Fundamental Limitations on Small Multi-Beam Antennas for MIMO Systems

(article starts on next page)

Fundamental Limitations on Small Multi-Beam Antennas for MIMO Systems

Per-Simon Kildal, Xiaoming Chen
Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden, per-simon.kildal@chalmers.se

***Abstract*—The paper finds theoretical limitations with MIMO technology of higher order when space is limited. The results show that it is possible to achieve up to six independent identically distributed (i.i.d.) channels in rich isotropic multipath (RIMP) by combining different incremental sources to an incrementally small 6-port antenna. This means that we with incrementally small antennas can generate MIMO performance with maximum six data streams in RIMP (rank 6). We also show that it is possible to achieve completely isotropic full-spherical angular coverage by using an incrementally small 3-port antenna consisting of three orthogonal electric or magnetic dipoles. However, it is possible to get isotropic spatial coverage with 3 dB higher directivity in all directions by using a 6-port antenna consisting of both three orthogonal electric dipoles and three orthogonal magnetic dipoles, or alternatively a 6-port Huygens antenna consisting of 6 uncoupled Huygens sources. In random-LOS (having only a single angle of arrival) there will be a maximum of two data streams (rank 2) available, associated with two orthogonal polarizations. We show that both streams can be received with the 3-port incremental dipole antenna, and with 3 dB higher power with either of the 6-port antennas. The randomness of the angle of arrival in LOS is caused by the arbitrary orientation and location of the user-terminal.**

***Index Terms*—antenna, propagation, measurement.**

I. INTRODUCTION

The 4th Generation (4G) mobile communication system, also referred to by the acronym LTE (Long Term Evolution), has become very flexible compared to previous systems by its advanced dynamic digital signal processing capability. This is enabled by using multi-port antennas at both the transmitting and receiving sides, and referred to as MIMO (Multiple Input Multiple Output) [1]. The MIMO technology used in mobile communication systems is not limited to this classical Line-Of-Sight (LOS) of a single arriving wave. The digital processing is in particular advantageous in multipath environments. Such fading causes outage (i.e. no reception) during periods of the time for moving users, and corresponding outage among some of many arbitrary distributed stationary users in the environment. The digital MIMO processing reduces the outage problem by using antenna diversity when receiving a single bit stream, and spatial multiplexing when receiving two or more bit streams. The present paper deals with the theoretical limitations on MIMO performance of small antennas in both rich isotropic multipath (RIMP) and pure LOS.

Multi-port antennas are in wireless MIMO systems used both for the base stations and in the user-terminals. The user and his terminal can be exposed both to LOS and multipath, and the base station can also be located inside the multipath environment together with the user and his terminal. This is in particular so for micro base transceiver stations (mBTS). This means that there may be a significant LOS contribution to the wireless channel between them. This LOS contribution may be much more significant than for terminals having contact with macro base stations. The LOS contribution will in a mobile wireless system be random due to the arbitrary orientation and location of the user, and it is therefore herein referred to as a random-LOS. Therefore, this needs also to be characterized in terms of its statistical performance, in the same way as fading due to multipath. This was discussed in [2] where it was proposed to introduce both the RIMP and the random-LOS as reference environments, referred to as limiting environments.

Throughout the paper, we assume a MIMO systems and we use ViRM-lab (Visual Random Multi-path environment Laboratory) [3] as the simulation tool to study performance in RIMP and random-LOS. The performance of the antenna is characterized in terms of its Probability of Detection (PoD) of different number of bit streams in RIMP and 3D random-LOS. The PoD of single bit streams follows the theories in [4] and multiple bit streams are generated by using the zero forcing (ZF) algorithm as outlined in [5]. We choose to quantify the detection probabilities at 95% level in dBiid, i.e., relative to the corresponding i.i.d. case [5]- [6].

Small antennas have a directivity limitation of 4.8 dB as described in [7]. This is achievable with an incremental Huygens source, which consists of an optimum combination of an electric and a magnetic incremental dipole. The Huygens source plays also an important role in the present paper.

It is well known that the number of independent field components in a multipath environment is six, and that this will make it possible to explore three times more channels through multipath than under LOS (under line of sight we have max independent channels corresponding to using two orthogonal polarizations). Still, the present paper contains new material, because it quantifies the performance of the six independent ports in rich isotropic multipath, as well as in pure random LOS. The paper also introduces the Huygens source as a very suitable theoretical element for theoretical studies of MIMO antenna systems, because it has the maximum achievable directivity of small antennas. The Huygens source has in addition a null in the backwards direction so that

978-88-907018-4-9/14/$31.00

Huygens sources can be mounted around a shielded central volume with electronic equipment that will not disturb the radiation performance.

II. INCREMENTAL SOURCES

The common incremental sources are incremental electric dipoles, incremental magnetic dipoles, and Huygens sources. The electric and magnetic dipoles are omnidirectional in one ϕ-plane with directivity 1.8 dBi, and the Huygens source is directional with directivity of 4.8 dBi. The Huygens source is actually the most directive small antenna possible, obtained by a specific combination of an electric and magnetic dipole. Small electric dipoles are realized by straight wires, and small magnetic dipoles by wires shaped as loops. The most commonly used practical small antenna is the inverted F-antenna, and this can have directivities up to 4.8 dBi and even larger if it is located in a large ground plane [7].

We assume in the present paper that these incremental antennas are impedance matched and lossless when we evaluate the performance.

The advantage of a MIMO system is that the antenna is adaptive. It adapts to one or more incident waves, to maximize the amplitude of the combined received voltage. We will now present the results for Huygens sources obtained by numerical simulations using ViRMlab. The MIMO-related results have been obtained by processing the channels from ViRMlab using the threshold receiver in [4], the Maximum Ration Combination (MRC) algorithm for one bit stream case, and the ZF algorithm for the multiple bit stream case, the latter being explained in [5]. We regard the Probability of Detection (PoD) of multiple bit streams as the PoD of detecting the weakest stream.

III. RADIATION PATTERNS AND ANGULAR MIMO COVERAGE PATTERNS

The radiation patterns of a single electric dipole and a Huygens source are shown in Fig. 1. The magnetic dipole has a similar patterns as the electric dipole, but the polarization is orthogonal, i.e. horizontal polarization if the pattern looks like that of the electric dipole in Fig 1.

The single-stream coverage patterns in random-LOS of three orthogonal dipoles, and of 6 orthogonal Huygens sources are given in Fig. 2. The latter are pointing in six different directions (along positive and negative x, y and z-axes), and we call them orthogonal because they are completely uncoupled with no correlation in RIMP. The coverage patterns have been obtained by applying the MRC algorithm to the 3 and 6 ports, respectively. We see that the three electric dipoles have an isotropic coverage when diversity-combined with MRC. The six Huygens sources have also an isotropic coverage, but with 3 dB higher directivity in all directions, i.e. they can together achieve an adaptive directivity in any direction of 4.8 dBi, which is the normal directivity in the main lobe direction of each one of them. Thus, a linear combination (i.e. MRC combination) of all six of them will give an isotropic coverage of the same directivity.

The PoDs in random-LOS are shown in Figs. 3 and 4 as a function of P_{av}/ P_t where P_{av} is the received power of an ideal single-port isotropic antenna that is polarization-matched to the single incident wave, and P_t is the sensitivity i.e. threshold of the ideal threshold receiver introduced in [4]. Fig. 3 shows the PoD for s single bit stream when we increase the number of orthogonal dipoles from 1 to 3, and the number of Huygens sources from 1 to 6. We have included the i.i.d. curves in the graphs for comparison, corresponding to the RIMP environment. We see how the PoD increases when we increase the number of antennas, and finally when we have 3 dipoles and 6 Huygens sources the PoD is a step function showing that the coverage is isotropic. Fig. 4 shows the PoD of two bit streams when using 3 orthogonal dipoles and 6 orthogonal Huygens sources in a 3x2 and 6x2 MIMO system, respectively. We see that 3 orthogonal dipoles gives an isotropic coverage of the PoD of 2 bit streams in random-LOS (i.e. the PoD is a step function). The 6 orthogonal Huygens sources has an isotropic coverage of 3 dB lower threshold due to the 3 dB larger directivity. The PoD thresholds for the two bit stream cases are located at 3 dB higher level than for the corresponding single bit stream case. Three orthogonal electric dipoles combined with three orthogonal magnetic dipoles gives the same coverage patterns as the six Huygens sources.

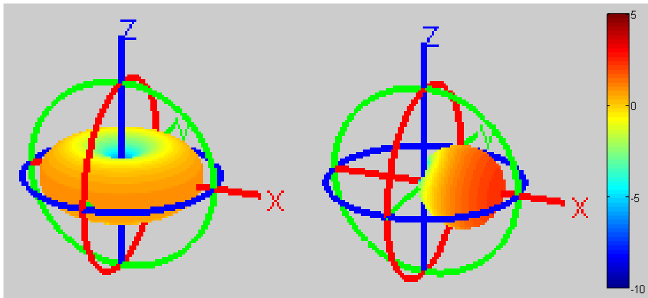

Fig. 1. Far field patterns of vertically polarized electric dipole (left) and Huygens source (right), representing the coverage patterns of single bit streams for the SISO case in random-LOS.

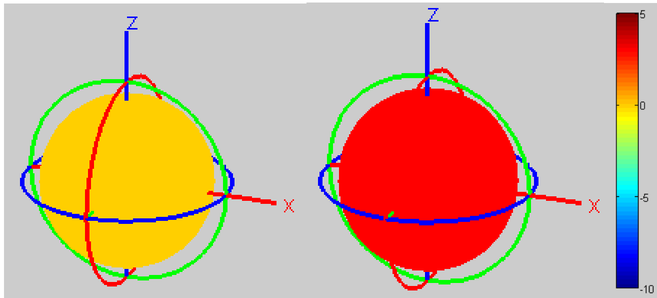

Fig. 2. Coverage patterns for a single bit stream for 3 orthogonal electric dipoles (left) and 6 orthogonal Huygens sources (right) in random-LOS when the antennas are used as receive antennas in a 3x1 and 6x1 MIMO system, respectively.

IV. PERFORMANCE IN RIMP

The performance in rich isotropic multipath (RIMP) is shown in the same Figs. 3 and 4 as the random-LOS performance. The results are marked as i.i.d. case, because they become identical to i.i.d. curves generated by a numerical random number generator.

V. CONCLUSION

The results show that it is possible to achieve three uncorrelated channels in rich isotropic multipath (RIMP) by using an incrementally small 3-port antenna consisting of three orthogonal electric or magnetic dipoles, and to achieve six uncorrelated channels by using an incrementally small 6-port antenna consisting of six orthogonal Huygens sources, or alternatively a 6-port antenna consisting of three orthogonal electric and three orthogonal magnetic dipoles. The same incrementally small 3-port and 6-port antennas have completely isotropic full-spherical coverage of two polarizations in pure LOS with constant directivities of 1.8 dBi and 4.8 dBi, respectively. The isotropic full-spherical coverage in pure random LOS is valid both for 1 and 2 bit steams, and more than 2 bit streams are not possible in a pure LOS. The characteristics of the 6-port Huygens sources make them attractive as reference sources in theoretical works on MIMO performance, and in particular in the presence of LOS. They represent also important limitations of the MIMO performance of small antennas in both RIMP and random-LOS.

The characterization in random-LOS is a concept introduced in [2] and used also in [8]. It is very important for the OTA characterization of micro base stations in [9].

REFERENCES

[1] C. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell Labs Tech. Journal*, vol. 1, pp. 41-59, 1996.

[2] P.-S. Kildal, C. Orlenius, and J. Carlsson, "OTA testing in multipath of antennas and wireless devices with MIMO and OFDM," Proc. IEEE, vol. 100, no. 7, pp. 2145-2157, July 2012.

[3] U. Carlberg, J. Carlsson, A. Hussain, and P. S. Kildal, "Ray based multipath simulation tool for studying convergence and estimating ergodic capacity and diversity gain for antennas with given far-field functions," in *20th Internat. Conf. Applied Electromagnetics and Communications (ICECom), 20-23 Sept. 2010*, Dubrovnik, Kroatia, 2010.

[4] P.-S. Kildal, A. Hussain, X. Chen, C. Orlenius, A. Skårbratt, J. Åsberg, T. Svensson, and T. Eriksson, "Threshold receiver model for throughput of wireless devices with MIMO and frequency diversity measured in reverberation chamber," IEEE Antennas and Wireless Propagation Letters, vol. 10, pp. 1201-1204, 2011.

[5] *X. Chen, P.-S. Kildal, and* M. Gustafsson, "Characterization of Implemented Algorithm for MIMO Spatial Multiplexing in Reverberation Chamber," IEEE Transactions on Antennas and Propagation, vol. 61, no. 8, pp. 4400-4404, Aug. 2013.

[6] P.-S. Kildal, "Rethinking the Wireless Channel for OTA testing and Network Optimization by Including User Statistics: RIMP, pure-LOS, Throughput and Detection Probability," in ISAP 2013, Nanjing, China, Oct. 2013.

[7] P.-S. Kildal and S. R. Best, "Further investigations of fundamental directivity limitations of small antennas with and without ground planes", IEEE International Symposium on Antennas and Propagation (IEEE AP-S), San Diego, July 2008.

[8] P.-S. Kildal, U. Carlberg, J. Carlsson, "Definition of Antenna Diversity Gain in User-Distributed 3D-Random Line-Of-Sight", Journal of Electromagnetic Engineering and Science (JEES), Vol. 13, No. 2, pp. 86-92, June 2013.

[9] M. Gustafsson, X. Chen, P.-S. Kildal, "OTA Characterization of □BTS Antenna in RIMP and Random-LOS", EuCAP 2014, The Hague, The Netherlands, 6-11 April 2014

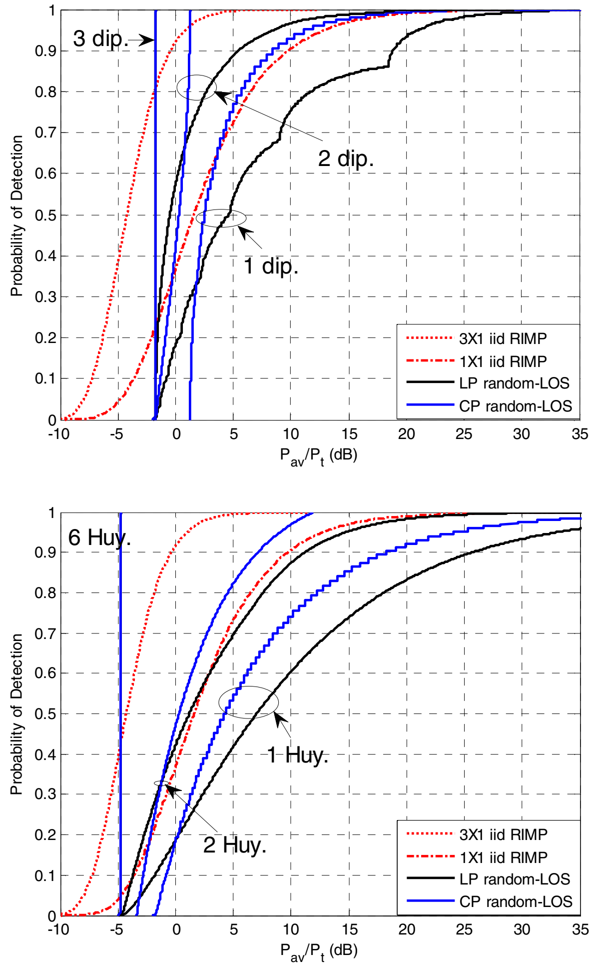

Fig. 3. PoD of dipoles and Huygens sources in random-LOS and in RIMP. The RIMP case is identical to the i.i.d. case.

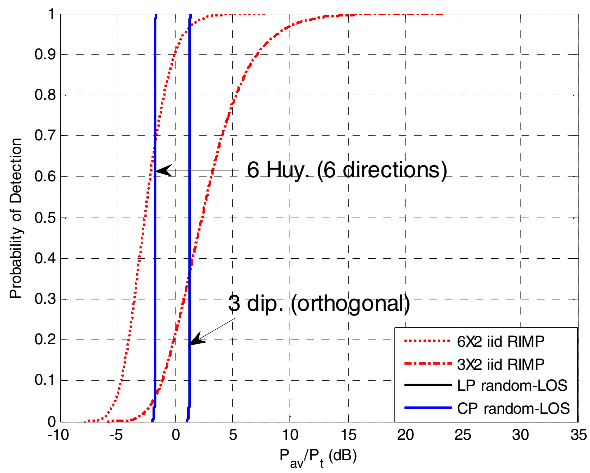

Fig. 4. PoD of 2 bit streams in random-LOS and in RIMP (i.e. i.i.d. case) when using 3 orthogonal dipoles and 6 orthogonal Huygens sources.