# REVERBERATION CHAMBER EVALUATION OF MULTI-ANTENNA HANDSETS HAVING LOW MUTUAL COUPLING AND HIGH EFFICIENCIES

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## ABSTRACT

This paper presents the evaluation of the diversity performances of several multi-antenna structures in a reverberation chamber. Firstly, a two-antenna system having low isolation between the radiators is measured. Its performances are compared with a second structure which uses a neutralization technique to enhance the radiating element's isolation. Then the performances of a four-antenna system with and without the neutralization method are measured and presented. Particularly, the total antenna efficiencies, the envelope correlation coefficients and the diversity gain of these systems are presented and discussed. We especially focus on the advantages of the neutralization technique.

## 1. INTRODUCTION

Nowadays, the use of wireless mobile communications is growing exponentially in several field of telecommunications. In modern applications, transferring large amounts of data is clearly needed and consequently, increasing the data rate transfer is necessary. The performances of wireless terminals can be greatly improved by introducing different diversity schemes in a communication link. In practice, terminals can be considered to operate in a so-called multipath propagation environment. This means that the electromagnetic fields will take many simultaneous paths between the transmitter and the receiver. The antennas of the handset must therefore be designed to properly work in such an environment, the most important parameters being the total efficiency and the diversity gain.

Several multi-antenna structures have been designed and fabricated at the LEAT of the University of Nice for diversity and MIMO purposes. These systems include from two to four antennas operating in the UMTS band (1920-2170 MHz). Particularly, a neutralization effect has been used to achieve high isolation between the antennas [1]. The prototypes have been characterized in terms of S parameters, total efficiencies and correlation coefficients [2]. All these measurements have proven that these structures have a strong potential for an efficient implementation of diversity at the mobile terminal side. However, their fully characterization in a uniform multi-path propagation environment needs some particular facilities and the associated expertise [3]. Chalmers Institute of Technology already possesses these capabilities through the Bluetest reverberation chamber [4].

This paper results from a short-term mission granted by the COST 284. The designing competences of the LEAT have been gathered with the measurement skills of Chalmers Institute of Technology. Several prototypes have been characterized in the Bluetest reverberation chamber in terms of total efficiency, envelope correlation coefficients and diversity gain. Particularly a two-antenna system with and without the neutralization line are compared at first; then we characterize a four-antenna structure. The efficiency results are compared with the measurements done with a Wheeler Cap set-up from the LEAT. The cumulative probability distribution functions are presented to compute the apparent and the actual diversity gain [3, 5]. We especially focus on the neutralization technique performance.

## 2. THE REVERBERATION CHAMBER

A reverberation chamber is an enclosure in which the electromagnetic environment is statistically isotropic and homogeneous (Fig. 1). Isotropic means that at each location of the chamber, far enough from the walls, the electromagnetic environment is statistically the same. The power injected in the chamber via a transmitting antenna will balance the losses in the chamber and build up a modal structure for each stirrer position. This modal structure will illuminate non uniformly the multi-antenna system. Rotating slightly the stirrer, a paddle or a scatterer change the electromagnetic boundary condition then perturb the modal structure and give a totally different illumination. The received incident field, powered by a probe that is linearly polarized in one dimension is distributed with two degrees of freedom. The ratio of peak to average is almost the same in whole the chamber volume if the receiving antenna is at a distance of $\lambda/2$ away from the wall.

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The chamber is excited by a transmit small antenna of any kind, located in a corner of the chamber, and preferably not radiating directly to the central part of the chamber, where the antenna under test (AUT) and its near-in environment are located. The transmit antenna excites the chamber with several resonant cavity modes. The chamber must be larger enough to support some hundreds of modes. The more modes exist, the more accurate results for the radiation efficiency will be. The transmission between the transmit antenna and the AUT must be measured and stored for several different modes distributions in the chamber. Each mode in the chamber can be described as a standing wave due to two or more waves propagating in different directions.

Several hundred resonant modes will therefore represent a multipath field environment, with at least two times more multipath than modes. In order to get an estimate of the radiation efficiency we need to measure the transmission for some hundreds of different mode distributions and average the results. The average transmission with the AUT must be compared with the average transmission of a reference antenna with known performances, e.g., a dipole with no losses and matched in impedance. The ratio represents then an estimation of the radiation efficiency of the AUT. The accuracy of the estimation depends of the number of independent transmission measurements (which cannot be more than the number of modes in the chamber). We need typically more than 100 independent transmission measurements to get accuracy better than 0.5 dB. The independent mode distributions are obtained by moving a metal object referred to us as a mode in the chamber.

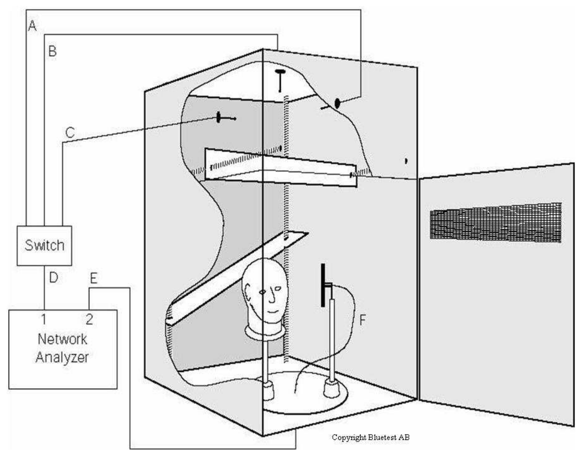


*Figure 1. Schematic drawing of the Bluetest reverberation chamber set-up*

**3. TWO AND FOUR-ANTENNA STRUCTURES**

The electromagnetic software IE3D was used to design the multi-antenna structures [6]. The procedure is described in [2]. The first designed two-antenna system is presented in Fig. 2. The PIFAs are symmetrically associated on a 40x100 mm² PCB and separated by a $0.12\lambda_0$ length (18 mm). They were optimized to cover the UMTS band with a return loss better than -6 dB. For that, each PIFA has a 26.5 mm length and a 8 mm width. They are fed by a metallic strip soldered to a SMA connector. They are shorted to the PCB by an identical metallic strip. The simulated and measured mutual coupling of this system is shown in Fig. 4. It reaches a -5 dB maximum in the middle of the UMTS band.

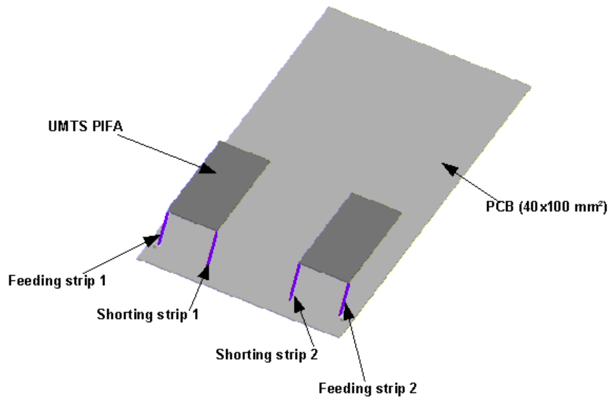


*Figure 2. 3D view of the two-antenna structure with low isolation between the radiators*

To increase the isolation of the radiating elements, a suspended line as a neutralization device has been inserted between the feeding strips of the two elements (Fig. 3). The optimization of this line was already explained in [1].

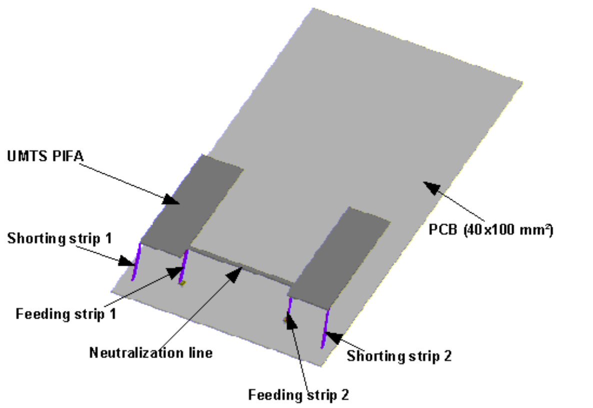


*Figure 3. 3D view of the two-antenna structure with high isolation between the radiators*

All the S-parameters of this last structure are presented in Fig. 4. A good matching is revealed. In addition, we can observe a strong enhancement of the insertion loss with a deep null in the middle of the bandwidth. The $S_{21}$ is always below -18 dB in the UMTS band.

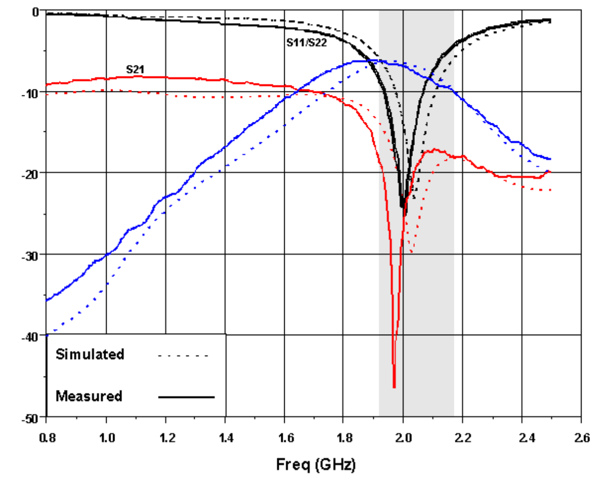


*Figure 4. Simulated and measured $S_{21}$ parameter of the two-antenna structure without the line (blue). Simulated and measured $S_{11}$, $S_{22}$ (black) and $S_{21}$ (red) of the two-antenna structure with the line.*

The same neutralization technique was also implemented in a four-antenna structure. The procedure is described in [2]. Two antennas were positioned at the top side of the PCB and the two others at the bottom side. To reduce the mutual coupling of the closest elements, a neutralization line was inserted between the feeding strips of the top elements of the PCB while a longer line was inserted between the shorting strips of the radiators located at the bottom side (Fig. 5).

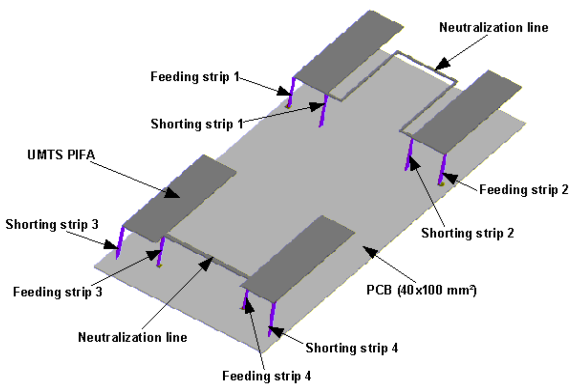


*Figure 5. 3D view of the four-antenna structure with neutralized PIFAs*

We can see in Fig. 6 that all the $S_{ij}$ parameters are always better than -15 dB. Moreover, the four PIFAs are well matched on the whole bandwidth. All these values are very satisfactory for diversity applications.

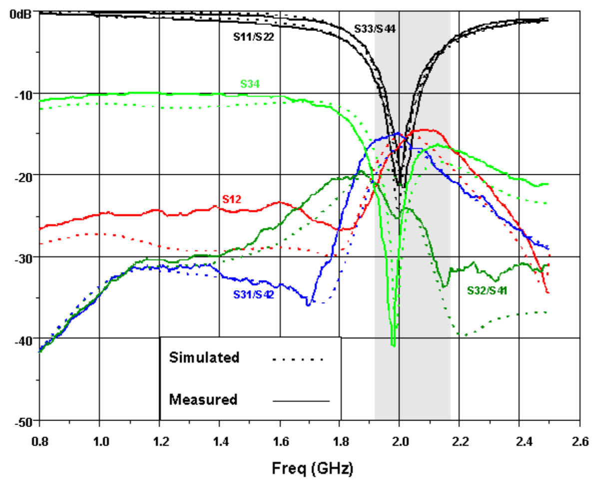


*Figure 6. Simulated and measured S parameters of the four-antenna structure with neutralized PIFAs*

## 4. MEASUREMENT OF THE EFFICIENCIES

Traditionally the radiation performance of an antenna is measured outdoor or in an anechoic chamber. In order to obtain the radiation efficiency, we need to measure the radiation pattern in all directions in space and integrate the received power density to find the total radiated power. This gives then the radiation efficiency when compared with the corresponding radiated power of a known reference antenna. The final result is obtained after a laborious and long measurement procedure. The efficiency can be measured very much faster and easier in the so-called reverberation chamber. However, it is necessary to first measure a reference case and then the Antenna-system Under Test (AUT). In fact, the transmission between the reference antenna and the excitation is already measured in the chamber with the reference antenna placed in free space that means at least half a wavelength away from any lossy objects and the walls of the chamber. As soon as the reference case is completed, we can measure the AUT but it is very important that the chamber is loaded in exactly the same way. From these both measurements, we can calculate $P_{ref}$ (Eq. 1) and $P_{AUT}$ (Eq. 2).

$$P_{ref} = \frac{\overline{|S_{11,ref}|^2}}{\left(1-|\overline{S_{11}}|^2\right)\left(1-\overline{|S_{22,ref}|^2}\right)} \quad (1)$$

$$P_{AUT} = \frac{\overline{|S_{21,AUT}|^2}}{\left(1-|\overline{S_{11}}|^2\right)\left(1-\overline{|S_{11,AUT}|^2}\right)} \quad (2)$$

$\overline{S_{21}}$ is the averaged transmission power level, $\overline{S_{11}}$ the free space reflection coefficient of the excitation antenna and $\overline{S_{22}}$ the free space reflection coefficient of the reference antenna (or the antenna under test). The $\overline{\ \ }$ denotes averaging on positions of the platform stirrers, polarization stirrer and mechanical stirrers.

The total efficiency can be then calculated from Eq. 3.

$$\eta_{tot} = \left(1 - \overline{\left|S_{22AUT}\right|^2}\right) \frac{P_{AUT}}{P_{ref}} \qquad (3)$$

The total efficiencies of the two-antenna structures (with and without the neutralization line) measured in the reverberation chamber are presented in Fig. 7 and compared with the same values obtained with the LEAT Wheeler-Cap test set-up [2]. Due to symmetry reasons, the efficiency of only one antenna by system is presented. The Wheeler Cap and reverberation chamber curves are in a very good agreement especially if comparing their maximum. The small frequency shift observed on the blue curve (dot points) is due to the fact that the antenna was slightly mechanically modified during transportation and in turn frequency detuned. The improvement given by the neutralization technique is clearly seen. The maximum total efficiency of the neutralized antennas are around -0.25 dB when the maximum total efficiencies of the initial structure are less than -1 dB.

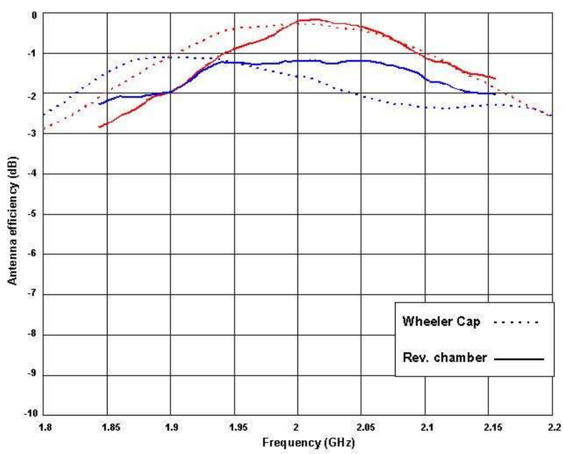


*Figure 7. Computed total efficiencies of the two-antenna structure without the neutralization line (blue) and with the neutralization line (red)*

These measurements were repeated for the neutralized four-antenna system (Fig. 8). Only the measurements of Antenna 1 and 3 are presented due to the symmetric configuration of the structure. Again, there is a very good agreement between the two measurement techniques. It is especially found that not all the PIFAs have the same maximum total efficiency values due to the fact that the $S_{ij}$ and the matching are slightly different for the top or bottom antennas. However, this neutralized antenna-system seems to be very competitive as the maximum of the total efficiencies of all the antennas are always better than -0.5 dB on the UMTS band. A four-antenna structure without any neutralization technique was also measured and exhibited maximum total efficiencies less than -1.1 dB.

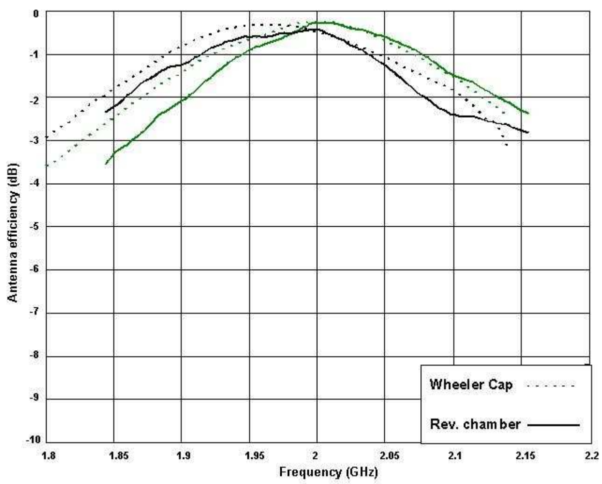


*Figure 8. Measured total efficiencies of the four-antenna structure in Reverberation Chamber and Wheeler Cap (Antenna 1=Green, Antenna 3=Black)*

## 5. MEASUREMENT OF THE ENVELOPE CORRELATION COEFFICIENTS AND THE DIVERSITY

The concept of diversity means that we make use of two or more antennas to receive a signal, and that we can combine the replicas of the received signal in a desirable way to improve the communication link. One requirement is that there must be low coupling between the antennas; otherwise the diversity gain will be lowered. To measure our antenna systems, each antenna branch is connected to a separate receiver, and the outputs of the receivers are combined in such a way that the signal-to-noise ratio S/N of the combined signal is larger than $S_1/N_1$ and $S_2/N_2$ of the signals in each branch. This is possible if the fading characteristics of signal $S_1$ and $S_2$ are uncorrelated in the two branches.

In this measurement, the correlation between the signal received by the two antennas of our prototypes (with and without the neutralization line) has been extracted and the envelope correlation coefficients are presented in Fig. 9. These coefficients are always lower than 0.15 on the whole UMTS band proving that the structures can give significant performance in terms of diversity [7]. As in [2], it is also seen that the neutralized structure provides a slightly better value than the other prototype in the whole bandwidth. It should be noted that the tendency observed in the reverberation chamber is quite the same as the one observed in [2] (see the discussion in this paper about the calculation of the correlation coefficient with the help of the S-parameters).

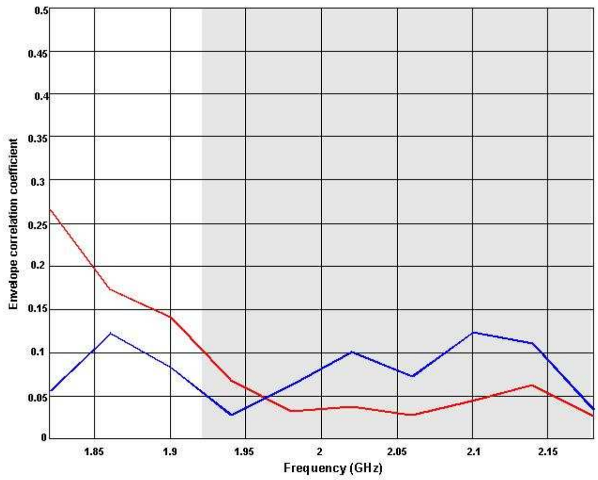


*Figure 9. Measured envelope correlation coefficients of the two-antenna systems in a reverberation chamber without the neutralization line (blue) and with the neutralization line (red)*

The envelope correlation coefficients of the neutralized four-antenna structure have also been measured in the reverberation (Fig. 11). These coefficients are always below 0.15 on the bandwidth of interest proving again the improvement of this new structure.

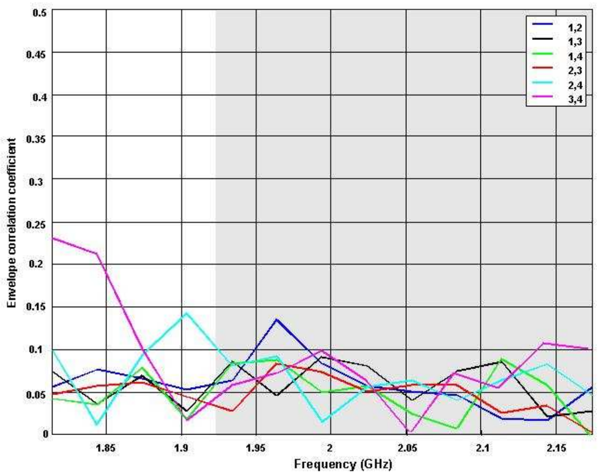


*Figure 10. Measured envelope correlation coefficients of the neutralized four-antenna system in a reverberation chamber*

The diversity gain $G_{div}$ relative to antenna 1, i.e. the apparent diversity gain, and the effective diversity gain $G_{diveff}$ , i.e. the actual diversity gain, are defined in Eq. 4 and Eq. 5 respectively.

$$G_{div} = \frac{S/N}{S_1/N_1} \quad (4)$$

$$G_{diveff} = \frac{S/N}{S_1/N_1}\eta_{tot1} \quad (5)$$

$\eta_{tot1}$ is the total efficiency of antenna 1. Note that this formula is valid only if the noise signals $N_1$ and $N_2$ are independent of the total efficiency. This is the case if the system noise is dominated by those of the receivers, or if the antenna noise temperature is the same as the surrounding temperature. The last condition is often close satisfied in mobile systems because the antenna is rather omni-directional and picks up thermal noise mainly from the environment (ground, buildings, trees, human) around the antenna, and less from the low sky temperature.

We can see in Fig.11 the power samples of each two-antenna system (without the neutralization line and with the neutralization line).

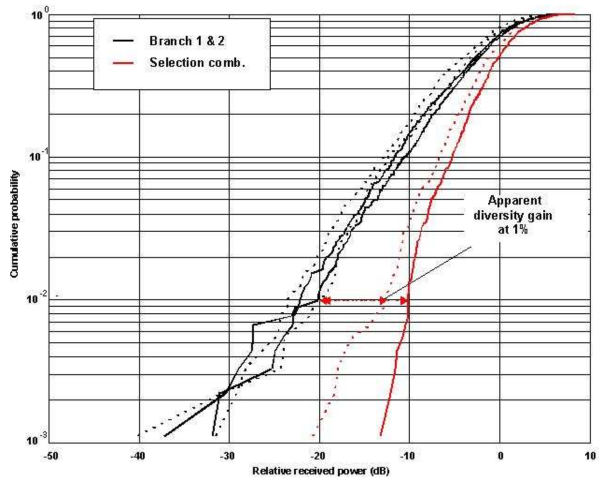


*Figure 11. Cumulative probability of the two-antenna structure without the neutralization line (dashed line) and with the neutralization line (plain line)*

On the right side, the combined power of the two-antenna element samples is plotted in red and marked as "selection comb.". The combined signal curves are steeper than the two curves of the antenna elements. For example, we also see that the power level at 1% probability is higher for the combined signal than for the antenna elements. This is the benefit of combining the two signals received by each antenna of the structure.

The diversity gain is determined by the power level improvement at a certain probability level. In Fig.11, we have chosen 1% probability. The apparent diversity gain is then the difference between the strongest antenna element curve and the combined signal curve. The power improvement is 7.6 dB for the system with low isolation and 9 dB for the system with low mutual coupling. When taking into account the total efficiencies of the antennas, we can calculate the actual diversity gain. The values are 6.3 dB for the system without the neutralization line and 8.55 dB for the other structure. These measurements have been done at the frequency point where the antennas are providing the best efficiencies. These results are consistent with other publication [8] and even slightly better due to the use of antennas with high total efficiency. The neutralization technique is giving a good improvement in terms of diversity gain. We should also notice that the apparent diversity gain and the actual diversity gain are not so different in this case due to radiators with high total efficiency [9].

The apparent gain of the neutralized four-antenna structure has also been measured (Fig. 12). Only the branches 1 and 3 are presented due to symmetry reasons. The apparent diversity gain is 16.9 dB. When the total efficiencies are taken into account, the actual diversity gain is just slightly lower: 16.7 dB. A four-antenna system without any neutralization device was also tested: 12.8 dB for the apparent diversity gain and 11.9 dB for the actual diversity gain.

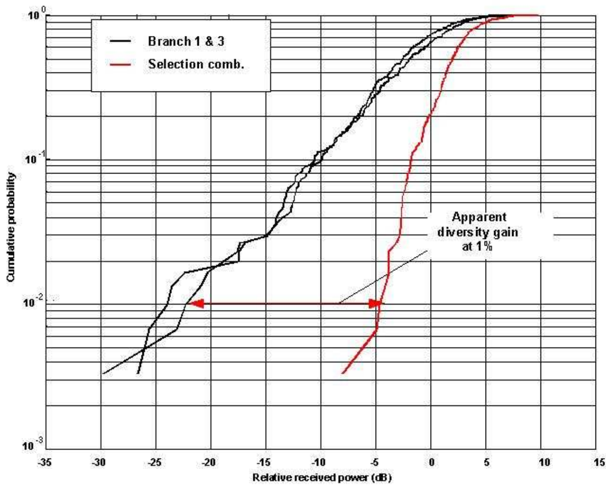


*Figure 12. Cumulative probability of the neutralized four-antenna structure*

As expected, the neutralization technique is giving a strong improvement in terms of diversity gain. We can also notice that the diversity gain increases with the number of the antenna elements of the system.

## 6. CONCLUSION

In this paper, we have presented several two-antenna structures with low and high isolation for diversity purposes. The reverberation chamber measurements at Chalmers University of Technology showed that even if the envelope correlation coefficients of these systems are very low, having low mutual coupling and high isolation will provide improvement in the total efficiency and then the actual diversity gain of the system. The same conclusions have been drawn from the measurements of several four-antenna structures with and without the neutralization technique. It was also confirmed that increasing the number of elements of a multi-antenna system will also increase the diversity gain and further more if the radiators are highly isolated. Next studies will concentrate on the effect of the neutralization technique when the antenna-systems are operating next a phantom head.

## 7. ACKNOWLEDGMENT


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## 8. REFERENCES


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