$$\begin{aligned} P_{EGA}(\gamma) &= \frac{1}{\gamma} e^{-\frac{2\gamma}{\gamma}} + \sqrt{\pi}^{-\frac{\gamma}{\gamma}} \left(\frac{1}{2\sqrt{\gamma\bar{\gamma}}} - \frac{1}{\gamma}\sqrt{\frac{\gamma}{\gamma}}\right) \\ &\times \left(1 + 2Q\left(\sqrt{2\frac{\gamma}{\gamma}}\right)\right) \end{aligned} \quad (10)$$

where $Q(.)$ is the Q-function and $\bar{\gamma} = \sigma^2/N$

2.2 Antenna Correlation

Fig. 2 shows an antenna configuration on limited space. The linear array with M antenna elements is configured on a fixed length D.

The relation between power correlation coefficient ρ and antenna spacing d is derived by Clarke [21] as

$$\rho = J_0^2\left(\frac{2\pi d}{\lambda}\right) \quad (11)$$

where $J_0(.)$ is the zero order Bessel function of first kind, and λ is the carrier wavelength. From [20] we will use this relationship to determine the correlation properties of the signal on each branch, expressed as

$$p_n(\lambda_c) - \rho = 0 \quad (12)$$

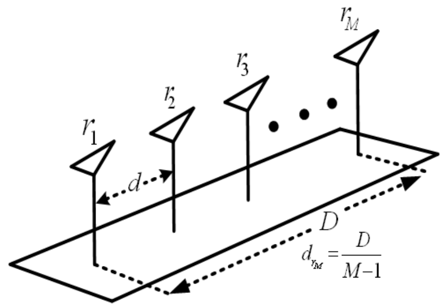

Fig.2: *Antennas configuration on limited space*

where $p_n(\lambda_c)$is the least squares n degree polynomial given in [20]. The parameter λ_c has been useful in analyze of the correlation signals. In [20] the authors found the special case of the correlation matrix given by

$$L = \begin{bmatrix} \sigma_x & 0 \\ \frac{1}{\sqrt{2}}\lambda_c\sigma_x(1+j) & \sigma_x\sqrt{1-\lambda_c{}^2} \end{bmatrix} \quad (13)$$

where σ_x is absolute desired signal power. By assuming that r_1 and r_2 are samples of two uncorrelated signals, the correlated signals are easily determined by

$$\mathbf{X} = \mathbf{Lr} \quad (14)$$

where $\mathbf{r} = [r_1 \quad r_2]^T$. Hence, the correlated signals between two branches can be easily generated

Fig. 3 and Fig. 4 show the examples of uncorrelated and correlated signals in a Rayleigh fading channel. For the correlated signals, the power correlation coefficient is 0.9. Fig. 3(a) and Fig. 3(b) present the uncorrelated and correlated signals for two branches while Fig. 4(a) and Fig. 4(b) present for four branches. It is clearly noticed the difference between correlated and uncorrelated signals. These figures are performed to confirm the concept of using correlation matrix in (13) for simulations.

For problem on limited space, the total length D is a fixed distance and the correlation coefficient is changed by number of antennas with an equal spacing. Thus, we will consider the effect of signal correlations via a changed spacing on the limited space instead.

3. NON CO-PHASE EGC ANALYSIS

Considering a block diagram of EGC diversity shown in Fig. 1, the signal output requires a co-phase operation before directly combining. It costs an unattractive complexity for implementation. In this light, the paper proposes the deletion of co-phase operation for EGC system, so called as non co-phase EGC diversity technique. Then the system as non co-phase operation only requires the combiner to directly

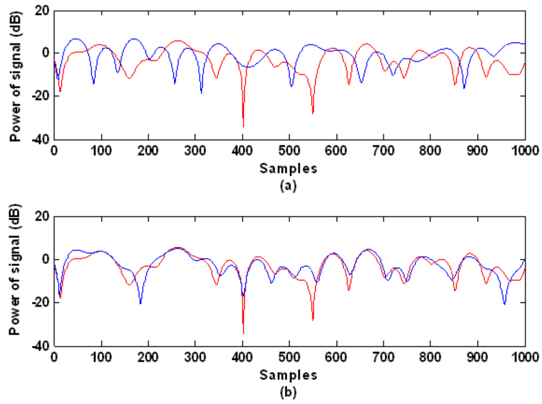

Fig.3: *Example of two signals in a Rayleigh fading channel, (a) uncorrelated signals, (b) correlated signals.*

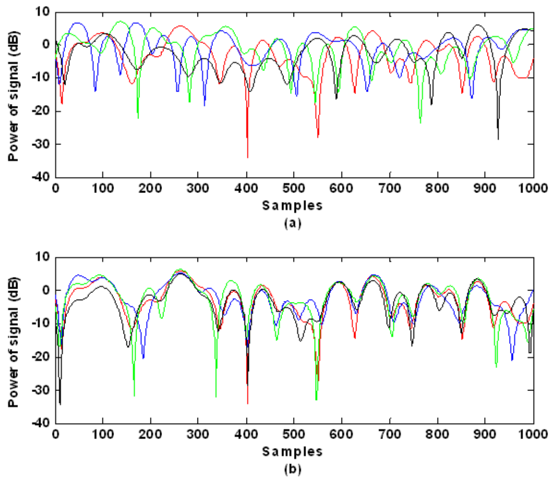

Fig.4: *Example of four signals in a Rayleigh fading channel, (a) uncorrelated signals, (b) correlated signals.*

sum all signals from antenna branches. No weighting procedure including phase estimator and phase shifter is necessarily used. Although the implementation of non co-phase is very easy but the trade-offs between complexity and performance of co-phase and non co-phase systems have definitely expected. In this section, the analytical attempt of two-branch non co-phase EGC diversity is described.

For non co-phase EGC diversity, the combined signal is expressed by

$$re^{j\theta} = \sum_{i=1}^{M} re^{j\theta_i} \qquad (15)$$

The joint distribution $p(r_1, r_2, \theta_1, \theta_2)$of two signals has already been determined in [1], which the joint density has a phase and envelope of signal as

$$p(r_1, r_2, \theta_1, \theta_2) = \frac{r_1 r_2}{4\pi^2\sigma^4(1-\rho^2)} \times \exp\left\{-\frac{1}{2\sigma^8(1-\rho^2)^2}\right.$$

$$\left.[\sigma^2(r_1^2+r_2^2)-2r_1r_2\mu_1\cos(\theta_2-\theta_1)-2r_1r_2\mu_2\cos(\theta_2-\theta_1)]\right\} \qquad (16)$$

Also, if both signals are independent, then $\mu_1 = \mu_2 = \rho = 0$ .Therefore

$$p(r_1, r_2, \theta_1, \theta_2) = \frac{r_1 r_2}{4\pi^2\sigma^4} \exp\left[-\frac{r_1^2 + r_2^2}{2\sigma^6}\right] \qquad (17)$$

For $M = 2$, assuming

$$re^{j\theta} = r_1 e^{j\theta_1} + r_2 e^{j\theta_2}$$

or

$$re^{j\theta} = r_1 e^{j\theta_1} + r_2 e^{j\theta_2}$$

Consequently,

$$r_2 = \sqrt{(r\cos\theta - r_1\cos\theta_1)^2 (r\sin\theta - r_1\sin\theta_1)^2} \qquad (18)$$

Replacing (18) into (17), yields

$$p(r,\theta) = \int_0^r\int_0^\theta p(r_1, r_2, \theta_1, \theta_2)\Big|_{r_2=\sqrt{(r\cos\theta-r_1\cos\theta_1)^2+(r\sin\theta-r_1\sin\theta_1)^2}} d\theta_1 dr_1 \qquad (19)$$

The integral of (19) does not appear to lend itself to a close-form evaluation, but it has been evaluated numerically by using Simpson's rule [22]. This technique is a method for numerical integration which is simply programmed by using MATLAB. In order to compare the probability density functions between co-phase and non co-phase systems, then result in (19) has to be independent from phase. Assuming combined output having phase with uniform distribution, then the probability density function of non co-phase amplitude is given by

$$p(r) = \frac{1}{2\pi}\int_0^{2\pi} p(r,\theta)d\theta \qquad (20)$$

The above integral is able to use the similar numerical method as (19), and thus the probability density function for non co-phase EGC diversity could be solved.

4. MEASUREMENT SETUP

The multiple antennas are located on the specific 29.5 cm length which is the approximate dimension of typical notebook. This paper only focuses on the uniformly-linearly spaced array antennas due to the ease of practical manufacturing. For the set of measuring equipments shown in Fig. 5, there are three parts including array antennas, combiner and

WLAN receiving module. For monitoring and recording WLAN signal strength, a freeware named WirelessMon 3.0 has been employed. For array antennas, the commercial monopole type with 5 dBi gain has been chosen. The paper also uses the commercial combiner manufactured by Minicircuit Company.

In order to justify simulation results, the measurements of non co-phase EGC diversity are necessarily undertaken. The measurements are performed at 4$^{\text{th}}$ floor of C Building, Suranaree University of Technology in which there are four Access Points (AP) serving for a whole coverage area. The signal strengths of WLAN signals are measured under the normally operating environments. The map of measurement area is illustrated in Fig. 6 where black spots indicate the measurement position. The total positions of measurements are 30 points. In each position, the repeated measurements are performed by 10 times for each antenna configuration

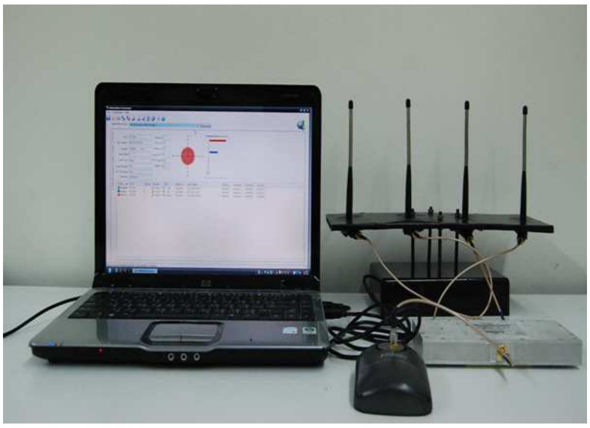

Fig.5: *Measurement hardware of non co-phase EGC diversity technique.*

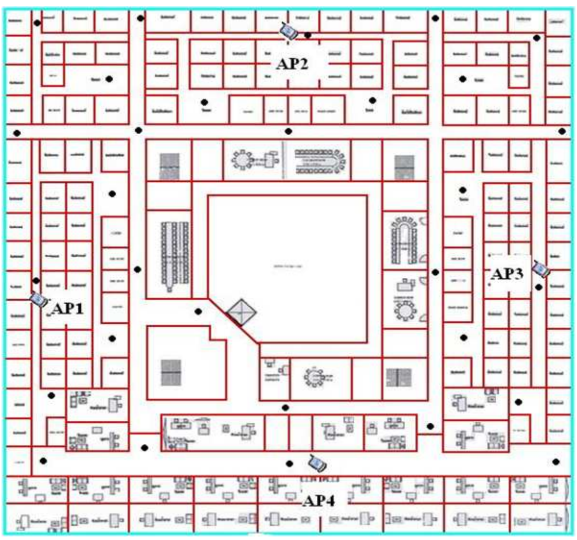

Fig.6: *Map of measurement area*

5. RESULTS AND DISCUSSIONS

In this section, the results are able to be considered into three groups. At first, the comparison between co-phase and non co-phase EGC diversity techniques are presented. Both analytical and simulated results have been provided to distinguish the actual performance between them. For second group, the simulation results of non co-phase EGC diversity on the problem of limited space are presented. The number of antennas and the type of fading channels are the main parameters to be investigated. In the last group, the results of measurements are given in order to validate the previous simulations.

The following plots in Fig. 7 are obtained as $\bar{\gamma}$ is 10 dB for co-phase and non co-phase techniques. It can be seen that both probability density functions are similar with the larger variance for non co-phase. To emphasize on numerical values, Table 1 provides details of peak and average values including their probabilities. As noticed in Table 1, both co-phase and non co-phase EGC diversity techniques provide all parameters close to each other. Hence, at this initial investigation, the non co-phase seems to be more attractive due to its low complexity. However, the previous analysis is limited by two specific conditions. One is the number of diversity branches set at two and the other is the AWGN fading channel. The reason why analytical solution does not support for other number of antennas and fading types is because it is hardly solved in terms of tabulated functions for $M \geq 3$.

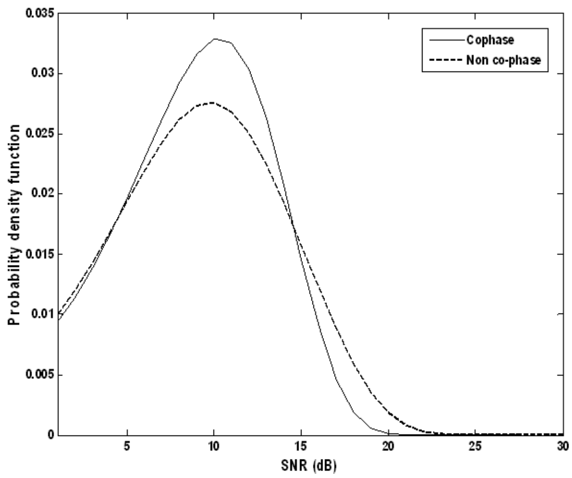

Fig.7: *Comparison of probability density functions of non co-phase and co-phase EGC diversity techniques.*

Therefore, the next task is to verify the use of non co-phase EGC diversity through simulations by changing other number of antennas and fading types. Fig. 8 shows the probability density function of output SNR for AWGN and Rician fading channels ( ) with 2 and 8 diversity branches. It can be noticed

Table 1: *Performance comparisons in term of peak and average values*

	Co-phase	Non co-phase
Peak (dB)	10.4	9.9
Prob (>Peak)	0.427	0.466
Average (dB)	9.8	9.3
Prob (>Average)	0.482	0.522

that the average power of signals is greater when applying more antennas. The significant differences between co-phased and non co-phased signals can be now noticed for Rician channel but not for AWGN channel. This is because under a rich multipath the fluctuation of signals due to Rician fading plays a major role on non co-phase signals. Hence, the variation of EGC output is more diverse for non co-phase diversity. These results strongly indicate that the very careful consideration is required to employ non co-phase EGC diversity under a fading condition.

Next, the issue of employing non co-phase EGC diversity technique into a limited space is on focus. Fig. 9 shows the probability density functions of output SNR for

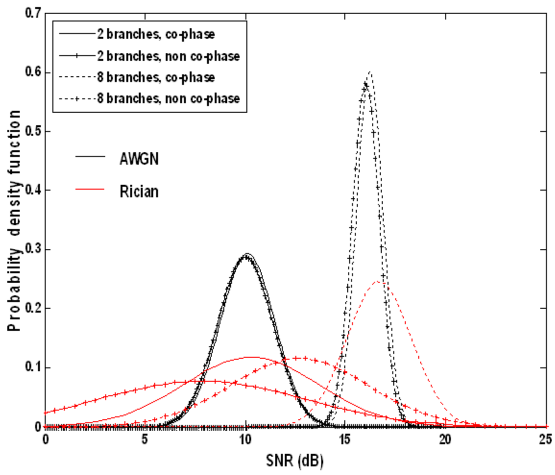

Fig.8: *Comparison of probability density functions of non co-phase and co-phase EGC diversity techniques by simulations.*

uncorrelated and correlated signals in AWGN fading channel. It can be observed that the average signal power is greater when applying more antennas. Also the differences between uncorrelated and correlated signals are more pronounced when applying more antennas. For Rician fading channel, the results are depicted in Fig. 10. It is interesting to notice that effect of limited space examining through antenna correlation provides a significant notice on both fading types and this effect increases as a function of number of antennas. Therefore, the design of multiple antennas on limited space is of important to

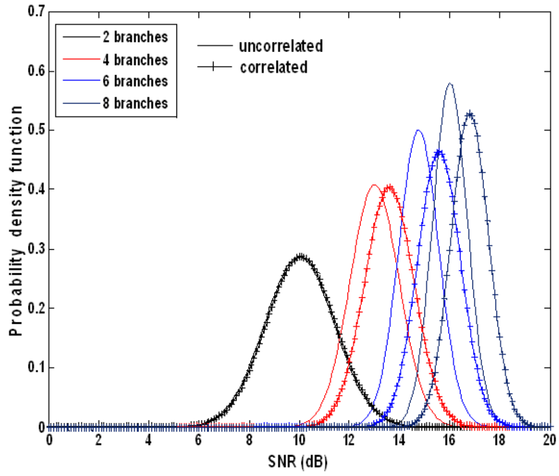

Fig.9: *Probability density functions of non co-phase EGC diversity technique in AWGN fading channel.*

deal with its correlation when implementing EGC diversity technique. Fig. 11 presents an average SNR versus number of antennas for co-phase and non co-phase as well as correlated and uncorrelated signals. As expected, the average SNR increases as a function of number of antennas for all conditions. By using the the results in this figure, the enhancements of WLAN signal strength can be predicted

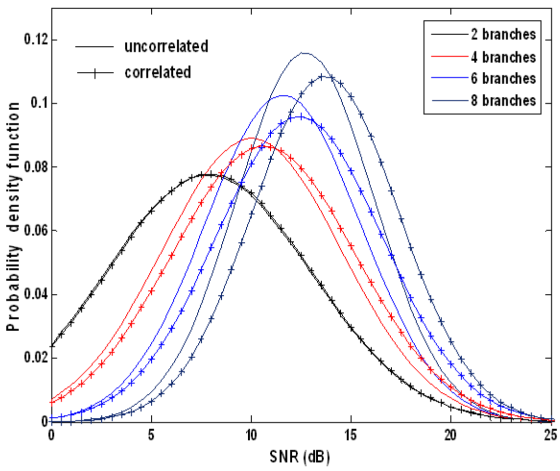

Fig.10: *Probability density functions of non co-phase EGC diversity technique in Rician fading channel.*

For measurement results, the probability density function of signal strength is presented in Fig. 12. It is obvious that the average power and variance of each case gradually increases as a function of number of antennas. These variations are not similar to either AWGN or Rician fading channels. It means that the propagation of WLAN signals in an indoor environment cannot be modeled by using simple mathematic models. Also, Fig 13 shows the output signal strength of non co-phase EGC diversity as a function of num-

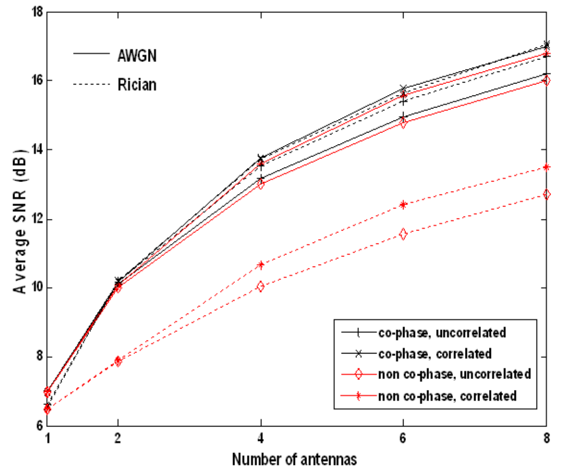

Fig.11: *Output SNR of non co-phase EGC diversity technique as a function of number of antennas in fading channels.*

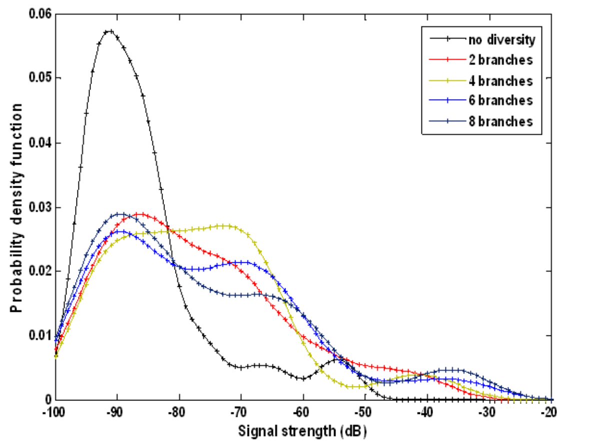

Fig.12: *Measured probability density function of non co-phase EGC diversity technique.*

ber antennas in measurements. It can be seen that improvement is accomplished when the non co-phase EGC technique is used.

It is interesting that the average signal strength gradually increases from 2 to 8 branches while it rapidly increases from 1 to 2 branches. In practice, the use of more than 2 branches at receiver is not feasible due to cost of antenna installment and layout complexity. These results emphasize that only 2 branches already provide a substantial improvement in the received signal by using non co-phase EGC diversity for WLAN systems.

6. CONCLUSION

In this paper, the performance investigation of EGC diversity technique is presented by comparing between co-phased and non co-phased signals in fading channels. The numerical and simulation results reveal the significant differences of performance only if the fading is not AWGN channel. Moreover, this paper presents both simulation and measurement results of using non co-phase EGC diversity technique with increased antennas on limited dimension of WLAN terminal like notebook. The effect of correlated signals due to limited space is seriously significant in AWGN and Rician fading channel. However, the real propagation channel does not behave like either AWGN or Rician channels. It was shown that the larger the number of branches, the better the system performance. However, for non co-phase EGC diversity technique, two branches already provide a substantial improvement.

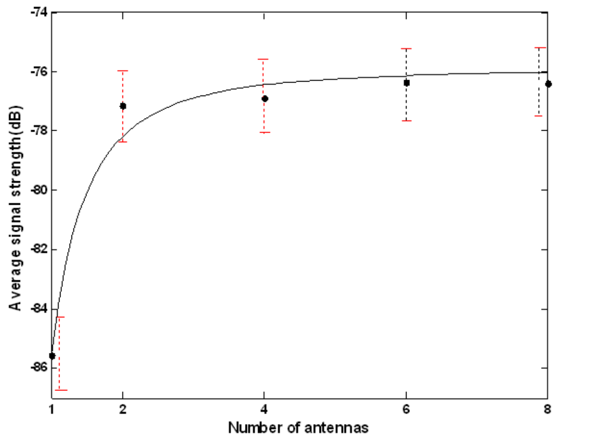

Fig.13: *Measured signal strength of non co-phase EGC diversity technique as a function of number of antennas.*

7. ACKNOWLEDGEMENT

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