MIMO antennas and their evaluation

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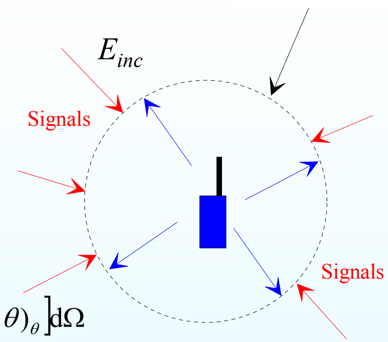
ANTENNA EVALUATION

Antenna in a multipath environment

- Normally the main beam of an antenna is directed towards the other end of the radio connection
- In mobile communications the multipath dispersion is strong especially at the mobile end
- The received signal is now:

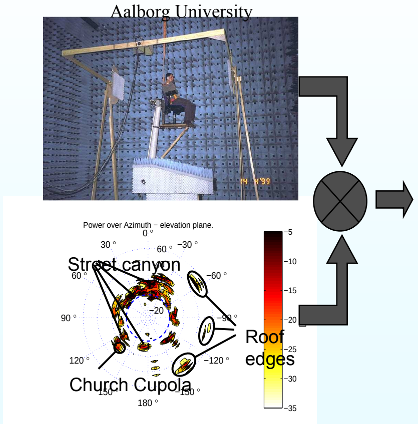


$$v_r \propto \int_\Omega \left[f(\phi,\theta)_\phi \cdot E_{inc}(\phi,\theta)_\phi + f(\phi,\theta)_\theta \cdot E_{inc}(\phi,\theta)_\theta \right] d\Omega$$

- where *f*() are the field patterns of the antenna and E_{inc} the incident field components at different polarisations

Evaluation of antennas in multipath environments

- Experimental method:
  - antenna under test (AUT) is transported in multipath environments and its received signal is recorded
  - laborous
  - requires a prototype of the AUT
- Computational method:



In front of Bank of Finland, Helsinki

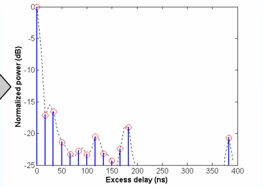
Computational evaluation

- The pattern of the antenna is normally known from measurements or simulations
- The incident fields can be obtained from
  1. statistical distributions
     – uniform, Gaussian, double-exponential
  2. propagation models
     – deterministic (e.g. ray-tracing simulations)
     – statistical: COST 259 and 273 models, 3GPP SCM, etc.
  3. measurements

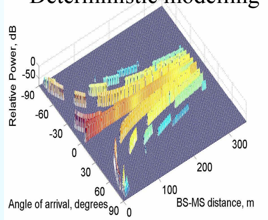
The research process at TKK SMARAD

Propagation measurements and directional analysis

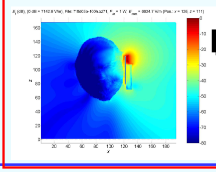
Parametric modelling



Deterministic modelling



Antenna design and evaluation



Radio interface research
- link capacity
- MIMO algorithms
- etc.

Radio system research
- interference
- multiuser MIMO
- etc.

Mean Effective Gain MEG

- originally introduced as an experimental parameter by J. Bach andersen et. al,
  – AUT and a fererence antenna transported along the same routes and the mean difference of the signals recorded
- Taga presented the formulas for combining the field distribution and antenna patterns:

$$G_e=\int_0^{2\pi}\int_{-\pi/2}^{\pi/2}\left[\frac{XPR}{1+XPR}G_\theta(\theta,\phi)p_\theta(\theta,\phi)+\frac{1}{1+XPR}G_\phi(\theta,\phi)p_\phi(\theta,\phi)\right]\cos\theta\, d\theta\, d\phi$$

- G_θ and G_ϕ are the θ- and ϕ-polarized components of the antenna power gain pattern
- $p_\theta(\theta,\phi)$ and $p_\phi(\theta,\phi)$ are the θ- and ϕ-polarized components of the angular power density functions of the incoming plane waves in a certain environment
- *XPR* is the cross-polarization power ratio, defined as the ratio of the mean incident θ- and ϕ-polarized powers along the route

MEG definitions

- the following conditions have to be met

$$\int_0^{2\pi}\int_{-\pi/2}^{\pi/2}\left[G_\theta(\theta,\phi)+G_\phi(\theta,\phi)\right]\cos\theta\, d\theta\, d\phi=\eta_{tot}4\pi$$

$$\int_0^{2\pi}\int_{-\pi/2}^{\pi/2}p_\theta(\theta,\phi)\cos\theta\, d\theta\, d\phi=\int_0^{2\pi}\int_{-\pi/2}^{\pi/2}p_\phi(\theta,\phi)\cos\theta\, d\theta\, d\phi=1$$

- η_{tot} is the total efficiency of the antenna, including all possible mechanisms (head, hand, internal losses, reflections) reducing the radiated power
- it is common to assume that when a mobile user moves randomly in any environment, the incident waves can arise from any azimuth direction with equal probability
- in the case of uniform distribution in azimuth, the angular power density functions reduce to:

$$p_\theta(\theta,\phi)=\frac{1}{2\pi}p_\theta(\theta)$$

$$p_\phi(\theta,\phi)=\frac{1}{2\pi}p_\phi(\theta)$$

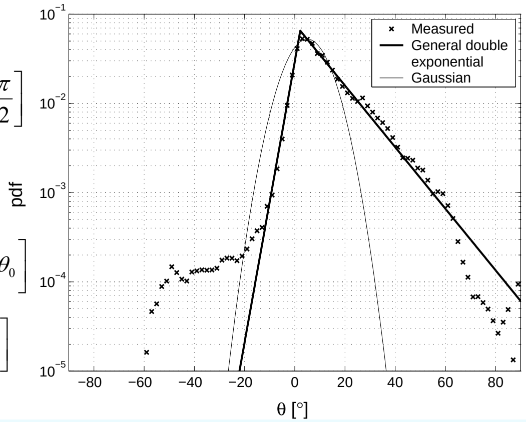
Signal distributions

- Gaussian distribution:

$$p(\theta) = A_1 \exp\left[-\frac{(\theta-\theta_0)^2}{2\sigma^2}\right], \qquad \theta \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$$

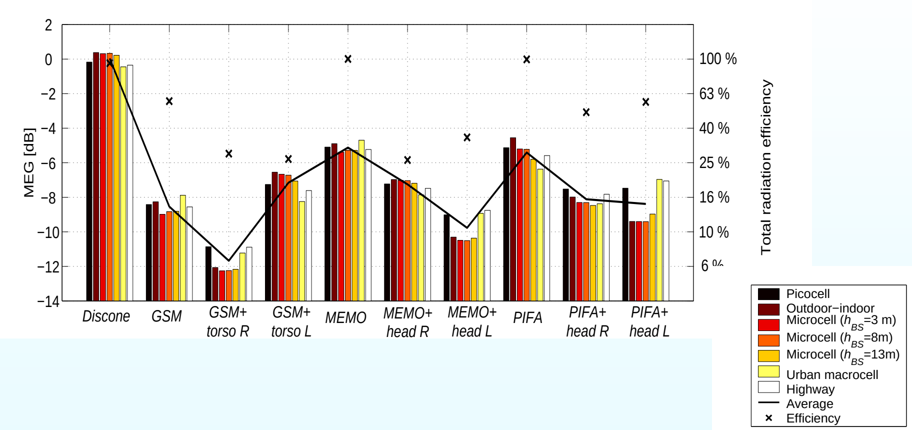
- Double-exponential:

$$p(\theta) = \begin{cases} A_2 \exp\left[-\frac{\sqrt{2}\left|\theta-\theta_0\right|}{\sigma^-}\right], & \theta \in \left[-\frac{\pi}{2}, \theta_0\right] \\ A_2 \exp\left[-\frac{\sqrt{2}\left|\theta-\theta_0\right|}{\sigma^+}\right], & \theta \in \left[\theta_0, \frac{\pi}{2}\right] \end{cases}$$



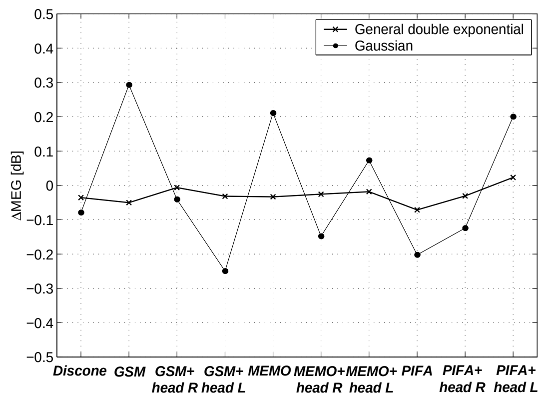
- θ_0 is the peak elevation angle, and parameters σ, σ^-, and σ^+ control the spread of the probability density functions

MEGs of different antennas



Difference of MEGs computed from measured and modeled EPDs

- **Average over all environments**



MIMO performance

- The limit capacity or mutual information:

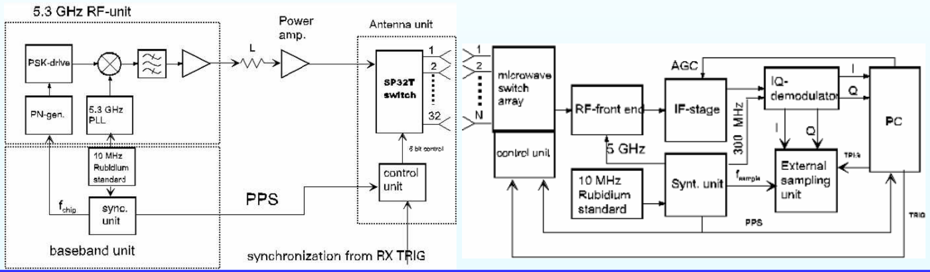
$$C = \sum_{i=1}^{N} \log_2\left(1 + \frac{\lambda_i P_i}{\sigma}\right)$$

- Depends on:
  - The eigenvalues λ_i of the correlation matrix
    - Depending on the antenna structure and environment
    - Lower correlation => lower eigenvalue spread
  - The received signal to noise ratio P_i/σ
    - Large and small scale fluctuations in the propagation environment

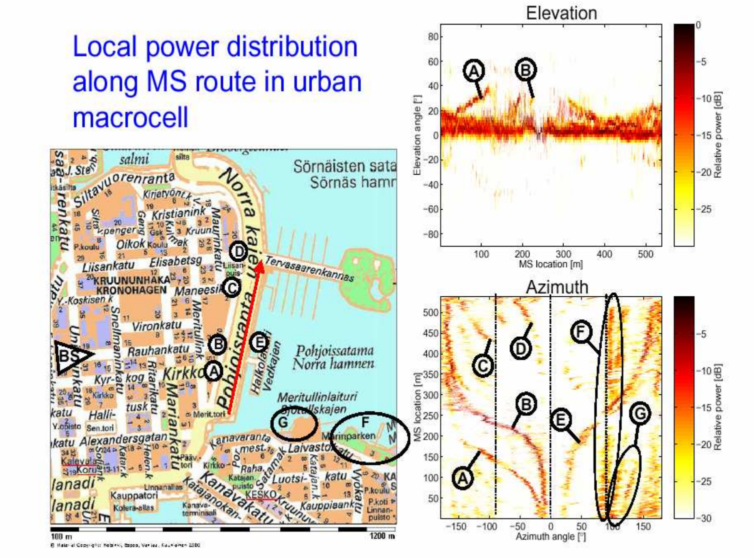
Measurements of spatial, temporal and polarization characteristics of mobile radio channels

5.3 GHz MIMO measurement system

-32 x 32 matrices, 16 dual polarized elements can be used in both TX and RX
-high power SP32T TX switch (5 W output)
-channel matrix is measured in 8.7 ms
-2 x 120 MHz sampling rate, 60 MHz chip rate
-measurements possible with about 120 dB propagation loss
-range about 500 meters in NLOS macrocell

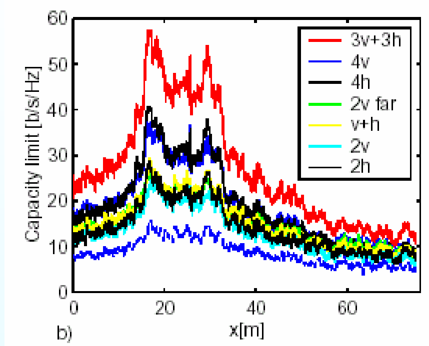


2 GHz 3D propagation measurement at MS



2 GHz MIMO measurements

Capacities with different BS antenna options:

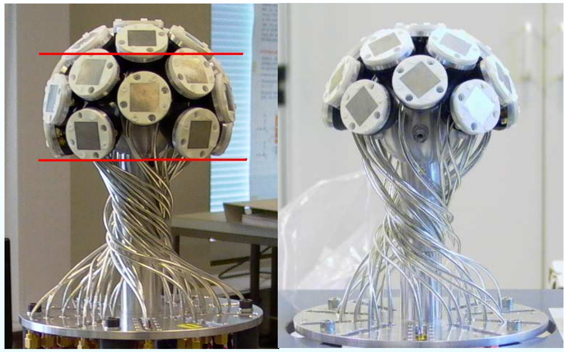


- two dual-polarised arrays
  - linear 2 x 8 at fixed station, spherical 2 x 32 at mobile station => maximum 16 x 64 MIMO configuration

5.3 GHz semispherical arrays

- Spherical arrays
  - non-slanted elements
  - slanted elements
- Dual-polarized elements
- 21 elements, 42 channels
- Used channels can be selected by cable connection
- All arrays have common interface

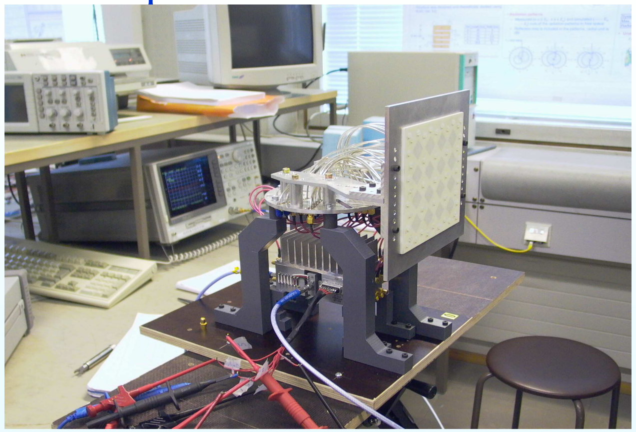
  => every antenna can be used in RX or TX



$$\theta = 50^\circ \ldots -30^\circ$$

$$\phi = 0^\circ \ldots 360^\circ$$

5.3 GHz planar 2 x 16 antenna array



- planar array is normally used in TX

5.3 GHz MIMO measurements

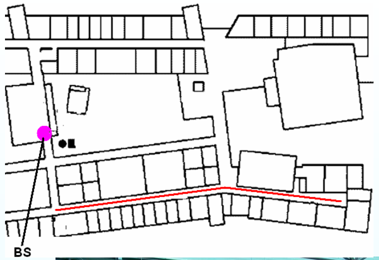
Environment	BS height	BS-MS distance	Setup	Amount of data
Indoor	At MS height	5 ... 50 m	30x30 MIMO	33000 / 500 m
Outdoor-indoor	~17 m, roof of opposite building	20 ... 100 m	32x30 MIMO	10000 / 150 m
Outdoor microcell, LOS	10 m	60 ... 400 m	32x30 MIMO	12000 / 180 m
Outdoor microcell, NLOS	10 m	60 ... 180 m	32x30 MIMO	16000 / 240 m
Urban macrocell	40 m or rooftop of a building	50 ... 600 m	32x30 MIMO	81000 / 1200 m

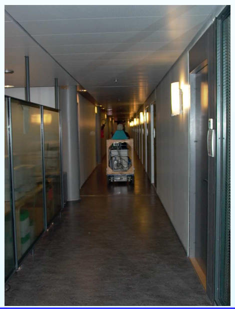
30x30 MIMO: 15 element spherical TX and RX arrays, dual-polarized

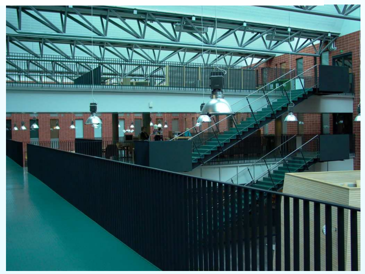
32x30 MIMO: 4x4 planar TX array and 15 element spherical RX array, dual-polarized

All elements in the antenna arrays are similar patch elements.

Indoor measurement





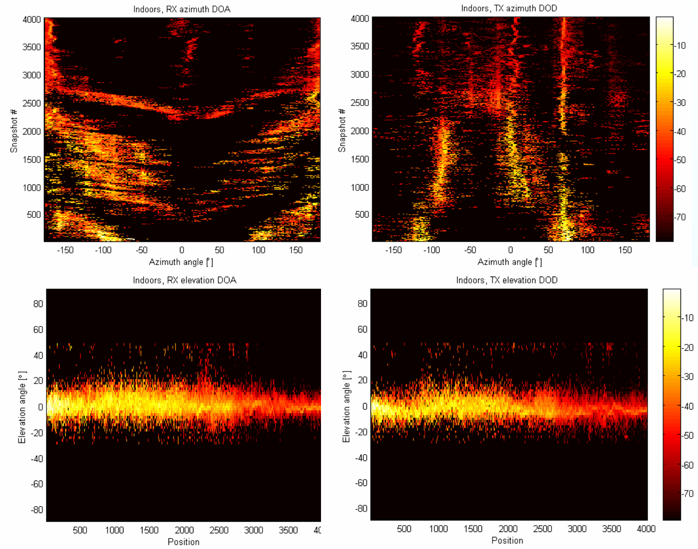


Indoor DOA and DOD

RX DoA | TX DoD

Azimuth

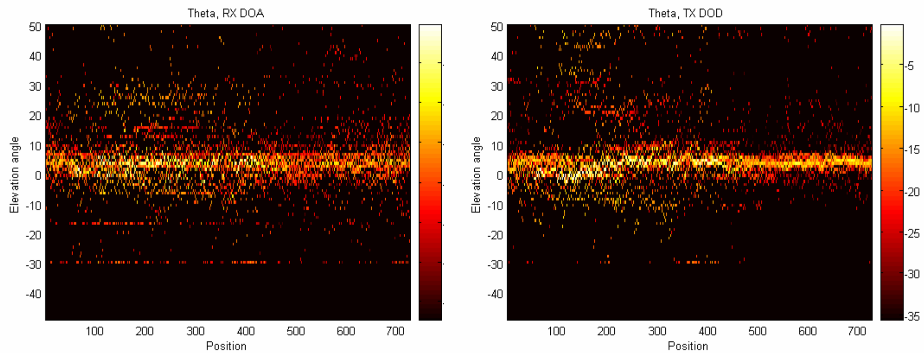
Elevation



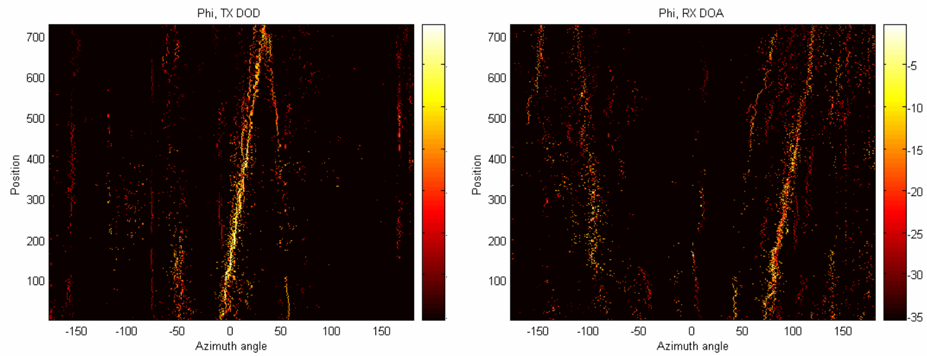
Outdoor measurement example

- Example of extracted DOA/DOD data
- SAGE estimation with 15 waves and 3 iterations
- The measurement is a 30x30 MIMO, measured outdoors from a spherical array to a spherical array in a LOS case

Elevation angles



Azimuth angles



Evaluation of performance of multi–antenna terminals using two approaches

Table of contents

1. Introduction

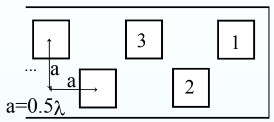
- Evaluation of antennas important also in the next generations of mobile systems
- The important properties of mobile antenna systems are:
  - Total transferred power (SISO, SIMO, MIMO)
  - Diversity gain (SIMO, MIMO)
  - Multiplexing gain (MIMO)
- Beneficial to test antennas already during the development process using the real propagation data and the simulated radiation patterns of antenna prototypes

1. Introduction (cont.)

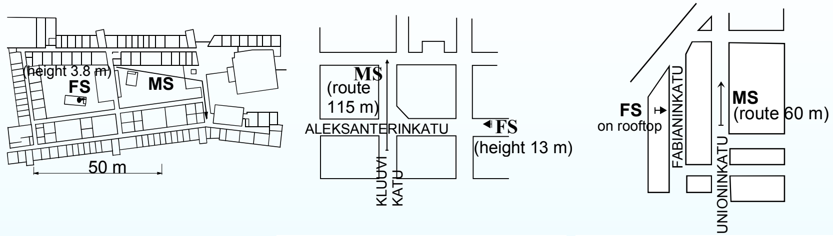
- A experimental plane–wave based method (EPWBM) is implemented to enhance and speed up the developing process of new prototype antennas
  - Previously, several hundred meters of measurement routes in the several types of propagation environments were needed in order to obtain significant results for comparing several antenna configurations
  - Now, the same measurement routes can be exploited for the several measured or simulated radiation patterns of prototype antennas
- The results of EPWBM are compared with the direct measurement results
- The diversity and MIMO analysis of multi–element antenna configurations are carried out to validate the usability of the EPWBM

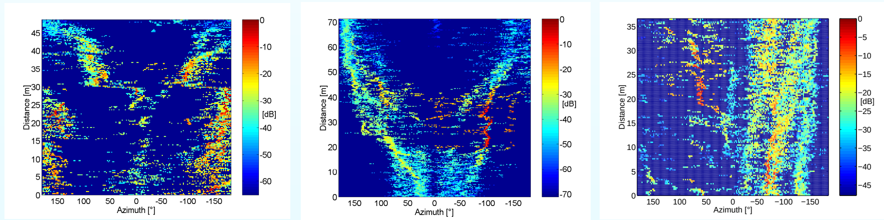
2. Direct measurements

- Tx and Rx antenna arrays were connected to a fixed transmitter and to a moving receiver of the wideband radio channel sounder, respectively
  - The linear array (zigzag) with dual–polarized patch antennas at Tx (upper figure)
  - The spherical array with dual–polarized patch antennas at Rx (lower figure)



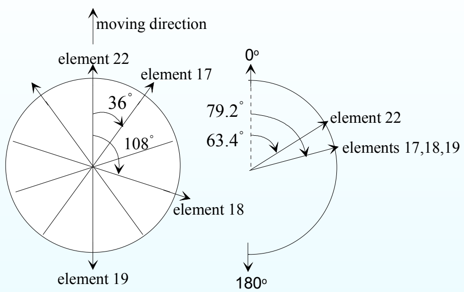
2. Direct measurements (cont.)





2. Direct measurements (cont.)

- In the direct measurement, the antenna elements are selected from the linear Tx and the spherical Rx antennas in order to obtain different test antenna configurations
- The performance of the system is estimated from the measured channel matrix of the selected antenna configurations
- The selected antenna element locations of the spherical array are presented in the figure



Azimuth cut
Elevation cut

3. Experimental plane–wave based method (EPWBM)

- EPWBM is based on the joint contribution of the estimate of the distribution of the signals and the complex 3–D radiation patterns of an antenna
- A beamforming algorithm is used to estimate the distribution of the signals
- The radiation patterns of the same elements as in direct measurement were measured/simulated

1) Direct method

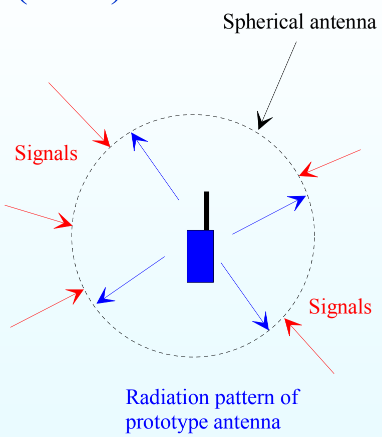
Tx signal weighted by Tx antennas + Effect of environment + Rx signal weighted by Rx antennas

2) EPWBM

Tx signal weighted by Tx antennas + Effect of environment + Rx signal without effect of Rx ant. + Effect of Rx rad. pattern

3. Experimental plane–wave based method (EPWBM) (cont.)

- The radiation pattern of an antenna is defined:
  $\overline{E}(\Omega) = E_\theta(\Omega)\overline{a}_\theta(\Omega) + E_\phi(\Omega)\overline{a}_\phi(\Omega)$
- The electric field of the incident plane wave is defined:
  $\overline{A}(\Omega) = A_\theta(\Omega)\overline{a}_\theta(\Omega) + A_\phi(\Omega)\overline{a}_\phi(\Omega)$
- The complex signal envelope at the antenna port is stated:
  $V(t) = \oint \overline{E}(\Omega,t)\cdot\overline{A}(\Omega,t)d\Omega$



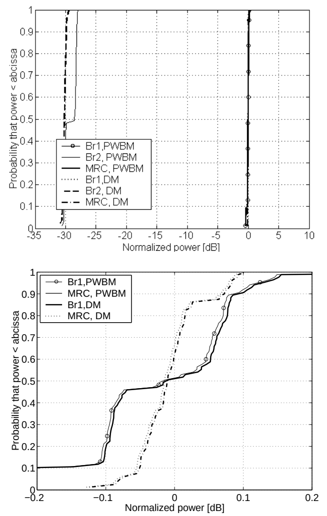
4. Comparison of methods

4.1. Diversity analysis

- Diversity gain is used as a figure of merit for comparing the results of two methods
  - The powers of both branches (Br1,Br2) and the power after maximum ratio combing (MRC) is presented using cdfs
- Two antenna arrangements are considered:
  - 1) **cross_pol:** vertically polarized feed of the element of the Tx array
    vertically and horizontally polarized feeds of the same element in the Rx array
  - 2) **co_pol:** vertically polarized feed of the element of the Tx array
    vertically polarized feeds of two adjacent elements in the Rx array
- Diversity gain results are normalized for the sum of mean powers of the branches over the measurement route

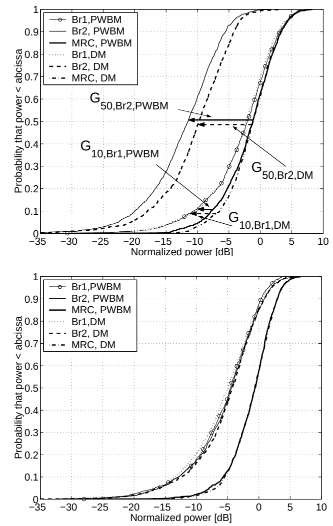
4.1. Diversity analysis (cont.)

- As a first validation, the measurements performed in an anechoic chamber are compared
  - Element 22 from the spherical array (**cross_pol**)
  - Tx and Rx were pointing towards each other (static measurement)
- The results of the experimental plane–wave based method agrees wery well with the results of the direct measurement
- Fluctuation of received power is caused by the unidealities of the measurement



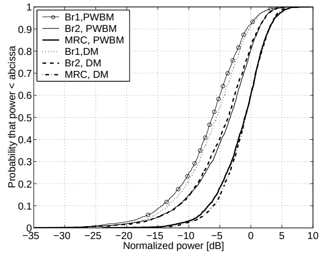
4.1. Diversity analysis (cont.)

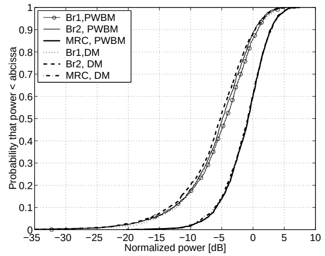
- Polarization–diversity arrangement (**cross_pol**)
  - Element 18 of the Rx array
  - Both feeds of the element 18
- Good agreement between the methods
- Space–diversity arrangement (**co_pol**)
  - Elements 17 and 18 of the Rx array
  - Vertically polarized feeds
- Very good agreement between the methods
- Macrocell environment



4.1. Diversity analysis (cont.)

- Realistic mobile terminal antenna (PIFA)
  - Located on the left and right upper corner of a metallic ground plane
- Antenna in free space (upper figure)
- Antenna beside a head model (lower figure)
- Picocell environment
- Really good agreement between the results





4. Comparison of methods

4.2. MIMO analysis

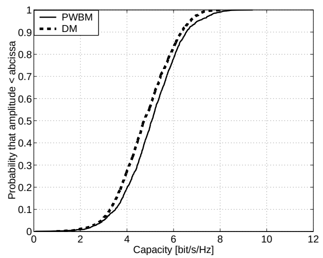
- Capacity and eigenvalues of normalized channel correlation matrix were used as figures of merit in MIMO analysis

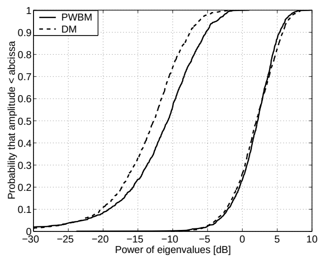
$$C = \log_2\left[\det\left(I + \frac{\rho}{n_t}\overline{R}_{norm}\right)\right]$$

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

4.2. MIMO analysis (cont.)

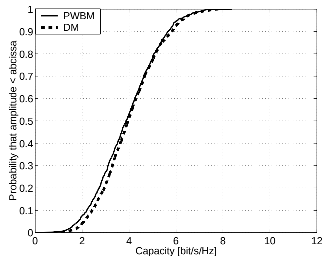
- First MIMO configuration includes two adjacent VP feeds from the elements at both ends of the link
  - Elements 17 and 18 selected from the Rx
  - The distributions (cdfs) of the capacity and eigenvalues presented in figure
- Small macrocell environment
- The strongest difference between the methods in the case of weaker eigenvalue – minor difference in capacity

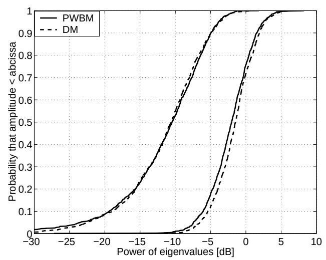




4.2. MIMO analysis (cont.)

- The second MIMO configuration includes HP and VP feeds from the adjacent elements at both ends of the link
  - Elements 17 and 18 selected from the Rx
  - The distributions (cdfs) of the capacity and eigenvalues presented in figure
- Small macrocell environment
- Almost perfect matching between the methods





5. Conclusions

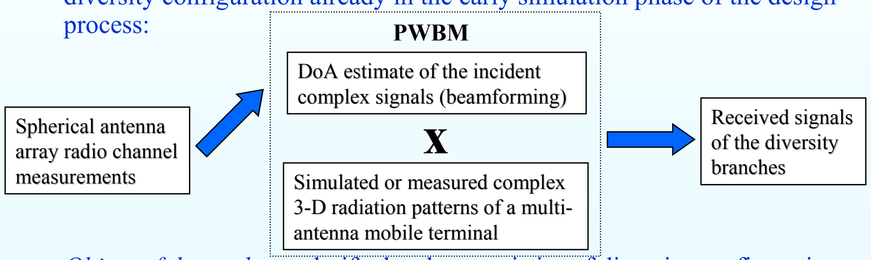
- Main points of EBWBM:
  - + Fast way to test antennas
  - + Antennas can be tested based on simulated radiation patterns
  - + Radiation patterns of antennas can be rotated easily in evaluation
  - + The radio channel stays exactly the same for all antenna configurations under test
  - – Physical limitations of the beamforming algorithm to estimate details of the scattering field and limitations in the measurement process as well
- Outlook:
  - – More advanced (reliable) channel estimation algorithm will be implemented/tested

Diversity Performance Analysis of Mobile Terminal Antennas

Juha Villanen[1], Jani Ollikainen[2], Outi Kivekäs[1], Clemens Icheln[1] and Pertti Vainikainen[1]

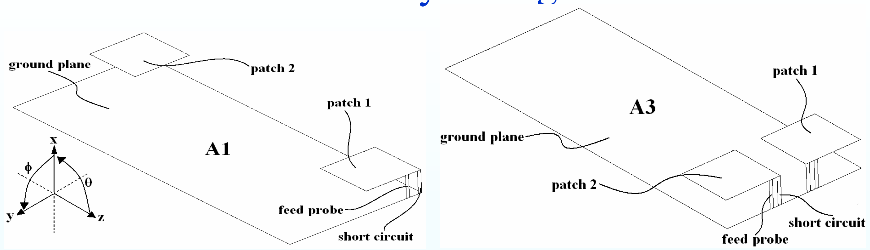
Introduction

- The performance of diversity reception in the mobile terminal end strongly depends on the characteristics of the radio propagation environment. Measurements in real propagation environments with prototype antennas are needed ➡ time consuming and expensive!
- A novel multi-antenna system evaluation tool, PWBM (Plane Wave Based Method), enables a fast and reliable evaluation of the performance of a diversity configuration already in the early simulation phase of the design process:



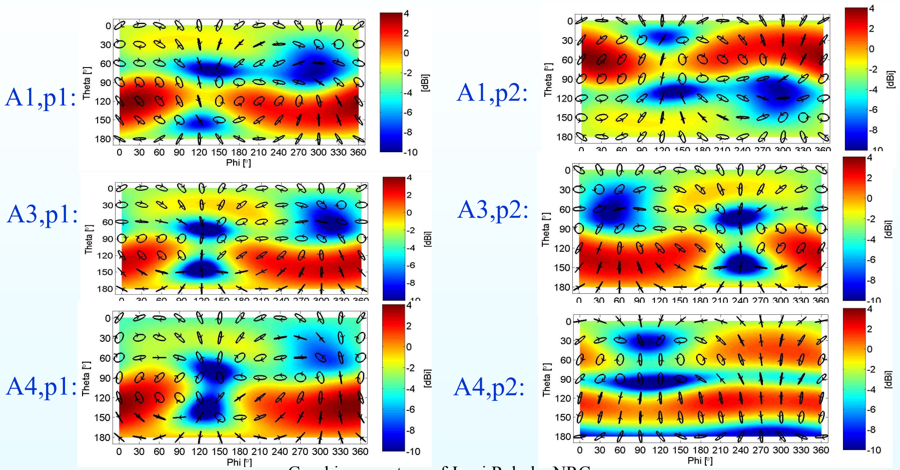
- *Object of the study*: to clarify the characteristics of diversity configurations and radio channels that are relevant for the obtained diversity performance

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.

Antenna patterns

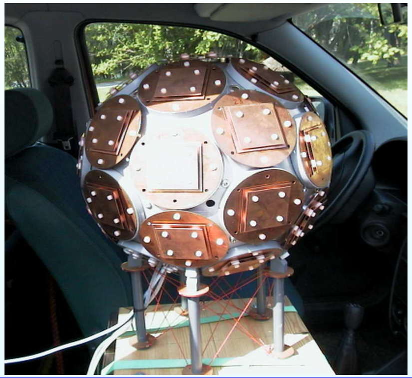


Graphics: courtesy of Jussi Rahola, NRC

Enviroments used in the evaluation (1)

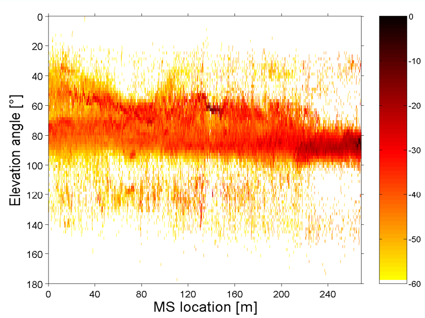
- In total eight routes were selected from the channel library of Helsinki University of Technology (HUT) to evaluate the performance of A1 – A4. The routes were grouped into four environment classes:

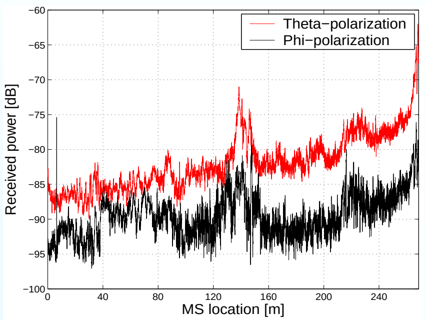
1. *Indoor Picocell*: One route inside the Computer Science Building of HUT.
2. *Microcell*: Three routes from downtown Helsinki. Transmitter antenna located 8 m above the street level.
3. *Macrocell*: Three routes from downtown Helsinki. Transmitter antenna located at the rooftop of a parking house.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



Enviroments used in the evaluation (2)

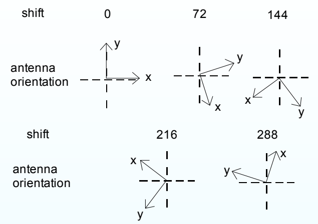
- Elevation power distribution and total incident theta- and phi-polarized powers in one of the evaluated macrocell routes (transmitter at the rooftop level):





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

Antenna evaluation methods (1)



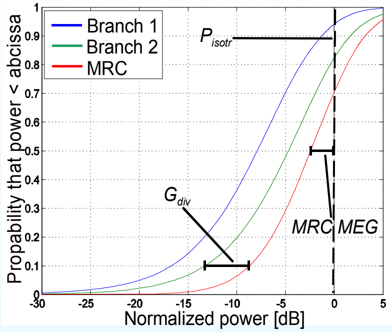
- To simulate the random azimuth orientation of a mobile terminal, each diversity configuration was ”driven” through each environment in 5 different azimuth positions:
- In order to remove slow fading, the power received by a computational isotropic radiator was used as a normalization vector. The used 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.

Antenna evaluation methods (2)

- 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}).



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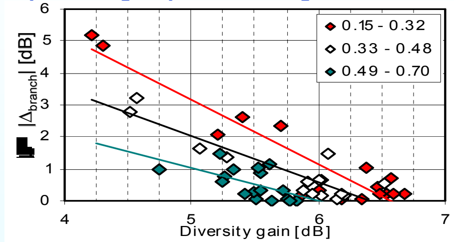
Results (1)

- 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.

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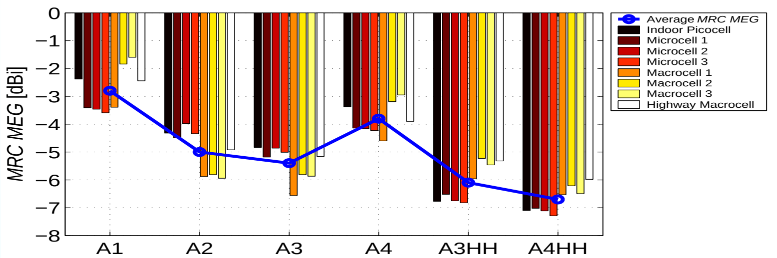
Results (2)

- *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??**

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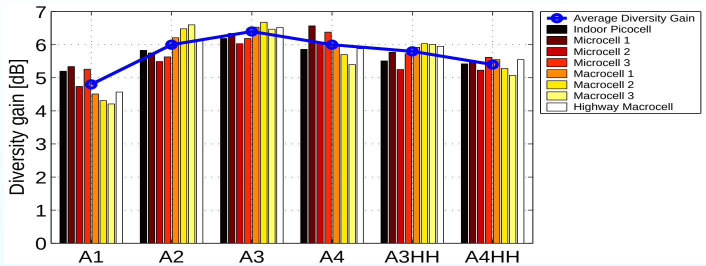
Results (3)

- 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*.

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!

Study of different mechanisms providing gain in MIMO systems

*K. Sulonen, P.Suvikunnas, J. Kivinen, L. Vuokko, P. Vainikainen

Outline

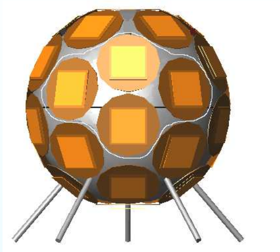
- Introduction
- Measurements
  - Potential MIMO environments
    - indoor picocellular
    - outdoor microcellular and macrocellular
- Results
  - Eigenvalue distributions
  - Effect of number of Tx elements
  - Effect of interelement spacing at Tx
- Summary

Introduction

- Scope of the work:
  - how Multi-Input Multi-Output channels could be exploited better.
  - measurements are used as the experimental basis for evaluation of MIMO antenna configurations at 2.15 GHz
- Propagation environment and antenna configurations affect MIMO performance
- Receiving antenna elements with orthogonal polarizations are equally effective with the co-polarized elements in capacity comparison.
- Dual polarized elements can be compact solutions to add diversity dimension with low correlation between antenna ports. In some cases, dual-polarized elements result in relatively high power unbalance between antenna ports that deteriorates the power gain in MIMO channel.
- Our evaluation is mainly based on
  - MIMO radio channel sounder measurements
  - The effects of increasing the number of Tx channels and increasing the inter-element spacing on the eigenvalue spread are studied.

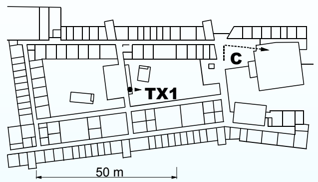
Evaluation method

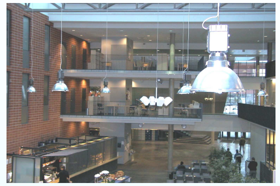
- Radio channel sounder masurements at 2.15 GHz.
- Antenna arrays
  - Linear antenna array of directive and dual-polarized antenna elements at Tx
  - Spherical antenna array of directive and dual-polarized antenna elements at Rx
  - Groups of Tx and Rx elements were selected in the arrays in the post processing of the measurement data. At Rx, similar groups of elements in five azimuth orientations are included in the analysis.
- Eigenvalues of normalized instantaneous channel correlation matrix are used here to study the effects of Tx antenna configurations on MIMO performance.
- Eigenvalues have been calculated using the eigenvalue decomposition of the normalized instantaneous correlation matrix and equal power allocation.



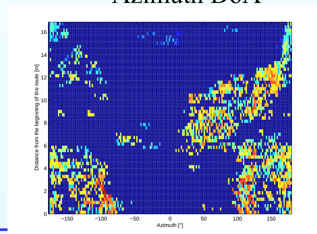
$$\overline{R}_{norm} = \frac{\overline{H}^H \overline{H}}{\frac{1}{n_t} E\left\{ \sum_{t=1}^{n_t} H_{1,t}^* H_{1,t} \right\}}$$

Indoor environment

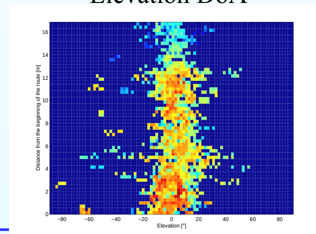




Azimuth DoA

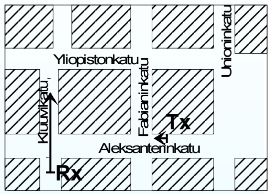


Elevation DoA

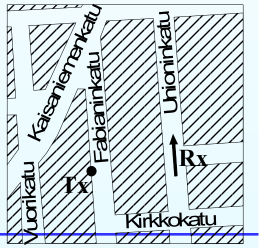


Outdoor environments

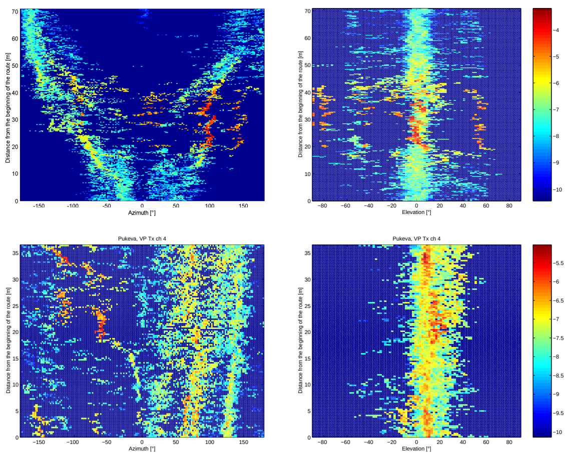
Outdoor Route 1



Outdoor Route 2



Azimuth DoA Elevation DoA

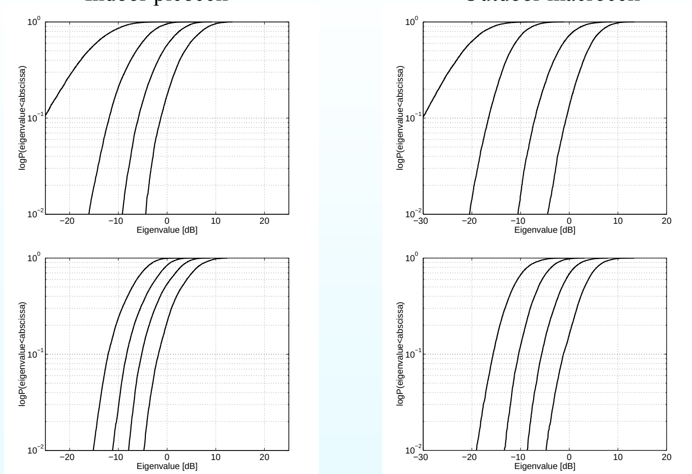


Effect of number of Tx channels

Indoor picocell Outdoor macrocell

4x4 MIMO

12x4 MIMO

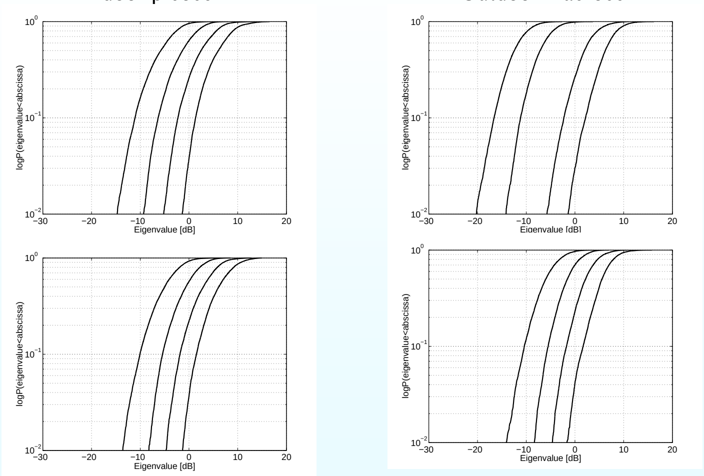


Effect of interelement spacing at Tx

Indoor picocell — Outdoor macrocell

0.5λ / 0.7 λ

2.5λ / 3.5 λ



Eigenvalue spread at 50 % probability level

EVSpread [dB]	Tx spacing 0.7λ/0.5λ	Tx spacing 2.5λ/3.5λ	2 Tx elements	6 Tx elements
picocell	12	11	20	10
microcell	20	14	28	17
macrocell	18	11	26	14
iid	9	9	18	7

$$EVSpread = \lambda_{max}[dB] - \lambda_{min}[dB]$$

λ_{max} and λ_{min} are the smallest and the largest eigenvalues at the probability level of 50 %

Summary and conclusion

- The eigenvalues of normalized instantaneous channel correlation matrix were used to study the effects of different Tx antenna configurations on MIMO performance.
- Increasing the distance between Tx antenna elements increases resolution by narrowing the main beam, which results in
  - decreased eigenvalue spread
  - increased capacity
  - The effect is smallest in picocellular indoor environment.
- Adding more elements at the Tx antenna configuration
  - increases Tx diversity, which is seen as sharper eigenvalue curves.
  - The effect is the strongest in picocellular indoor environment.
- When comparing three environments, the smallest eigenvalue spread is indoors.

Comparison of MIMO Antennas: Performance Measures and Evaluation Results of Two 2X2 Antenna Configurations

Pasi Suvikunnas, Jari Salo, Jarmo Kivinen, Pertti Vainikainen

SMARAD/Radio Laboratory/HUT

I. Introduction

- Multiple-Input Multiple-Output (MIMO) concept is an attractive solution to increase capacity in wireless communication systems
- Requirements of functional MIMO system
  – Complex signal propagation environment
  – Optimized antenna arrays (groups)
- Figure of merit needed for evaluation of antenna arrays
  – Mean Effective Gain (MEG) is used in Single-Input Single-Output (SISO) systems
  – Mean Effective Link Gain (MELG) is proposed for MIMO systems in this paper
- Normalization of the results critical for the evaluation of different MIMO systems

II. Normalization of capacity results

- The instantaneous normalized channel capacity is given by (1)

$$C_{\mathbf{H}}^{(i)} = \log_2 \left| \mathbf{I} + \frac{\rho}{n_t} \mathbf{R}_{norm}^{(i)} \right| \quad (1)$$

- Normalized channel correlation matrix is expressed by (2) in which normalization is performed by (3)

$$\mathbf{R}_{norm}^{(i)} = \frac{\mathbf{H}^{(i)} \mathbf{H}^{(i)H}}{\frac{1}{n_t n_r} G_{norm}^{(i)}} \quad (2)$$

$$G_{norm}^{(i)} = \frac{1}{2N+1} \sum_{i-N}^{i+N} \left\| \mathbf{H}_{norm}^{(i)} \right\|_F^2 \quad (3)$$

II. Normalization of capacity results (cont.)

- In many considerations normalization of the results is performed for the ”antennas itself” by (4)
- In the case of different type of antennas this approach gives misleading results for the achieved capacity and for the power of eigenvalues
  – The gain of antennas is removed!
- Better way to normalize results is to use some reference antenna system (5)
  – The gain of antennas is taken into account
  – Different MIMO antenna systems are comparable to each other

$$\mathbf{H}_{norm}^{(i)} = \mathbf{H}^{(i)} \quad (4)$$

$$\mathbf{H}_{norm}^{(i)} = \mathbf{H}_{ref}^{(i)} \quad (5)$$

III. Generalization of MEG for MIMO systems

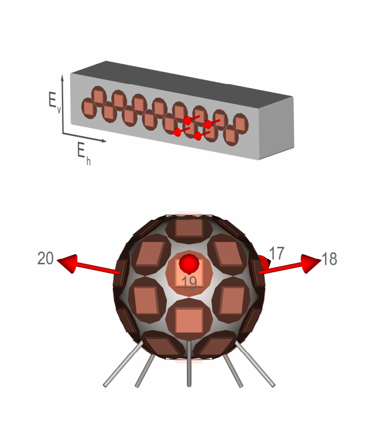
- The performance of an antenna can be estimated using mean effective gain (MEG)
  – The power received by an antenna compared to some reference antenna
- Mean effective link gain (MELG) is proposed for the evaluation of MIMO antenna prototypes
  – The instantaneous link gain is defined having the sum of link powers normalized by the link powers of isotropic antennas with the same number of elements (6)
  – The mean effective link gain (MELG) is given by (7)

$$G_{link}^{(i)} = \frac{\left\| \mathbf{H}^{(i)} \right\|_F^2}{G_{norm}^{(i)}} \quad (6)$$

$$MELG = \frac{1}{N_s} \sum_{i=1}^{N_s} G_{link}^{(i)} \quad (7)$$

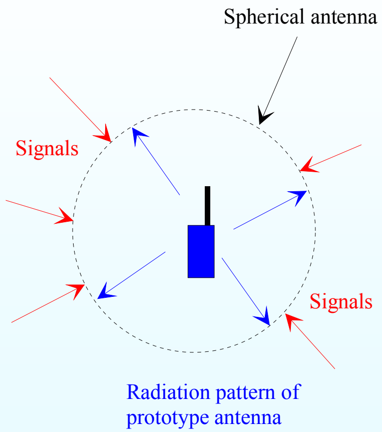
IV. Measurement set-up

- The wideband channel sounder was adopted in measuring two separate routes
  - Microcell (line of sight)
  - Small macrocell (non line of sight)
- Measurement antennas used in the measurements
  - Zigzag antenna array with two-polarized patch antennas at Tx (upper figure)
  - Spherical antenna array with two-polarized patch antennas at Rx (lower figure)



IV. Measurement set-up

- Beamforming process at Rx
  - Spherical antenna array acts as a isotropic sensor
  - Impulse responses of measurement process were post processed having directional information from the signals arriving at Rx
  - Directional data was convolved (weighted) with antennas under test

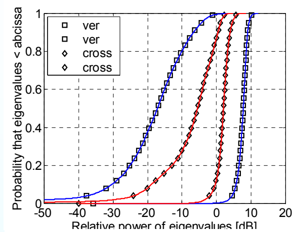


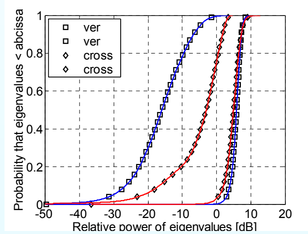
IV. Measurement set-up (cont.)

- Two 2×2 MIMO antenna systems were investigated to demonstrate the combined effect of the antenna and eigenvalue spread to the attained capacity of the system:
  - 1) Two vertically polarized antennas and two vertically polarized dipoles at Tx and Rx, respectively (Co–polarized configuration)
  - 2) Vertically and horizontally polarized antenna at Tx, and vertically and horizontally polarized dipole at Rx (Cross–polarized configuration)
- The Rx dipole array was rotated in six positions by 30° steps
- Inter–element spacing of the antennas was 0.5λ at both ends of the link
- Normalization (5) was performed with two vertically polarized antennas and two isotropic sensors at Tx and Rx, respectively

V. MIMO antenna evaluation results

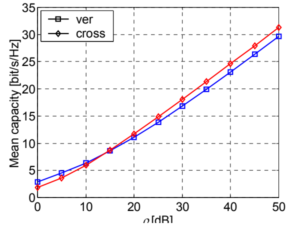
- Eigenvalue analysis from the microcell route
  - Normalization for isotropic sensors used in upper figure (5)
  - Normalization for antennas itself used in lower figure (4)
- Normalization by (4) shifts eigenvalues to the right in the cross polarized case (red curves)

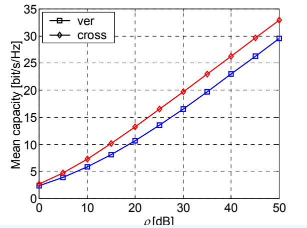




V. MIMO antenna evaluation results (cont.)

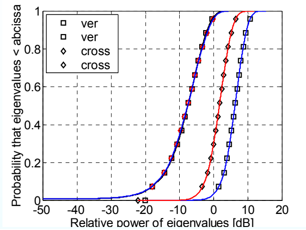
- Capacity analysis from the microcell route
  - Normalization for isotropic sensors used in upper figure (5)
  - Normalization for antennas itself used in lower figure (4)
- The capacity difference between investigated antenna configurations smaller in upper figure → takes into account antenna gain!

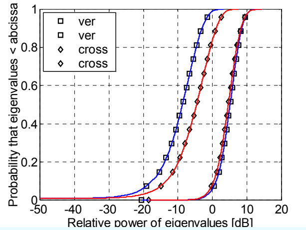




V. MIMO antenna evaluation results (cont.)

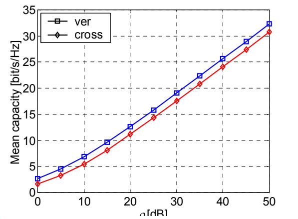
- Eigenvalue analysis from the small macrocell route
  - Normalization for isotropic sensors used in upper figure (5)
  - Normalization for antennas itself used in lower figure (4)
- Normalization by (4) shifts eigenvalues to the right also in the cross polarized case (red curves)
  - The difference in eigenvalue spreads not so remarkable than in the microcell case

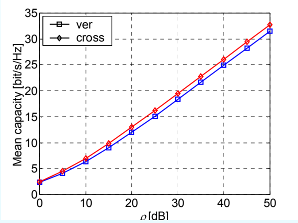




V. MIMO antenna evaluation results (cont.)

- Capacity analysis from the small macrocell route
  - Normalization for isotropic sensors used in upper figure (5)
  - Normalization for antennas itself used in lower figure (4)
- Vertically polarized configuration deliver higher capacity when using (5) in normalization
- Cross polarized configuration seems to deliver higher capacity in the whole range when using (4) in normalization!





V. MIMO antenna evaluation results (cont.)

- MELG values using (4) and (5) in normalization
  - Upper figure: (5) used in normalization
  - Lower figure: (4) used in normalization
- The effect of antenna gain is considered in the upper case!
- The effect of antennas is basically removed in the lower case!

Ant./Env.	microcell	small macrocell
Co-pol.	4.7 dB	4.1 dB
Cross-pol.	0.2 dB	0.1 dB

Ant./Env.	microcell	small macrocell
Co-pol.	2.9 dB	3.0 dB
Cross-pol.	2.9 dB	3.0 dB

VI. Conclusion

- Both eigenvalue spread and total tranferred power are needed to evaluate the performance of MIMO system
  - Eigenvalue spread measures the capability of the propagation environment and the antennas to create parallel data "pipes"
  - MELG characterizes the capability of the antennas to transfer signal power from transmitter to receiver
- MIMO system having a narrower eigenvalue spread does not necessarily provide higher capacity if it's MELG is lower
- Normalization of the results is critical issue in MIMO considerations
  - The total transferred power will be wrongly predicted if the same reference antennas are not used for the comparison of different MIMO systems (MELG values are not comparable !)

A NOVEL MIMO ANTENNA FOR LAPTOP TYPE DEVICE

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FINLAND

1.Introduction

- Multiple-Input Multiple-Output (MIMO) systems increse capacity of wireless communications systems as compared to the "traditional" systems
  - exploits multiplexing gain (parallel channels) – unique property for MIMO systems
  - exploits diversity gain and array gain
  - exploits antenna gain
- Verification of MIMO systems using real propagation data and real antennas is still under consideration and development
  - how to achieve the best possible performance of the system considering the used antennas (antenna type, antenna placement)
- Laptop type device is sufficiently large platform to integrate several antennas on it
  - wireless local area network (WLAN) could be a feasible application

2. Capacity analysis

- Mutual information (instantaneous capacity) of MIMO system is defined by (1)
  - $\mathbf{H}_{norm}^{(i)}$ is a normalized complex channel matrix
  - ρ is signal to noise ratio
  - $\mathbf{I}$ is identity matrix
  - n_t is the number of transmitter antennas
- Two quality factors are used in the comparison of antennas
  - Mean capacity (C) was calculated over analyzed samples as a function of ρ (2)
  - Variance of capacity (σ_C^2) was calculated as well (3)

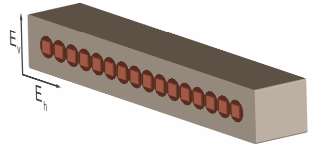
$$C_{\mathbf{H}}^{(i)} = \log_2 \left| \mathbf{I} + \frac{\rho}{n_t} \mathbf{H}_{norm}^{(i)} \mathbf{H}_{norm}^{(i)H} \right| \quad (1)$$

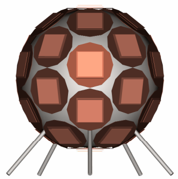
$$C = \frac{1}{N_s} \sum_{i=1}^{N_s} C_{\mathbf{H}}^{(i)} \quad (2)$$

$$\sigma_C^2 = \frac{1}{N_s} \sum_{i=1}^{N_s} \left(C_{\mathbf{H}}^{(i)} - C \right)^2 \quad (3)$$

3. Channel measurement system

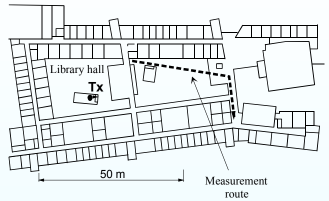
- Dual polarized patch antenna arrays were used in measurement
- Linear array (Tx) in transmission (upper figure)
  - 2 active elements (4 feeds) from the 16 elements were selected in this study
  - Inter-element spacing of 0.7 λ
- Spherical array (Rx) in reception (lower figure)
  - 32 active elements (64 feeds)
  - Inter-element spacing of 0.78 λ or 0.87 λ
  - Full coverage in azimuth and elevation

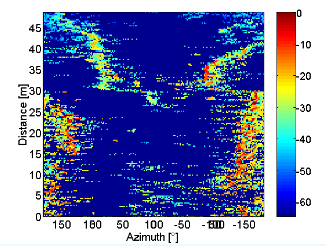




4. Channel measurement

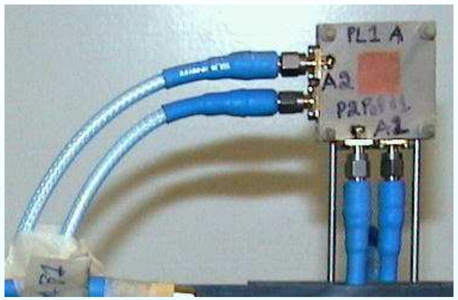
- Indoor picocell measurement was carried out in modern office building (upper figure)
  - Length of the dynamic measurement 50 m
- Beam-forming algorithm implemented for the spherical array enables to parametric description of the channel
  - Amplitude, delay, polarization state, and angle of arrival (lower figure) of multi-paths of electromagnetic field were estimated at Rx
- The data were combined (convolved) with the simulated 3D-radiation pattern of the antenna prototype under test to be presented next!





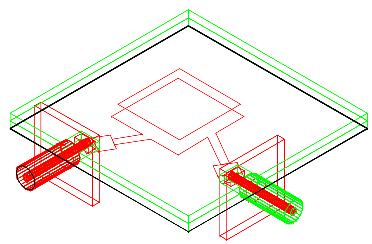
5. Antenna characteristics

- Compact antenna group (prototype) was developed
  - Two polarized micro-strip antenna element is located at both sides of the structure
  - Four antenna feeds were integrated to the small area!
  - Dimensions:
    - thickness of total structure 11 mm
    - quadratic ground plane (40 mm × 40 mm × 5 mm)
    - substrate 1.52 mm thick duroid (Relative permittivity 2.94)



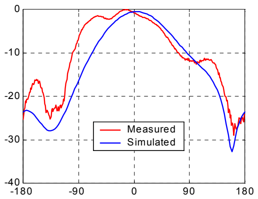
5. Antenna characteristics

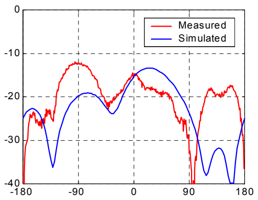
- Frequency range of 5.3 GHz
- 400 MHz bandwidth for 5 dB return loss (2 port 2 layer patch)
- Bandwidth for the pattern correlation less than 0.2 is 1000 MHz
- Stacked structure (4 ports):
  - skewness provides space for the connectors of the other side of the structure
  - coupling between ports on the different sides of the structure is less than –30 dB



6. Antenna measurement/simulation

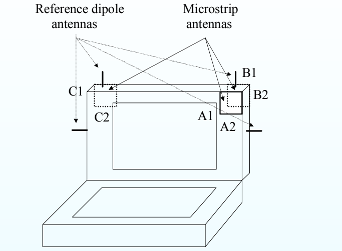
- 3D-radiation patterns of antenna feeds were simulated (HFSS)
  - Two orthogonal polarizations (θ and ϕ)
  - Resolution of radiation pattern 3°
- 2D-radiation patterns were measured in anechoic chamber
- 2D-cuts from the measured and simulated radiation pattern are presented
  - Unidealities (mutual coupling, near- field effects, cables, etc) are not accurately predicted in the simulated results

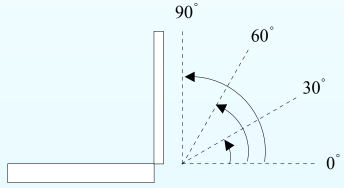




7. Placement of antenna prototypes

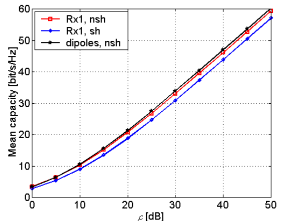
- Antenna prototype was "mounted" to laptop type device (upper figure)
  - Rx 1) Patches at both sides of the cover (A1/ A2 and B1/B2)
  - Rx 2) Patches next to each other (B1/B2 and C1/C2)
- Laptop is "invisible" (interference caused by that was neglected)
  - Laptop "screen" was tilted for different positions in elevation
  - Laptop was rotated for six positions in azimuth
- Analysis was performed with and without shadowing of "human body"
  - ±30° shadowing in azimuth and ±70° shadowing in elevation

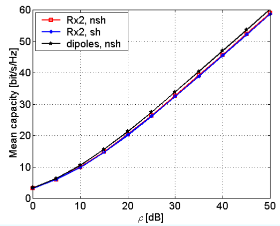




8. Results of antenna evaluation

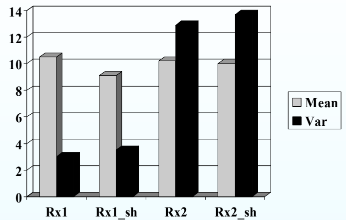
- Mean capacity of two 4x4 MIMO systems were analysed with (blue curve) and without (red curve) shadowing
  - Upper figure: antenna group Rx1(patches against to each other)
  - Lower figure: antenna group Rx2 (patches side by side)
  - Ideal dipole group (black curve) was used as a reference
- Mean capacity results are fairly similar for the both prototype antenna groups
- Prototype antenna groups perform well as compared to the ideal dipole group!

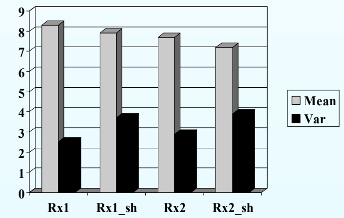




8. Results of antenna evaluation

- Mean and variance of capacity results were calculated over the whole route and over all orientations of device (ρ = 10dB)
  - Tilting angle of cover 90° (upper figure)
  - Tilting angle of cover 0° (lower figure)
- Shadowing increses variance and decreses mean of capacity (expected!)
- Rx1 is more robust for the variations of channel (expected!)
- Tilting angle of 0° causes only small capacity degradation (not expected!)





9. Conclusions

- New compact antenna prototype was developed for the laptop type device
- Two different antenna systems were compared
  - Antennas mounted against to each other (Rx1)
  - Antennas mounted next to each other (Rx2)
- Variance of capacity results is smaller in the case of Rx1 (as compared to Rx2)
- The performance of the both antenna systems (Rx1 and Rx2) are competitive as compared to the dipole group!
- The difference of the mean capacity results with two tilting angles (0°, 90°) is surprisingly small!
- The developed MIMO antenna prototype is feasible e.g. for WLAN applications