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Advances in Diversity Performance Analysis of Mobile Terminal Antennas

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I. INTRODUCTION

The performance of mobile communication systems can greatly be enhanced by utilizing diversity reception in the mobile terminal end [1-2]. Diversity improvement, however, depends strongly on the radio propagation environment. This makes the design of diversity configurations for mobile terminals challenging. A fast and reliable evaluation method is needed already in the early simulation phase of the design process. Such a method was used in [3] and later validated in [4]. It is based on the measured channel impulse responses and on the simulated or measured complex 3-D radiation patterns of a multi-element antenna arrangement. First, the arrival angles and powers of the incident signals are extracted from the channel data, and after that combined with the radiation pattern data. The presented tool proved to be a reliable method for evaluating the performance of diversity configurations [4]. The goal of this study is to identify the characteristics of a diversity configuration and of the radio channel that are relevant for the obtained diversity performance. Four mobile terminal diversity configurations are analyzed with the method of [4] in eight environments. A new measure of quality for diversity configurations is introduced. Last, conclusion about the causal connections between the diversity configuration's performance, its radiation pattern characteristics and the radio channel are given.

II. EVALUATED DIVERSITY CONFIGURATIONS

During the work, four diversity configurations (A1 – A4) for mobile terminals were evaluated in different environments. The diversity configurations were designed with the Method of Moment simulator, IE3D (by Zeland, Inc.). The geometries of A1 and A3 are presented in Fig. 1. They consist of two separate, nearly square-shaped PIFAs. Configuration A2 is similar to A3, except that in A2 the short circuits and feed pins are located at the corners of the ground plane. Configuration A4 is a more realistic mobile terminal diversity arrangement. The ground plane length in all cases was 100 mm.

The radiation patterns obtained with IE3D were used to predict the performance of A1 – A4 in free-space. Diversity configurations A3 and A4 were further analyzed with XFDTD (by Remcom, Inc.) in talk position beside human head and hand models (denoted by "HH"). The simulated free-space 3-D radiation patterns for A1, A3 and A4 are presented in Fig. 2. Also polarization ellipses obtained from the complex 3-D radiation patterns are plotted [5]. The radiation pattern of A2 is similar to that of A3 and is therefore not presented separately. In all free-space cases, the antenna models were aligned on the standard spherical co-ordinate system according to Fig. 1. (a). In XFDTD simulations, the diversity configurations were located on the right side of the head model, with the nose pointing towards the positive x-axis. The simulation frequency in all cases was 2.154 GHz. The simulated total efficiencies of A1 – A4 are presented in Table 1. The mutual coupling between the diversity elements of A2 was rather large. Therefore, its total efficiency is clearly smaller than that of the other free-space cases.

III. EVALUATED ENVIRONMENTS

In total eight routes were selected from the radio channel library of Helsinki University of Technology (HUT) to evaluate the performance of A1 – A4. The channel library is based on routes measured at 2.154 GHz with the spherical radio channel sounder system documented in [6]. The eight selected routes were grouped into four distinct environment classes: Indoor Picocell, Microcell, Macrocell and Highway Macrocell.

In all routes, the transmitter antenna was vertically polarized. For the class Indoor Picocell, one route measured inside the Computer Science building of HUT was chosen. For the class Microcell, three routes from downtown Helsinki were selected. The transmitter antenna was located 8 m above the street level. For the class Macrocell, three routes from downtown Helsinki were selected. The transmitter antenna was located at the rooftop of a parking house. In the Highway Macrocell class, the receiver was located in a car moving along a highway during high traffic. The transmitter antenna location was macrocellular, i.e. ~17 meters above the ground level, on the roof edge of a building. Fig. 3 presents as an example the elevation power distribution and the total incident theta- and phi-polarized powers in one of the evaluated macrocell routes.

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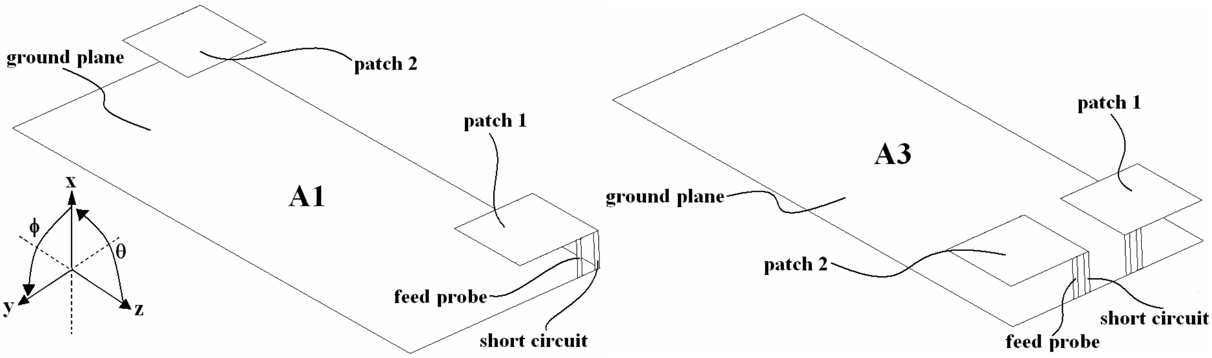


Figure 1. Geometries of diversity configurations A1 and A3.

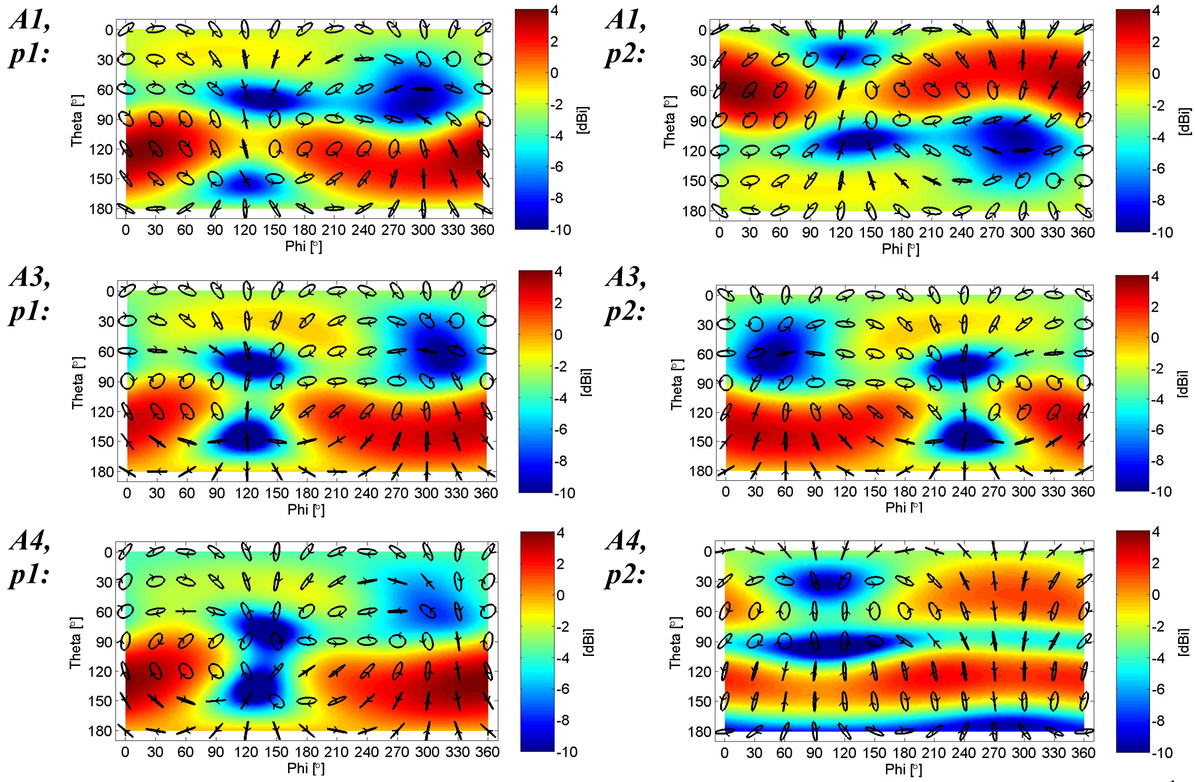
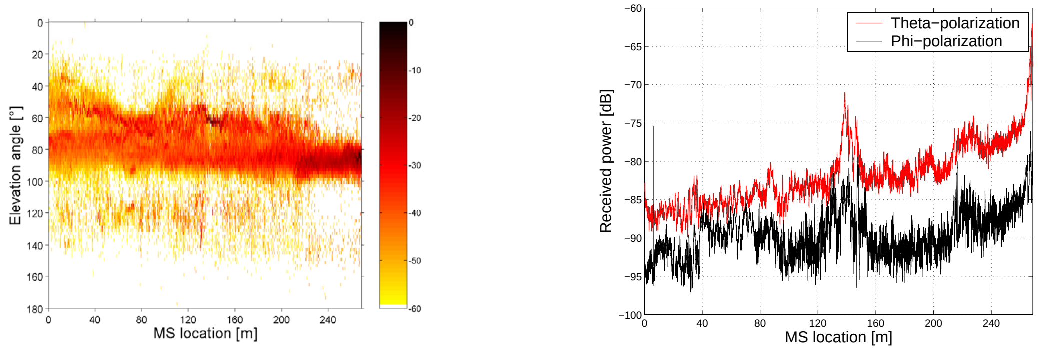


Figure 2. 3-D radiation patterns and polarization ellipses for A1, A3 and A4 (p1=port1 & p2=port2)[1].



(a) (b)

Figure 3. (a) Elevation power distribution and (b) total incident theta- and phi-polarized powers in one of the evaluated macrocell routes.

TABLE I. SIMULATED TOTAL EFFICIENCIES OF THE EVALUATED DIVERSITY CONFIGURATIONS.

	A1	A2	A3	A4	A3HH	A4HH
Total efficiency (port1/port2) [%]:	79/79	64/64	73/73	77/73	36/31	43/21

[1]*The visualization software by courtesy of Jussi Rahola (NRC/Finland)*

IV. EVALUATION METHODS

To simulate the random azimuth orientation of a mobile terminal, each diversity configuration was "driven" through each environment in five different azimuth positions (72 degree steps). The received signals of the five cases were then inserted one after the other, as if they represented just one route. After that, maximal ratio combining (MRC) was used to combine the signals of the diversity branches. In order to remove the slow fading from the received signal in a specific route, the power received by a computational isotropic radiator was used as the normalization vector. The normalization vector was averaged with a sliding window with the length of about 2.8 m. Envelope correlation was calculated from the received signals according to [1]. In addition, branch power difference was calculated as the absolute value of the difference between the average received powers of the diversity branches.

In this work, two different figures of merits were used to evaluate the performance of diversity configurations – diversity gain (G_{div}) and so-called *MRC MEG*. Diversity gains have been calculated as the difference between the stronger diversity branch and the MRC power at the level that 90% of the signals exceed. The new figure of merit for diversity configurations, *MRC MEG*, is determined as the MRC signal level that 50% of the signals exceed [see Fig. 4. (a)]. Thus, *MRC MEG* can be interpreted in two different ways. On one hand, it can be seen as the median difference between the MRC power and the power received by an isotropic antenna (P_{isotr}). On the other hand, it can be seen as the combined *MEG* (Mean Effective Gain) of the two diversity branches.

V. RESULTS

The diversity gain and *MRC MEG* results for the evaluated diversity configurations in all eight environments are presented in Fig. 4. (b-c). For each configuration, a group of eight bars is plotted. Each small bar represents the diversity gain or *MRC MEG* result in one environment. Blue lines with circles present the average diversity gains and *MRC MEG*s for the evaluated antennas. Fig. 4. (d) presents the diversity gain results of each diversity configuration in all evaluated routes as a function of branch power difference. Also the effect of envelope correlation is included by grouping the results according to the envelope correlations into three distinct groups marked with different colors.

Traditionally, diversity gain has been calculated as the difference between the MRC power and the stronger branch power. Thus, the smaller the branch power difference between the diversity branches is, the larger is the MRC power and the larger becomes the diversity gain. The strong effect of branch power difference on diversity gain can be seen clearly from Fig. 4. (d). For example, for the results marked with red color, the diversity gain decreases almost linearly from about 6.5 dB to 4.3 dB as the

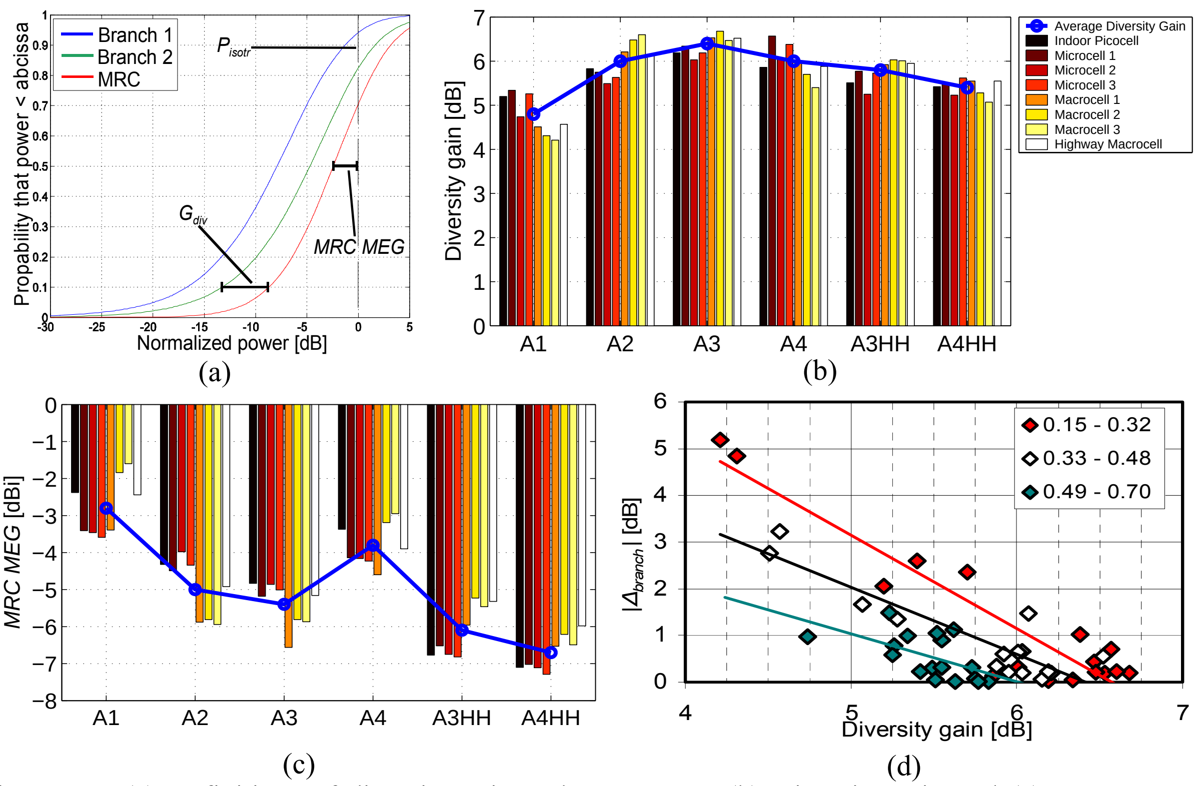


Figure 4. (a) Definitions of diversity gain and *MRC MEG* (b) Diversity gain and (c) *MRC MEG* results for diversity configurations A1 – A4 (d) Diversity gain vs. branch power difference vs. envelope correlation. The solid lines represent linear fitting for the results within each group.

branch power difference increases from 0 dB to about 5 dB. Thus, the effect of branch power difference on diversity gain can be over 2 dB if the envelope correlation is kept almost constant. Similar behavior can be observed also for the results marked with white and green colors. Branch power difference, however, does not explain all the performance differences between the diversity configurations.

As can be expected, the envelope correlation affects the diversity gain of the studied prototypes [see Fig. 4. (d)]. This can be noticed especially at the lower region of Fig. 4. (d), where the branch power difference is between 0 – 1 dB. Different colors are clearly clustered so that the higher envelope correlations (green color) are on the left and lower envelope correlations are on the right (red color). The difference between the red and green clusters seems to be in average 1 dB, which is clearly less than the maximum effect of branch power difference (over 2 dB, as described earlier). From the free-space cases, A4 has clearly the smallest envelope correlations (not shown in Fig. 4.) – in six out of eight routes it falls into the red group in Fig. 4. (d). The envelope correlations of A1, A2 and A3 are more distributed between the three groups.

As shown in Fig. 3. (a), major part of the incident signal power arrives from the directions somewhat above the azimuth plane. Actually, that is the case in most of the evaluated routes – especially at the macrocell routes in which the transmitter antenna is located at the rooftop level. From the free-space cases, A1 and A4 perform clearly the best in terms of *MRC MEG*. From Fig. 2 it can be noticed that A1 and A4 both have a main lobe pointing above the azimuth plane, where most of the incident signal power is coming from. In contrast, the main lobes of both diversity branches of A2 and A3 are pointing towards the ground, for which reason they receive less power than A1 and A4. Only when located beside head and hand, A3 seems to have slightly larger *MRC MEG* than A4. The likely reason for that is the very low total efficiency (21 %, see Table 1) of the branch 2 of A4HH.

Since branch 1 of A1 receives much less power than branch 2, the branch power difference of A1 becomes very large. For the same reason, the branch power difference of A4 is large compared with those of A2 and A3. As described earlier in this section, large branch power difference causes low diversity gain. Therefore, A1 has the lowest diversity gain of the free-space cases [see Fig. 4 (b)], although it was the best diversity configuration in terms of *MRC MEG*. Based on branch power difference, low diversity gain would also be expected for A4. The rather low envelope correlation of A4 in most environments, however, compensates the effect of the large branch power differences.

VI. CONCLUSIONS

Four diversity configurations for mobile terminals were analyzed with a novel method in eight selected routes. To obtain the received signals, the simulated complex 3-D radiation patterns of the diversity configurations were combined with the directions of arrivals estimates of the incident signals in the evaluated routes. A new measure of quality for diversity configurations, called *MRC MEG*, was introduced. Together with diversity gain, it was used to identify the characteristics of a diversity configuration and of the radio channel that are relevant for the obtained diversity performance. Branch power difference was shown to be the main contributor on the diversity gain of the studied prototypes. In addition, envelope correlation affected the diversity gain, although the effect was smaller than the one of branch power difference. The diversity configurations with a main lobe pointing in the direction where most of the incident signal power is coming from, performed the best in terms of *MRC MEG*. As an interesting observation, the diversity configuration with the lowest diversity gain received on average over 2.5 dB more power than the configuration with the largest diversity gain. In diversity configuration performance point of view, the total received power is the most important measure of quality. Therefore, the *MRC MEG* can be considered to be a more reliable tool than diversity gain for predicting the performance of multi-antenna terminals.

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