Radio channel measurement based evaluation method of mobile terminal diversity antennas

S-72.333, Postgraduate Course in Radio Communications

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2. Introduction

- The performance of diversity reception in the mobile terminal end strongly depends on the characteristics of radio propagation environment. Measurements in real propagation environments with prototype antennas are needed.
- A Plane–Wave Based Method (PWBM) is implemented to enhance and speed up the design and evaluation process of new mobile terminal diversity and MIMO antenna configurations.

- Objects of the study:

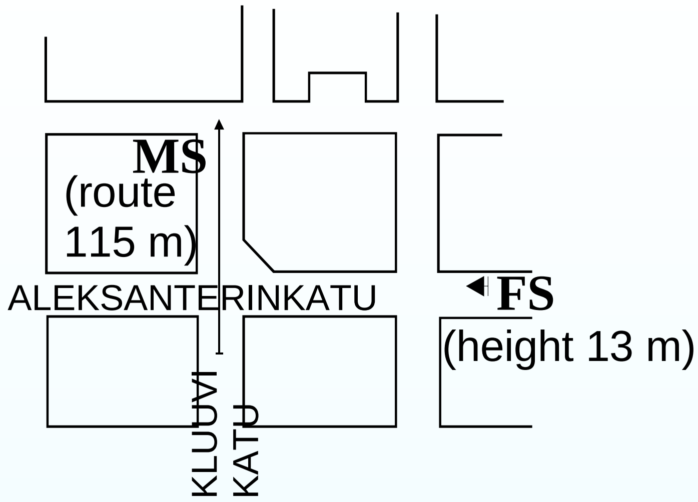
1. To validate the performance and usability of PWBM by analyzing the diversity and MIMO performance of several antenna configurations in several environments with two methods (PWBM and DM).
2. To clarify the characteristics of diversity configurations and radio channels that are relevant for the obtained diversity performance.

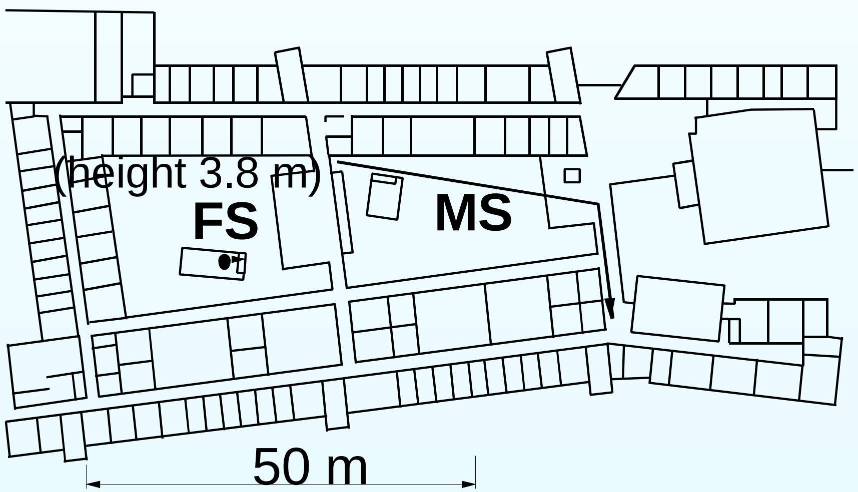
3. Channel Measurement Setup

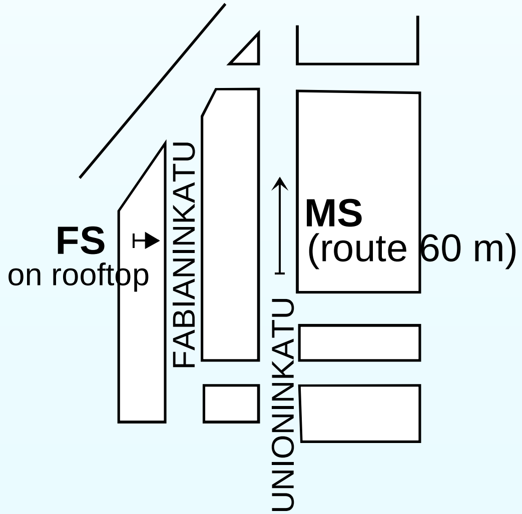
- The transmitting (Tx) antenna system consisted of a linear antenna array with dual–polarized patch antennas.
- The receiving (Rx) antenna system consisted of a spherical antenna array with 32 dual–polarized patch antennas [64 feeds, see the Figure].
- The Tx and Rx antenna arrays were connected to a fixed transmitter and to a wideband radio channel sounder, respectively.
- The complex impulse response of each feed was measured using a fast 64-channel RF switching unit (approximately 5 samples/wavelength).

3. Channel Measurement Setup (cont.)

- The signals measured in three distinctive propagation environments were analyzed using two approaches (DM, PWBM).
  - o Indoor picocell
  - o Outdoor microcell
  - o Small outdoor macrocell

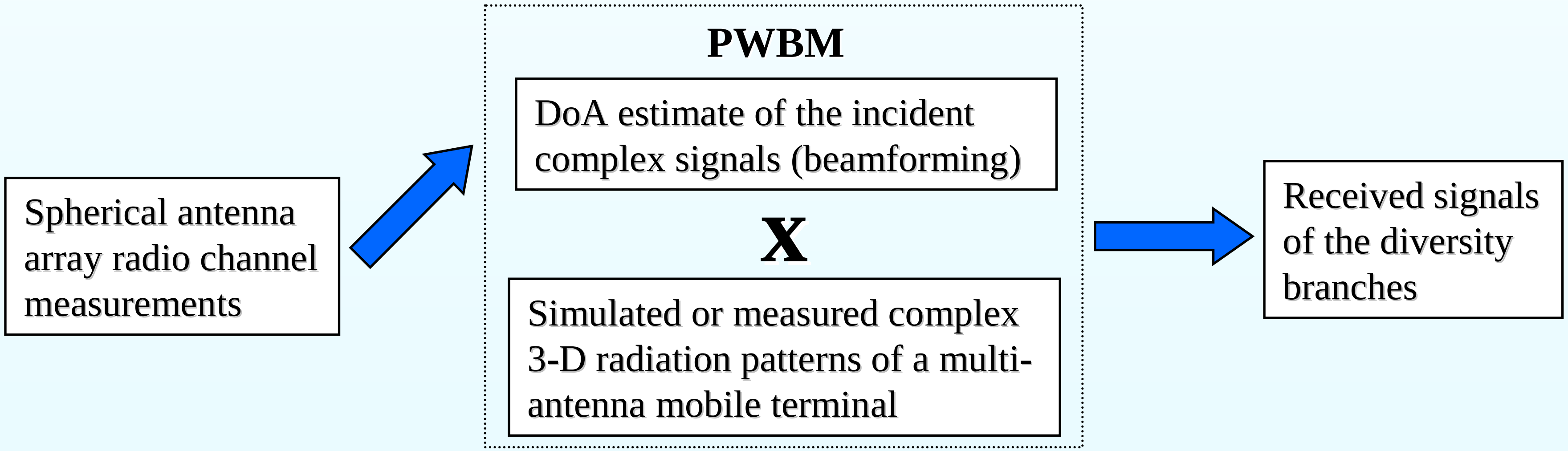






4. PWBM and DM (Direct Measurement)

- The **<u>Plane–Wave Based Method (PWBM)</u>** is based on the previously measured channel impulse responses in some specific environment and on the simulated or measured complex 3-D radiation patterns of a diversity configuration.
- Beamforming algorithm is used to compute the estimate of the direction of arrival (DOA) distribution of the incident signals in the mobile terminal end.



4. PWBM and DM (Direct Measurement)

- The radiation pattern of an antenna can be defined as:

$$\overline{E}(\Omega) = E_\theta(\Omega)\overline{a}_\theta(\Omega) + E_\phi(\Omega)\overline{a}_\phi(\Omega)$$

- The electric field of the incident plane wave is defined as:

$$\overline{A}(\Omega) = A_\theta(\Omega)\overline{a}_\theta(\Omega) + A_\phi(\Omega)\overline{a}_\phi(\Omega)$$

- The complex signal envelope at the antenna port is then:

$$V(t) = \oint \overline{E}(\Omega, t) \cdot \overline{A}(\Omega, t) d\Omega$$

- During the validation analysis of PWBM, the measured 3-D radiation patterns of the spherical antenna array antenna elements were used to compute the received signals in the selected environments.
- Several different Rx antenna combinations were analyzed.

4. PWBM and DM (Direct Measurement)

- In order to validate the reliability of PWBM, the received signals in the selected environments were also directly calculated (DM) from the impulse responses measured with the channel sounder system.
- In the **<u>direct measurement (DM)</u>,** the same Rx antenna elements (feeds) were selected from the spherical antenna array as in the PWBM-analysis.
- Ideally, DM and PWBM should lead into the same result.

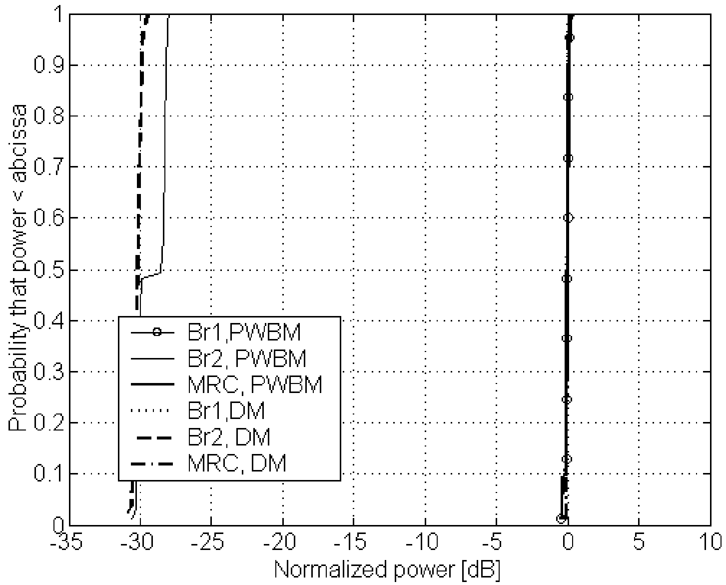
5.1. Diversity Analysis

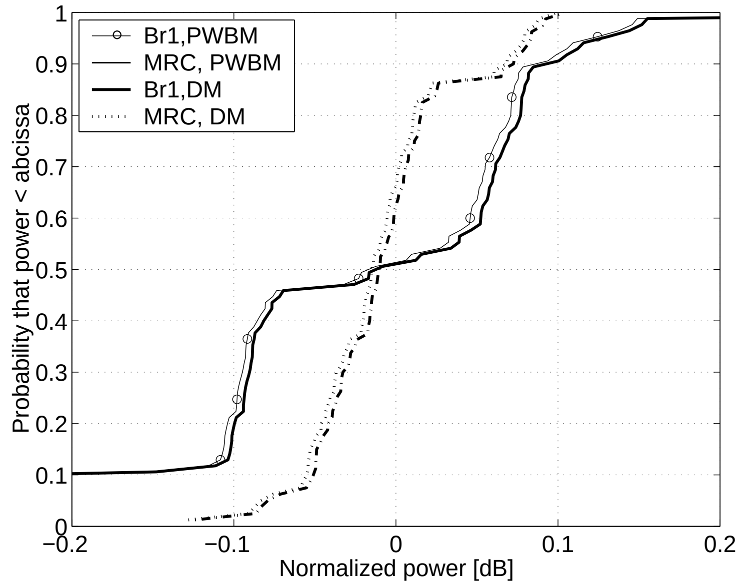
- Diversity gain was used as a figure of merit for comparing the results of PWBM and DM.
- Two different Rx diversity arrangements were considered:
  1) The vertically and horizontally polarized feeds from a single spherical array antenna element were selected as the diversity branches. The transmitter polarization was vertical.

  2) The vertically polarized feeds from two different spherical array antenna elements were selected as the diversity branches. The transmitter polarization was vertical.
- The powers received by the diversity branches were normalized to the sliding average (100 samples normalization distance) of the sum of the powers received by the diversity branches.

5.1. Diversity Analysis (cont.)

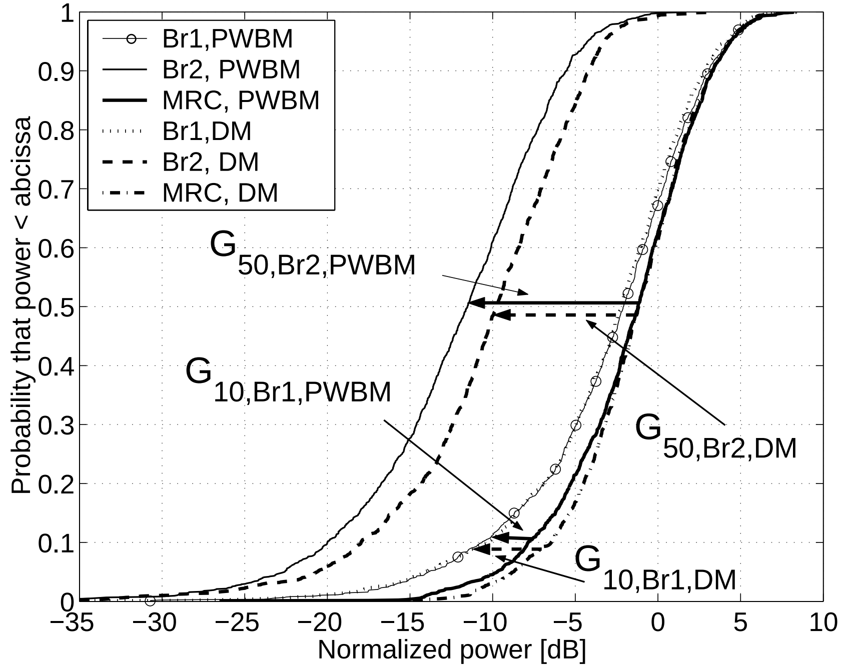
- As a first validation, PWBM and DM were compared in an anechoic chamber.
  - o The horizontally and vertically polarized branches of a single element from the spherical antenna array were selected as the Rx antenna configuration.
  - o The Tx antenna and the selected spherical array Rx antenna element were directly pointing against each other.
- PWBM agrees well with the direct measurement.





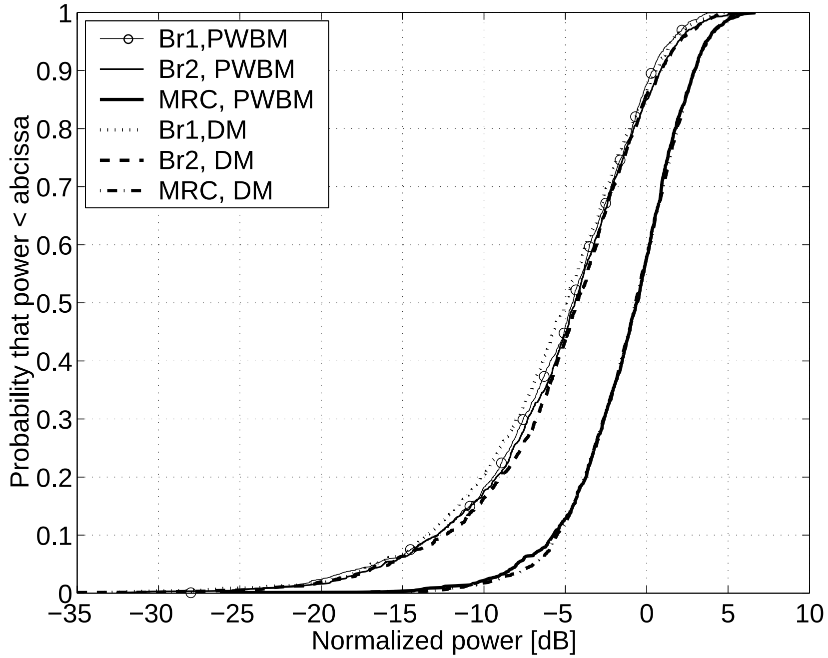
5.1. Diversity Analysis (cont.)

- Polarization diversity arrangement
- The vertically and horizontally polarized feeds from a single spherical array antenna element were selected as the diversity branches.
- Macrocell environment
- Good enough agreement between PWBM and DM



5.1. Diversity Analysis (cont.)

- Space–diversity arrangement.
- The vertically polarized feeds from two different spherical array antenna elements were selected as the diversity branches.
- Macrocell environment.
- Very good agreement between the two methods.



5.2. MIMO Analysis

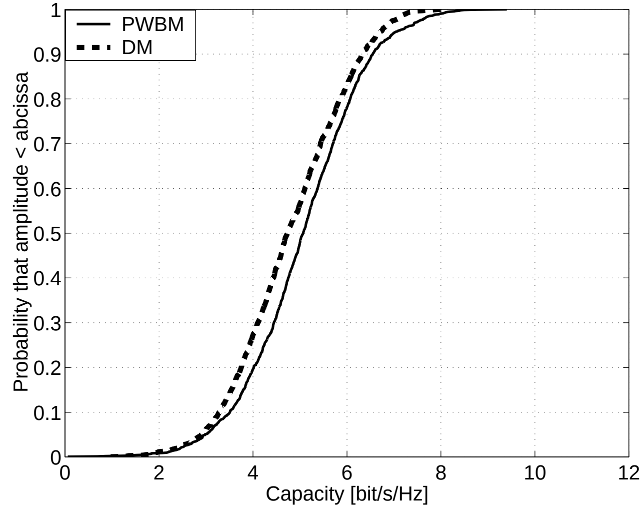
- The capacity and the eigenvalues of normalized channel correlation matrix were used as figures of merit in the MIMO analysis.

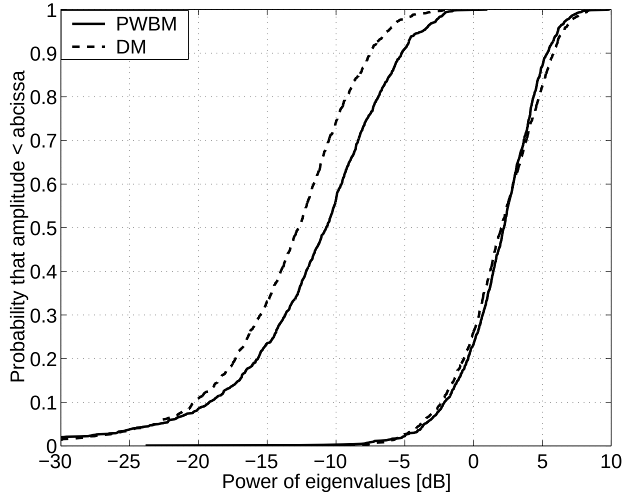
$$C = \log_2 \left[\det \left(I + \frac{\rho}{n_t} \overline{R}_{norm} \right) \right]$$

$$\overline{R}_{norm} = \frac{\overline{H}^H \overline{H}}{\frac{1}{n_t n_r} E\left\{ \sum_{t=1}^{n_t} \sum_{r=1}^{n_r} H^*_{r,t} H_{r,t} \right\}}$$

5.2. MIMO Analysis (cont.)

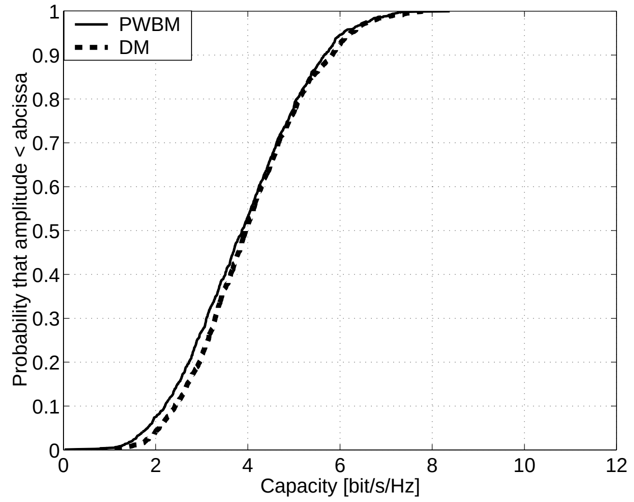
- MIMO configuration: two vertically polarized feeds from adjacent elements selected at both ends of the link.
  - o The distributions (cdfs) of the capacity and eigenvalues are presented in the Figures.
- Small macrocell environment.
- The largest difference between the methods in the case of weaker eigenvalue – minor difference in capacity.

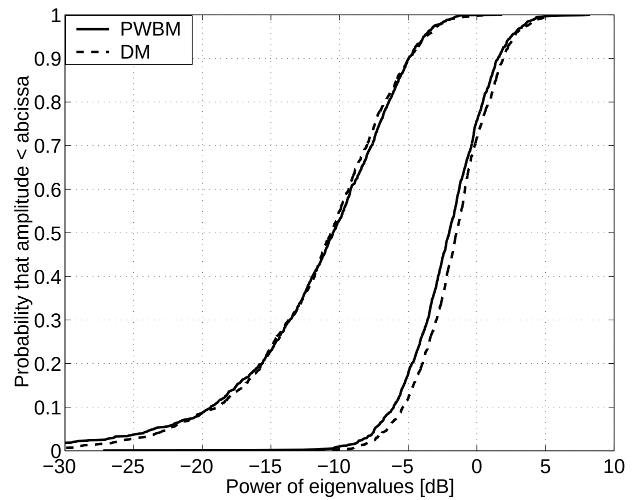




5.2. MIMO Analysis (cont.)

- MIMO configuration: horizontally and vertically polarized feeds from adjacent elements selected at both ends of the link.
  - o The distributions (cdfs) of the capacity and eigenvalues are presented in the Figures.
- Small macrocell environment.
- Almost perfect matching between the methods.

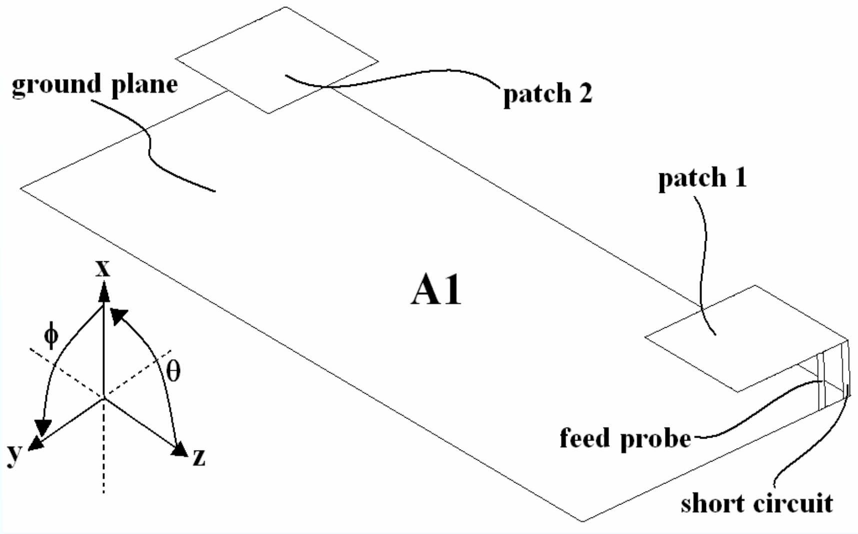


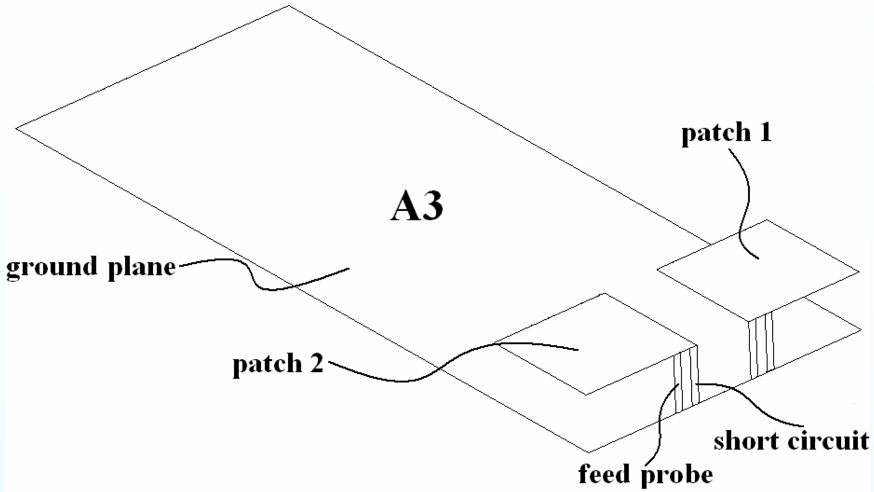


6. Mobile Terminal Antenna Evaluation

- According to the presented results, PWBM can be considered to be a reliable method for evaluating the diversity and MIMO performance of different antenna configurations.
- The next step was to use PWBM to evaluate the diversity performance of multi-antenna mobile terminals.
- In total four different diversity configurations were analyzed.
- In order to get statistically reliable results, each antenna configuration was analyzed in eight different environments.

7. Evaluated Diversity Configurations



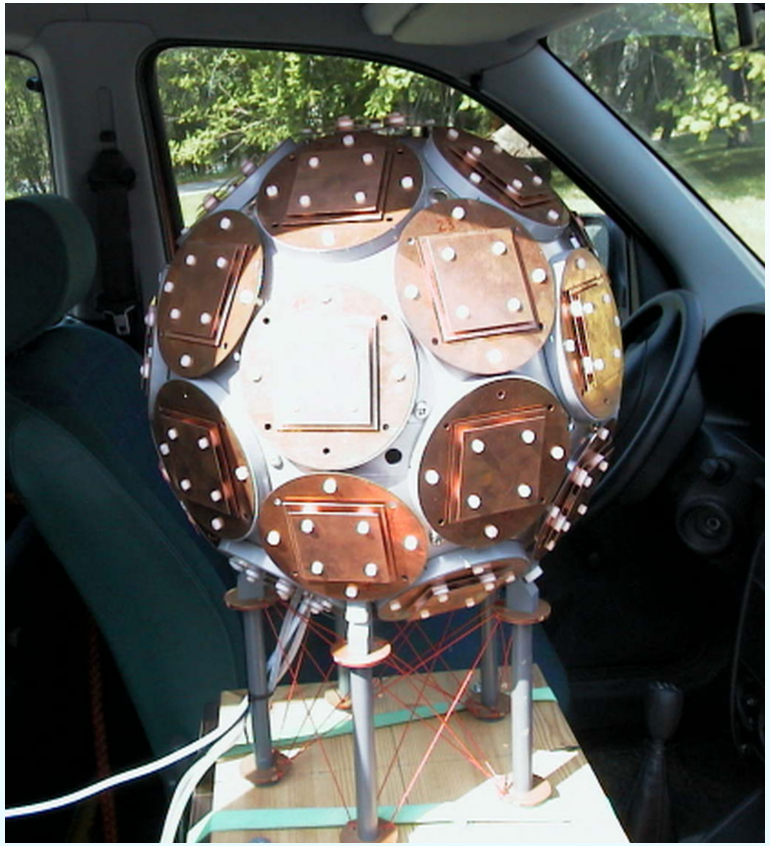


- A2 is otherwise similar to A3, except that in A2, the feed pins and short circuits are located at the corners of the ground plane
- A4 is a more realistic mobile terminal diversity configuration
- The radiation patterns obtained with IE3D were used to evaluate A1 – A4 in free-space. A3 and A4 were further analyzed with XFDTD in talk position beside human head and hand models (later denoted by ”HH”).
- The antennas were designed to work in the UMTS band.

8. Enviroments Used in the Evaluation

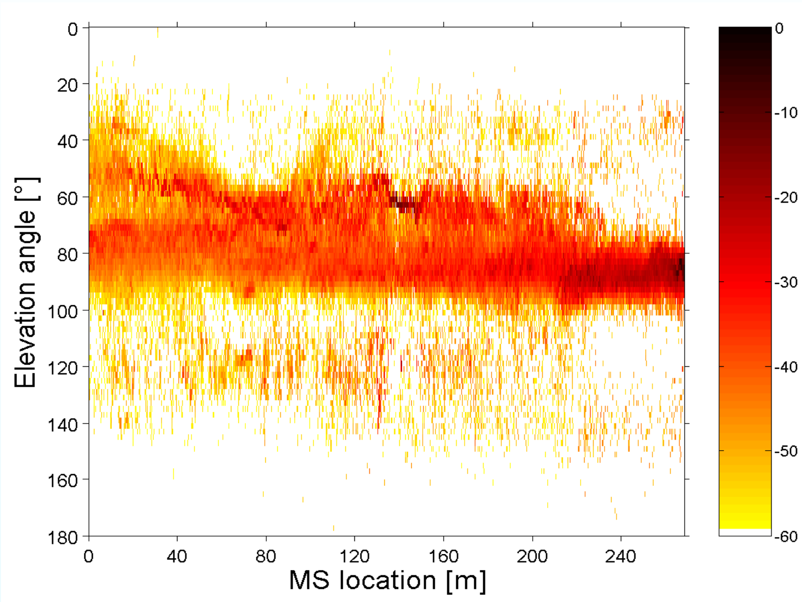
- In total eight routes were selected from the channel library of Helsinki University of Technology (HUT) to evaluate the performance of A1 – A4. The routes were grouped into four environment classes:

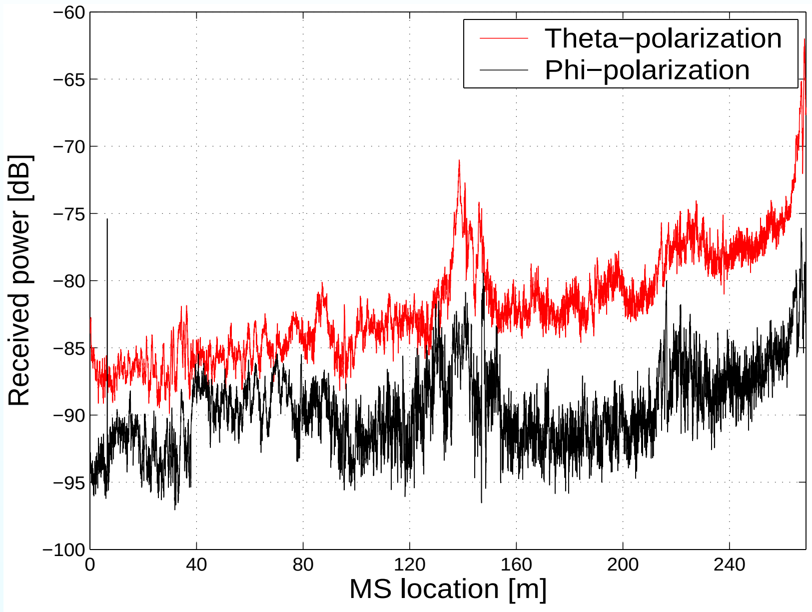
1. *Indoor Picocell*: One route inside the Computer Science Building of HUT.
2. *Microcell*: Three routes from downtown Helsinki. Transmitter antenna located 8 m above the street level.
3. *Macrocell*: Three routes from downtown Helsinki. Transmitter antenna located at the rooftop of a parking house.
4. *Highway Macrocell*: Reveiver located in a car moving along a highway. Transmitter antenna 17 m above the ground level.



8. Enviroments used in the evaluation (cont.)

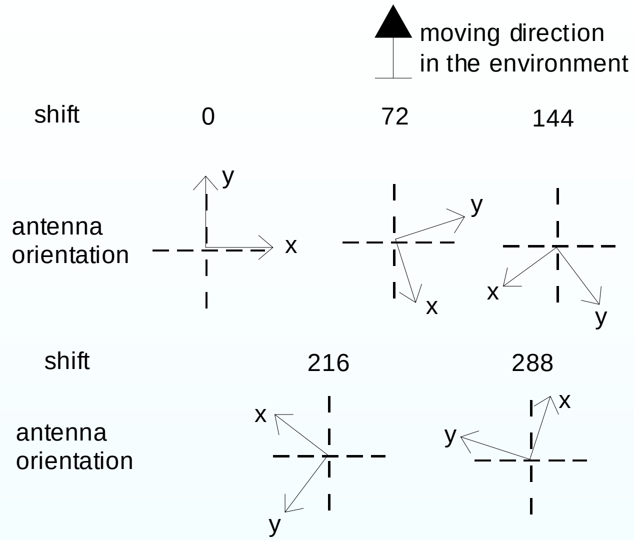
- Elevation power distribution and total incident theta- and phi-polarized powers in one of the evaluated macrocell routes (transmitter at the rooftop level):





- Major part of the incident signal power arrives from the directions somewhat above the azimuth plane!! True especially at the macrocell routes.

9. Antenna evaluation methods



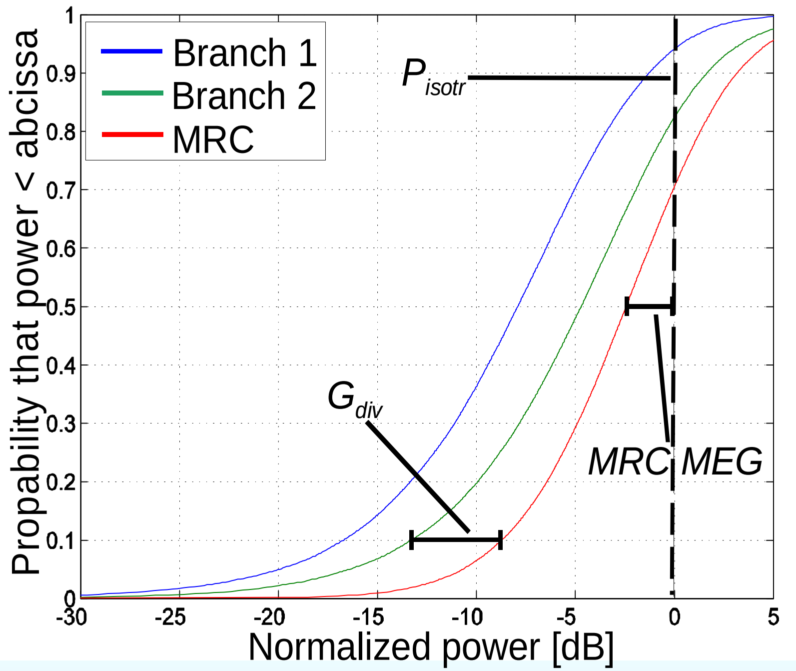
- To simulate the random azimuth orientation of a mobile terminal, each diversity configuration was ”driven” through each environment in 5 different azimuth positions:
- In order to remove slow fading, the power received by a computational isotropic radiator was used as a normalization vector. The used sliding window normalization distance was 100 samples (in most cases about 2.8 m).
- Maximum Ratio Combining (MRC) was used to combine the signals received by the diversity branches.
- Branch power difference was calculated as the absolute value of the difference between the average receiver powers of the diversity branches.
- Envelope correlation was calculated according to the well-known definition.

9. Antenna evaluation methods (cont.)

- Two figures of merits were used to evaluate the performance of the diversity configurations:

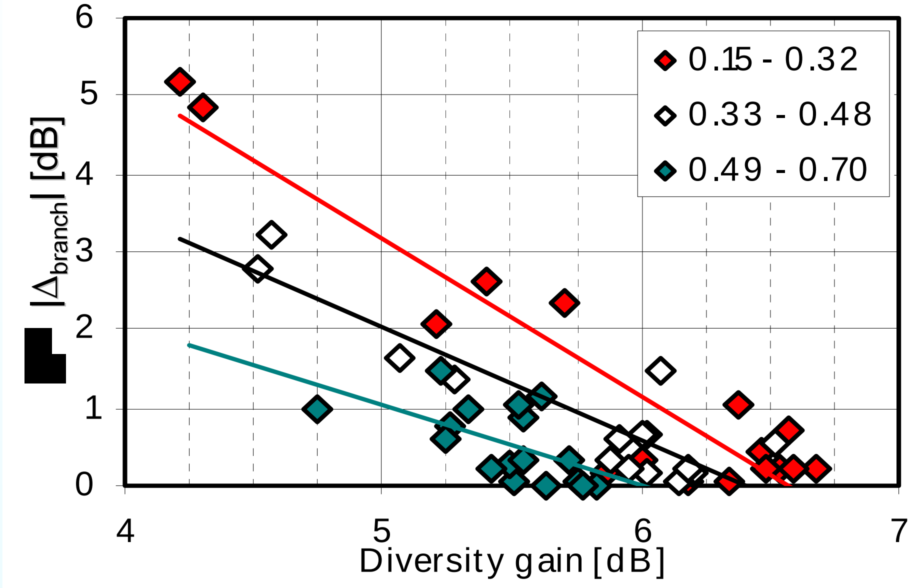
o ***Diversity gain***: The traditional measure of quality. Calculated as the difference between the MRC power and the stronger branch power at the level that 90 % of the signals exceed. Strongly affected by branch power difference and envelope correlation (according to theory).

o ***MRC MEG***: A new measure of quality. Determined from the MRC signal level that 50 % of the signals exceed. Indicates the median difference between the MRC power and the power received by a lossless isotropic radiator (P_{isotr}).



10. Results

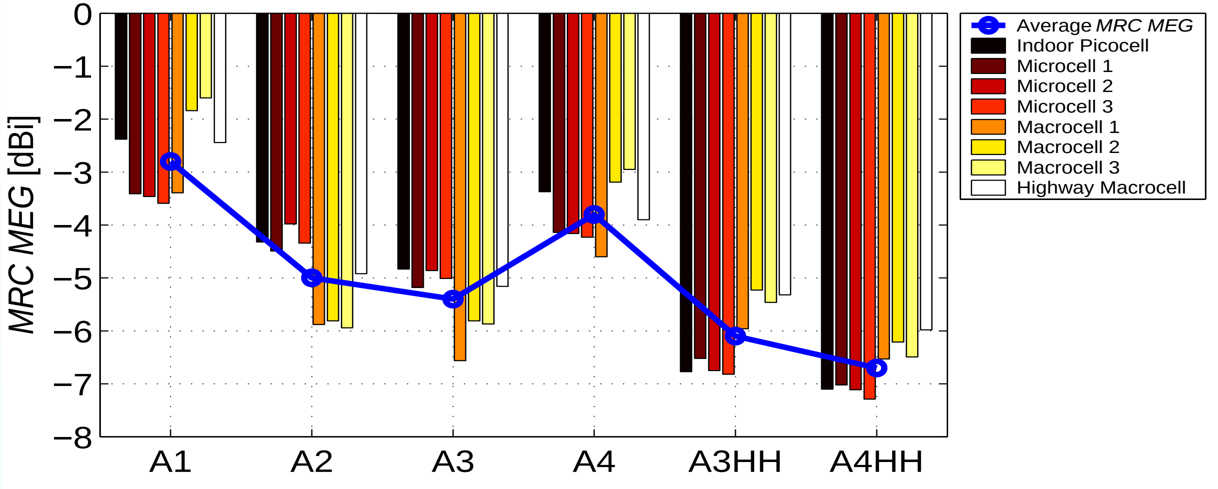
- Diversity gain vs. branch power difference vs. envelope correlation. Each diamond represents one diversity configuration in one enviroment. Results are grouped in 3 groupes according to the envelope correlation levels.



- The strong effect of $|\Delta_{branch}|$ on diversity gain can clearly be seen (over 2 dB decrease in diversity gain when $|\Delta_{branch}|$ increases from 0 to 5 dB (red group)).
- As expected, also envelope correlation affects diversity gain. Different colors are clearly clustered, especially at the region where $|\Delta_{branch}|$ is below 1 dB.

10. Results (cont.)

- *MRC MEG* results for the evaluated diversity configurations in all eight environments. Blue circles present the average *MRC MEG*s.

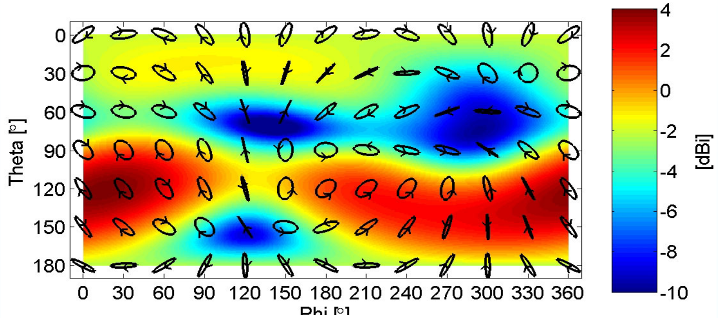


	A1	A2	A3	A4	A3HH	A4HH
Total efficiency (port1/port2) [%]:	79/79	64/64	73/73	77/73	36/31	43/21

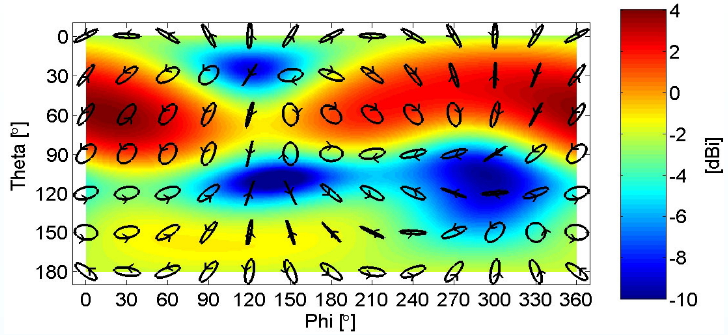
- The *MRC MEG*s for A3HH and A4HH are very low due to the very low total efficiencies of the diversity configurations when located beside head and hand:
- A1 and A4 perform clearly the best from the free-space cases. **WHY??**

10. Results (cont.)

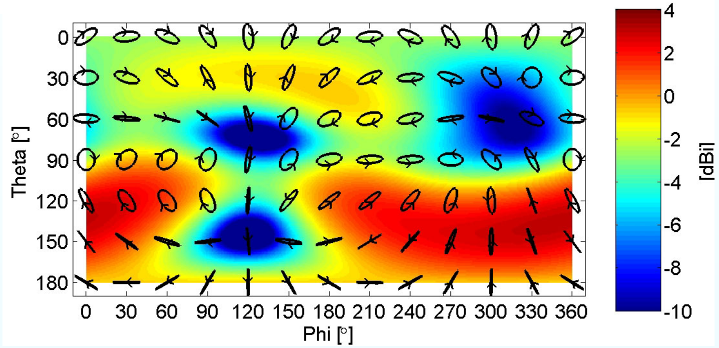
A1,p1:



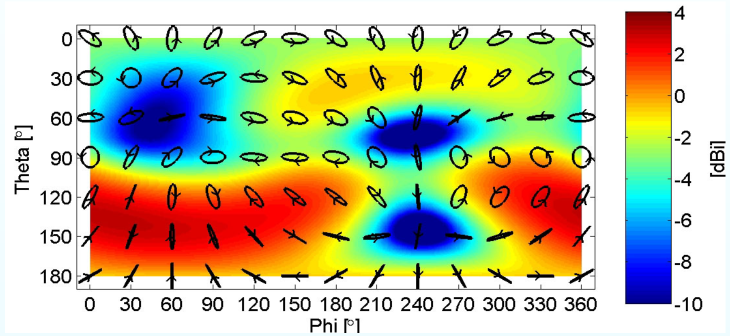
A1,p2:



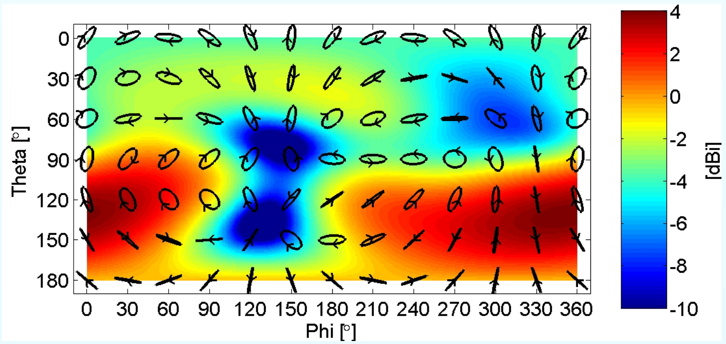
A3,p1:



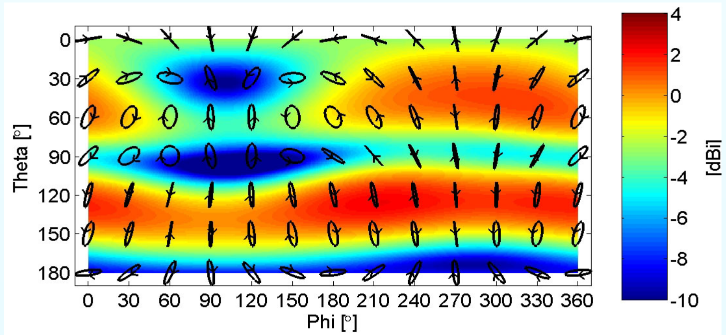
A3,p2:



A4,p1:

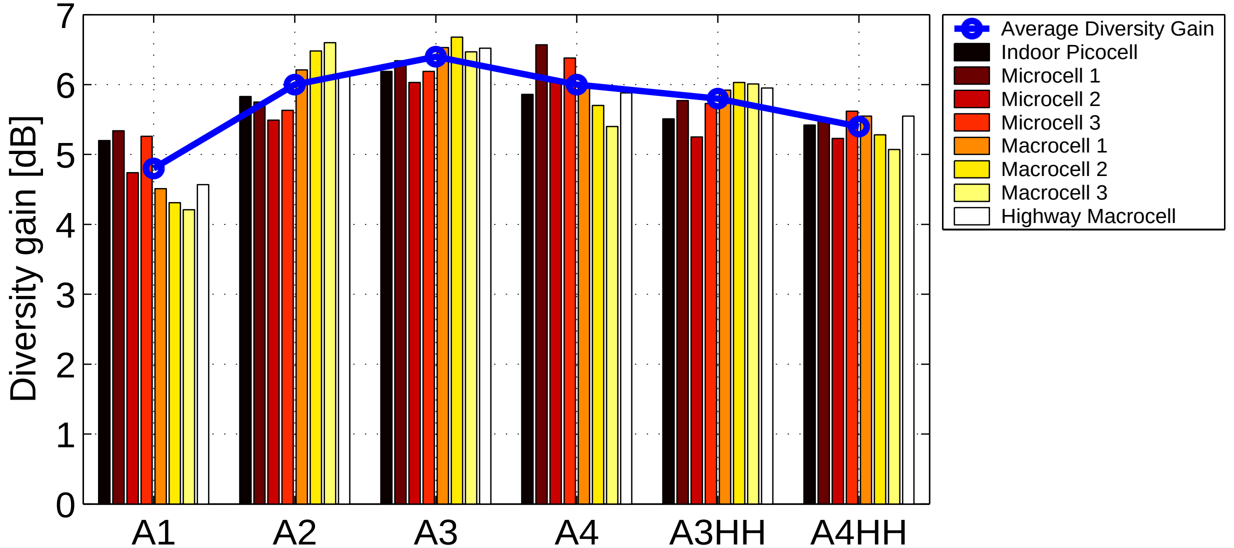


A4,p2:



10. Results (cont.)

- Diversity gain results for the evaluated diversity configurations in all eight environments. Blue circles present the average diversity gains.



- Now, A1 and A4 perform the worst of the free-space cases!
- Since branch 1 of A1 receives much less power than branch 2, the branch power difference of A1 becomes very large. Therefore, A1 has the lowest diversity gain of the free-space cases although it was the best diversity configuration in terms of *MRC MEG*.

11. Discussion and Conclusions

- BWBM
  - o Fast to test antennas (+)
  - o Radiation patterns of antennas can be rotated easily (+)
  - o Antennas can be tested based on the simulated radiation patterns (+)
  - o The radio channel stays exactly the same for all antenna configurations under test (+)
  - o The physical limitations of the beamforming algorithm to estimate details of the scattering field (-)
- DM
  - o More accurate to test antennas (+)
  - o Much work is needed (-)
  - o Prototype antennas have to be constructed for each evaluation (-)
- In the future:
  - o More advanced (accurate) channel estimation algorithm should be implemented/tested

11. Discussion and Conclusions

- A new measure of quality for diversity configurations, called *MRC MEG*, was introduced.
- Branch power difference was shown to be the main contributor on diversity gain of the studied prototypes. Also, envelope correlation affected diversity gain, although the effect was smaller than the one of branch power difference.
- 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 performace point of view, the total received power is the most important measure of quality

⇒ *MRC MEG* can be considered to be a more reliable tool than diversity gain for predicting the performance of multi-antenna terminals!

- Diversity gain would better characterize the advantage of using additional diversity antenna if the original antenna would be used as a reference for calculating diversity gain!!!

References

[1] P. Suvikunnas, K. Sulonen, J. Villanen, C. Icheln and P. Vainikainen, ”Evaluation of Performance of Multi-antenna Terminals Using Two Approaches”, *IEEE IMTC2004 conference*, Como, Italy, May 2004.

[2] J. Villanen, P. Suvikunnas, C. Icheln, J. Ollikainen and P. Vainikainen, ”Advances in Diversity Performance Analysis of Mobile Terminal Antennas”, *ISAP 2004 conference*, Sendai, Japan, August 2004.

Homework

- Traditionally diversity gain has been defined as the difference between the combined signal power (e.g. MRC or EGC) and the stronger diversity branch power at some probability level.

1. What problems this kind of definition causes? Does it well describe the performance of the diversity antenna configuration?
2. How the possible problems of the traditional definition of diversity gain could be avoided?