

EVALUATION OF DIVERSITY AND MIMO PERFORMANCE OF ANTENNAS FROM PHASELESS RADIATION PATTERNS

Joonas Krogerus⁽¹⁾⁽²⁾, Pasi Suvikunnas⁽²⁾, Clemens Icheln⁽²⁾, Pertti Vainikainen⁽²⁾

⁽¹⁾*Nokia Research Center, Radio Technologies Laboratory
P.O. Box 407, FIN-00045 NOKIA GROUP, Finland*

⁽²⁾*Helsinki University of Technology, IDC/SMARAD/Radio Laboratory
P.O. Box 3000, FIN-02015 TKK, Finland
Email: joonas.krogerus@tkk.fi*

ABSTRACT

We investigate the significance of phase information of radiation patterns for the performance estimates of diversity and multiple-input-multiple-output (MIMO) antenna configurations at 2 GHz band. We also propose a random-phasing technique for performance analysis when the phase information is not available. In the performance analysis we use the Experimental Plane-Wave Based Method (EPWBM) where 3-D radiation patterns of the antennas and measured 3-D signal distribution of the propagation environment are combined. The results show that use of phaseless radiation patterns leads to unacceptable underestimation of performance of multielement antenna systems. However, the use of a random phasing technique with phaseless radiation patterns is shown to be an attractive method for simplifying the antenna evaluation process.

1. INTRODUCTION

Multielement antenna systems have been introduced to enhance the performance of mobile radio communication systems. It has been shown that even with small-sized mobile terminals, diversity and multiple-input-multiple-output (MIMO) techniques can increase the performance of the system, see e.g. [1]. The evaluation of the performance of a multielement antenna configuration is therefore important but at the same time more challenging than the evaluation of a conventional single-antenna system. Direct test-route measurements, fading field simulators, and the Experimental Plane-Wave Based Method (EPWBM) [2] have been proposed for diversity (or single-input-multiple-output, SIMO) and MIMO antenna performance evaluation. Conventionally the EPWBM, and in general all computational techniques of diversity and MIMO performance evaluation, require that both the amplitude and the phase information of the antenna 3-D radiation patterns are available. However, phase information is available only when measuring RF cable-fed antenna prototypes but not when measuring active functional mobile terminals using their internal transmitters or receivers. In this paper we investigate the reliability of diversity and MIMO performance estimations when the phase information of the antenna

3-D radiation patterns is not available. Further, we present a new technique where the missing phase information is substituted with random phase.

2. MULTIELEMENT SYSTEM MODEL

2.1. Channel model and experimental plane wave based method (EPWBM)

In this study a wideband radio channel sounder able of diversity and MIMO measurements was utilized [3] [4]. Multidimensional radio channel library has been collected from extensive measurement campaigns at 2.154 GHz. The transmitted signal was estimated using a beam-forming algorithm implemented for the spherical antenna array, which provides directional signal distribution identifying complex amplitude, polarization, and angle of arrival of multi-path components of the received signal [3]. The measurement system also estimates delay but this study includes only narrowband analysis. Hence, the channel matrix sequences, the size of $n_t \times n_r$, can be expressed by $\{\mathbf{M}_\theta^{(i)(n)}\}_{i=1}^{N_s}$ and $\{\mathbf{M}_\phi^{(i)(n)}\}_{i=1}^{N_s}$ for theta and phi polarizations in spherical coordinates, where n_t and n_r are the numbers of the transmitter and the receiver antennas, respectively. Further, N_s denotes the number of measured samples of the channel. The channel matrix sequences represent antenna independent realizations of the channel or the channel in which isotropic antennas are located at selected locations according to virtual antenna configuration. The effect of slow fading is removed from the channel matrices with a sliding mean [5]. In this work a sliding window of 20λ (100 samples or about 2.8 m) was used.

The EPWBM [2] is used in this work for combining the estimated radio channel with the radiation patterns of the receiver antennas. The antenna system under test can be defined by the complex gain pattern matrices $\mathbf{G}_\phi^{(n)}$ and $\mathbf{G}_\theta^{(n)}$, where the columns of the matrices are devoted to different receiver antenna branches of the antenna system, duplicated over every transmitter antenna branch. Hence, the entries of the matrices

duplicated over each row are the samples of complex gain patterns depending on angles of arrival of multipath components (n). The entries can be defined by $\bar{g}_r^{(n)} = g_r^{(n)} e^{-j\varphi}$ where $r = 1 \dots n_r$ goes over each receiver antenna branch. The antennas under test (AUT) are embedded on the estimated signal distribution forming antenna-dependent channel matrix for the each samples of the channel by

$$\mathbf{H}^{(i)} = \sum_{n=1}^N [\mathbf{M}_{\phi}^{(i)(n)} \circ \mathbf{G}_{\phi}^{(n)} + \mathbf{M}_{\theta}^{(i)(n)} \circ \mathbf{G}_{\theta}^{(n)}]. \quad i = 1 \dots N_s. \quad (1)$$

All antenna-dependent properties, which differ between different antenna candidates (e.g. efficiency and radiation pattern), are included in $\mathbf{H}^{(i)}$. Comparisons with direct test-route measurements have shown that the EPWBM provides reliable estimates of diversity and MIMO performance of antenna systems with less than 1 dB difference in diversity gain and 1 bit/s/Hz in mutual information [2].

Based on the EPWBM the gain patterns of prototype antennas are rotated in 60° steps in azimuth for six orientations in the signal environment afterwards, which increases reliability of antenna evaluation and emulates different possible orientations of a mobile communication device. Hence, the received signal has been calculated for every antenna position and the results are concatenated, which represents a single long route. Thus, the prototype antennas are ‘‘virtually driven’’ through the characterized signal environment. Several instantaneous and mean values of the figures of merit, e.g. maximal ratio combined (MRC) signal power, can be defined over the measured routes and antenna orientations.

2.2. Performance figures of merit

Three different figures of merit are used in the analysis. In the case of multielement antenna systems the (instantaneous) transferred signal power can be stated by

$$P_{MRC}^{(i)} = \|\mathbf{H}^{(i)}\|_F^2, \quad i = 1 \dots N_s, \quad (2)$$

where $\|\bullet\|_F$ denotes a Frobenius norm. In the special case of diversity channel the matrix simplifies into a vector and thus Eq.2 represents a maximal ratio combined (MRC) power of the system. Eigenvalue dispersion [6] expressed as

$$ED^{(i)} = \frac{m_g^{(i)}}{m_a^{(i)}} = \frac{\left(\prod_{k=1}^K \lambda_k^{(i)}\right)^{1/K}}{\frac{1}{K} \sum_{k=1}^K \lambda_k^{(i)}}, \quad i = 1 \dots N_s, \quad (3)$$

is a ratio of arithmetic ($m_g^{(i)}$) and geometric ($m_a^{(i)}$) means of the eigenvalues of $\mathbf{H}^{(i)H} \mathbf{H}^{(i)}$. It defines the ability of a MIMO system to utilize parallel spatial channels. In the assumption that receiver knows the channel the mutual information can be expressed by [7]

$$C^{(i)} = \log_2 \left| \mathbf{I} + \frac{\rho}{n_t} \mathbf{H}^{(i)H} \mathbf{H}^{(i)} \right|, \quad i = 1 \dots N_s, \quad (4)$$

where ρ is system signal to noise ratio at the input of the receiver antennas, \mathbf{I} is identity matrix, and $|\bullet|$ denotes a determinant. Evidently, both the transferred signal power and eigenvalue dispersion affect the mutual information of a MIMO system [8].

Sequences of $\{P_{MRC}^{(i)}\}_{i=1}^{N_s}$, $\{ED^{(i)}\}_{i=1}^{N_s}$ and $\{C^{(i)}\}_{i=1}^{N_s}$ for transferred signal power, eigenvalue dispersion, and mutual information are extracted from the measurements, respectively. All of the parameters are used in the MIMO analysis and the first one is used in the diversity analysis. The outage formulation $\text{prob}[A^{(i)} < A_p] = p$ where A denotes the respective parameter is used in the analysis of the results. The diversity results are analyzed at 10% probability level. Two probability levels (P), 10% and 50%, and three system signal to noise ratios (ρ) of 10 dB, 20 dB and 30 dB, are used in the MIMO analysis.

2.3. Radiation pattern scenarios

Three different scenarios for antenna radiation patterns were considered in the analysis:

- $G(\varphi = \varphi_{meas})$: Original measured complex radiation pattern matrix ($\varphi = \varphi_{meas}$).
- $G(\varphi = 0)$: Radiation pattern matrix with zero phase values ($\varphi = 0$), i.e. phaseless.
- $G(\varphi \in [0 \dots 2\pi])$: Radiation pattern matrix with pseudo-random phase values uniformly distributed between 0 and 2π ($\varphi \in \text{Random}[0 \dots 2\pi]$).

The results of the scenario a) were regarded as the reference results for the two other scenarios b) and c). In case c) a uniformly distributed pseudo-random phase value between 0 and 2π was added to the amplitude-only radiation pattern at each discrete angular point. Separate random phase values were added in both polarization components. Moreover, the random phases were separately generated for each antenna branch and each diversity antenna configuration.

3. MULTIELEMENT ANTENNA SYSTEM PERFORMANCE BASED ON DIFFERENT RADIATION PATTERN INFORMATION

3.1. Multielement antennas

Five diversity antenna prototypes were used as test cases both in the diversity analysis and four in the MIMO analysis. The 3-D radiation patterns of the antennas had been either simulated with an EM field simulator or measured in an anechoic chamber. The antennas in prototypes P1 – P3 are PIFA and IFA antennas placed in different corners of a PWB. The prototype P4 represents a more complex antenna configuration involving a multi-band PIFA as the main antenna and a diversity IFA antenna. The ground plane length is 100 mm for prototypes P1 – P4. The prototype P5 is a practical implementation of P4 into a passive mock-up of a mobile phone. The total efficiencies of the diversity antennas range from 17/32% (branch1/branch2) beside the head (measured, P5), to 79/79% (branch1/branch2) in free space (simulated, P1). The prototypes P3, P4, and P5 were simulated or measured both in free space and beside a head phantom, so in total there were eight different radiation pattern test cases. The prototypes P1 – P4 were also used in [1].

3.2. Measurement environments and transmitter antennas

A total of eight and four test routes were selected from the radio channel library for the diversity and MIMO performance analysis, respectively. The outdoor routes in the diversity analysis can be divided into three different categories namely Microcell, Macrocell and Highway Macrocell. Further, the outdoor routes in the MIMO analysis consist of one Macrocell and two Microcell scenarios. In the diversity analysis a modified vertically polarized GSM 1800 antenna was used at the fixed transmitter (base station). In the MIMO analysis a zigzag antenna array (8 elements, 16 channels) equipped with dual-polarized patch antennas [5] was used. Two outermost antenna elements (four channels) were selected from the measurement arrays – two channels for both theta and phi polarization, respectively.

The indoor route used both in the diversity and the MIMO analysis was measured in the Computer Science building in the campus area of Helsinki University of Technology (TKK). A linear antenna array (8 elements, 16 channels) equipped with dual-polarized patch antennas [5] was used in this study. In the diversity analysis one vertically polarized feed from the patch antenna was selected. In the MIMO analysis two outermost elements of the array were used. Additionally, independently and identically distributed (IID) Rayleigh channel was used as an interesting reference environment.

The selected test routes exhibit typical radio channel properties of current cellular communications systems. The length of the measurement routes range from 50 m (Indoor Picocell) to 1960 m (Highway Macrocell). The cross-polarization ratios (XPRs) of the routes range from 3.6 dB of Highway Macrocell route to 11.1 dB of one of the microcell routes. The XPR is defined in [9]. More details on the used routes are described in [1].

3.3. Diversity results

The maximal ratio combined power (MRC) at 10% probability level $P_{MRC,10\%}$ was used as the figure of merit in the diversity performance analysis. The MRC results are averaged over the eight test routes for each diversity antenna configuration. In the analysis we used Selection Combining (SC), Equal-Gain Combining (EGC), and Maximum-Ratio Combining (MRC) schemes [10]. The relative differences in the results, however, are closely similar between the diversity combining schemes applied. Thus, we concentrate here to the MRC results as an example.

Fig. 1 presents $P_{MRC,10\%}$ for each of the multielement antenna prototypes, averaged over the eight test routes. The results are sorted to the descending order according to the results of $G(\varphi = \varphi_{meas})$. It can be seen that the use of $G(\varphi = 0)$ changes the performance order of the prototypes to some extent, but the effect is slightly smaller when using $G(\varphi \in [0 \dots 2\pi])$. Table 1 shows the differences in the results when averaged over the test routes and Table 2 when averaged over the test routes and the diversity antenna prototypes. The difference is -1.5 dB between the results of $G(\varphi = 0)$ and $G(\varphi = \varphi_{meas})$, and 0.6 dB between the results of $G(\varphi \in [0 \dots 2\pi])$ and $G(\varphi = \varphi_{meas})$. The maximum errors in the cases of some individual test routes for individual prototypes are somewhat larger than the error in the average result: the maximum error of about -2.6 dB was observed for $G(\varphi = 0)$ and 1.5 dB for $G(\varphi \in [0 \dots 2\pi])$.

$P_{MRC,10\%}$ was also analyzed for each measurement route separately by taking an average over all the diversity antennas to study the effect of propagation environment. The results show that the use of $G(\varphi \in [0 \dots 2\pi])$ gives particularly small errors, only about 0.1 – 0.2 dB, on one of the macrocell routes, the Indoor Picocell route, and the IID route. The tendency seems to be that the more random the field distribution in the environment, the smaller the error. The maximum error in the average results on all the other individual test routes is about 0.9 dB. On the other hand, the absolute value of the error with $G(\varphi = 0)$ is about 1 dB or more on all the individual test routes. It is also observed that the

theoretical IID route overestimates the diversity performance about 2 dB as compared to the average result of the eight realistic test routes.

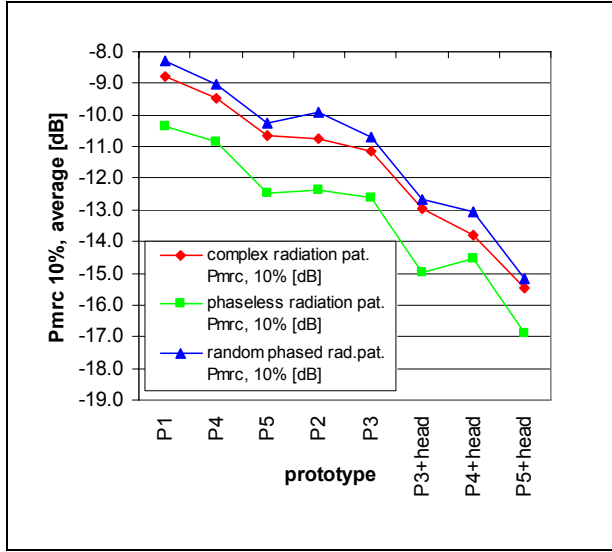


Figure 1. $P_{MRC,10\%}$ (defined in Eq. 2) averaged over the test routes.

Table 1. Differences in $P_{MRC,10\%}$ (averaged over the test routes).

Prototype	absolute - correct	random phased - correct
P1	-1.5 dB	0.5 dB
P4	-1.3 dB	0.5 dB
P5	-1.8 dB	0.4 dB
P2	-1.7 dB	0.8 dB
P3	-1.5 dB	0.4 dB
P3+head	-2.0 dB	0.3 dB
P4+head	-0.7 dB	0.8 dB
P5+head	-1.4 dB	0.3 dB

Table 2. Differences in $P_{MRC,10\%}$ (averaged over the test routes and the prototypes).

absolute - correct	random phased - correct
-1.5 dB	0.6 dB

3.4. MIMO results

Outage mutual information, transferred signal power and eigenvalue dispersion for signal to noise ratio of $\rho = 20$ dB are presented in Fig. 2. When using absolute (i.e. phaseless) radiation patterns instead of complex ones degradation in capacity is due to decreased eigenvalue dispersion, see Fig 2. The underestimation in the mean capacity over all the antennas when using $G(\varphi = 0)$ is about 15%, see Table 3. The results where $G(\varphi = \varphi_{meas})$ was replaced with $G(\varphi \in [0 \dots 2\pi])$ were close to each other. The use of $G(\varphi \in [0 \dots 2\pi])$ overestimates the capacity less than 5% when averaged over all the considered antenna prototypes (Table 3).

Table 3. Relative difference (%) between the MIMO results when using: 1) absolute and correct phase, 2) random and correct phase.

$P \backslash \rho$	20 dB (absolute)	30 dB (absolute)	20 dB (random phased)	30 dB (random phased)
10%	-15.8 %	-14.1 %	2.9 %	2.2 %
50%	-16.7 %	-12.6 %	3.3 %	2.1 %

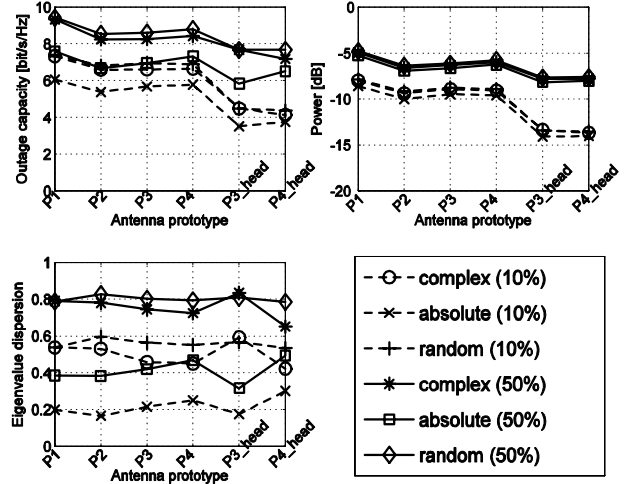


Figure 2. Outage capacity, transferred signal power, and eigenvalue dispersion are presented at two probability levels of 10% and 50% for system signal to noise ratio of 20 dB.

4. CONCLUSIONS

In this work we have investigated the reliability of performance estimates of multielement antenna systems at the 2 GHz band when phase information of 3-D gain patterns of the antennas is not available. This is the case e.g. when measuring active mobile terminals with diversity or MIMO antenna systems.

Three different ways of using the antenna radiation pattern were compared: original complex gain patterns, phaseless gain patterns, and random-phased gain patterns. The normalized MRC combined power at 10% probability level $P_{MRC,10\%}$ was used as the figure of merit in the diversity analysis. In the MIMO analysis the outage mutual information, transferred signal power, and eigenvalue dispersion were used as the figures of merit.

In the diversity analysis, when the results were averaged over all the test routes and the antennas, the use of absolute radiation patterns produced an error of about -1.5 dB to the average $P_{MRC,10\%}$, as compared to the average result with the reference complex gain patterns. When random phase was added to the phaseless

radiation patterns the error in the average result was about 0.6 dB.

In the MIMO analysis the underestimation in outage mutual information over all the antennas and routes when using phaseless radiation patterns was about 15%. The use of random phases overestimated the average capacity less than 5%. The error is mainly due to wrongly estimated eigenvalue dispersion.

Both the diversity and the MIMO analysis show that the direct use of phaseless gain patterns leads to too large errors in the performance evaluation. However, the new random-phasing technique that was presented reduces considerably the error. This shows the feasibility of this approach where only a phaseless 3-D radiation pattern is measured and the random phases are added in post-processing. It may be possible to utilize this technique for developing a method to evaluate the performance of active mobile devices with multielement antennas.

5. ACKNOWLEDGEMENT

This research was partially funded by Nokia, LK-Products, TEKES, and the Academy of Finland. The first author would also like to thank the Nokia Foundation and the HPY Research Foundation for financial support.

REFERENCES

- [1] J. Villanen, P. Suvikunnas, K. Sulonen, J. Ollikainen, P. Vainikainen, "Advances in diversity performance analysis of mobile terminal antennas," In *Proc. of the 2004 Int. Symp. on Ant. and Prop. (ISAP'2004)*, Sendai, Japan, August 2004, pp. 649–652.
- [2] P. Suvikunnas, J. Villanen, K. Sulonen, C. Icheln, J. Ollikainen, P. Vainikainen, "Evaluation of the Performance of Multi-Antenna Terminals Using a New Approach," *Accepted in December 2005 for publication in IEEE Trans. Instr. and Meas.*
- [3] K. Kalliola, H. Laitinen, L. Vaskelainen, P. Vainikainen, "Real-Time 3-D Spatial-Temporal Dual-Polarized Measurement of Wideband Radio Channel at Mobile Channel," *IEEE Trans. Instrum. Meas.*, vol. 49, no. 2, pp. 439–448, April 2000.
- [4] J. Kivinen, P. Suvikunnas, D. Perez, C. Herrero, K. Kalliola, P. Vainikainen, "Characterization system for MIMO channels," in *Proc. 4th Int. Symp. Wireless Personal Multimedia Communications (WMPMC'01)*, Aalborg, Denmark, 2001, pp. 159–162.
- [5] K. Sulonen, P. Suvikunnas, L. Vuokko, J. Kivinen, P. Vainikainen, "Comparison of MIMO antenna configurations in picocell and microcell environments," *IEEE J. Select. Areas Commun., MIMO systems and applications*, vol. 21, no. 5, pp. 703–712, June 2003.
- [6] J. Salo, P. Suvikunnas, H. M. Sallabi, and P. Vainikainen, "Ellipticity Statistic as a Measure of MIMO Multipath Richness," *IEE Electronics Letters*, vol. 2, no. 3, pp. 160–162, Feb. 2006.
- [7] G. J. Foschini, M. J. Gans, "On the limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, no. 3, pp. 311–335, March 1998.
- [8] P. Suvikunnas, J. Salo, L. Vuokko, J. Kivinen, K. Sulonen and P. Vainikainen, "Empirical comparison of MIMO antenna configurations," in *Proc. IEEE Veh. Tech. Conf.*, vol. 1, Stockholm, Sweden, 30 May – 1 June 2005, pp. 53–57.
- [9] T. Taga, "Analysis for mean effective gain of mobile antennas in land mobile radio environments," *IEEE Trans. Veh. Technol.*, vol. 39, no. 2, pp. 117–131, May 1990.
- [10] W. C. Jakes, Y. S. Yeh, M. J. Gans, and D. O. Reudink, "Fundamentals of diversity systems," *Chapter 5 in Microwave Mobile Communications*, W. C. Jakes, (Editor), New York, 1974, IEEE Press, 642 p.