Analysis of compact Arrays for MIMO based a on complete RF System Model

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Abstract—**A model for an extended MIMO transmission channel including transmitter, receiver, antennas and the physical channel is presented. For the analysis of compact MIMO systems for small handheld devices, it is inevitable to consider this extended model, since the antennas couple and interact, which influences both SNR and the channel matrix H. Capacity calculations for diversity and beamforming based MIMO systems are given.**

I. Introduction

Recent studies have shown the potential of multiple transmit and multiple receive (MIMO) antennas to reach high spectral efficiencies [1]. MIMO systems combine diversity and beamforming techniques. The capacity or spectral efficiency respectively depends on the signal to noise ratio (SNR) and the correlation properties among the channel transfer functions of different pairs of transmit and receive antennas. Uncorrelated channel transfer functions or channel coefficients in the flat fading case lead to high capacities for MIMO systems, that are based on multiplexing and use several subchannels, [2]. On the other hand, it is attractive to use only the best subchannel since the complexity of the signal processing is lower and long term statistics of the channel can be well exploited, see [3]. Additionally, using the best subchannel is often the optimal solution for maximum data throughput in multi user MIMO scenarios, see [4]. If only the best subchannel is used, correlation among the channel coefficients is necessary and increases the capacity. For such systems, the signal processing reduces to an intelligent beamforming. For that reason MIMO systems, that use only the best subchannel, are called beamforming based in the following.

Many handheld devices like laptops or palmtops require small antenna spacings. This requirement is contrary to uncorrelated channel coefficients for MIMO systems based on space diversity, thus other diversity techniques have to be applied. For beamforming based systems, small antenna spacings lead to correlated channel coefficients, thus do at first sight not decrease the channel capacity.

In almost all studies about MIMO, the SNR is assumed to be independent of the correlation properties of the channel matrix H, which contains the channel coefficients. Especially for small antenna spacings this assumption does not hold, as mutual coupling influences both SNR and H. In recent studies about mutual coupling this effect has been neglected, see [5], [6]. The same holds for mismatching of the antenna arrays. For beamforming based MIMO systems the SNR is reduced for small antenna spacings, since the effective gain of the antennas is reduced, which decreases the capacity.

For compact antenna arrays it is necessary to analyze the SNR and the properties of H together. Therefore an extended channel, including transmitter (Tx), receiver (Rx), antennas and the physical channel is taken into account. The model allows to analyze the whole radio frequency transmission chain, including mutual coupling and mismatching effects. Some ideas of this approach are taken from [7], but this paper includes the transmitter and presents results for different kinds of MIMO systems.

In section II the system model is given. Section III presents capacity calculations for the above mentioned MIMO systems.

II. System Model

The complete radio frequency transmission chain consists of 5 elements: Tx - Tx antennas - channel - Rx antennas - Rx, given in figure 1. The transmitter is characterized by an impedance matrix for the output ports and determines the transmit power distribution among the antennas, thus realizes e.g. beamforming. The transmit (and receive) antennas are described by their input impedance matrix and the far field ports. The input impedance matrix consists of the self-impedance on the main diagonal and the mutual coupling impedances at the off-diagonal elements. The far field ports describe the radiated field (i.e. the pattern). The channel is modelled by a path based stochastic channel model, that takes the spatial propagation conditions into account. The receiver is characterized by its input impedance matrix which defines the load the antennas are connected to. The antennas and the channel are directive, which makes the mathematical description of the complete system difficult. To simplify the model, the radiation pattern, which belongs to the antenna network, may be assigned to the channel properties, thus the characterization of the antennas is not directive anymore. Hence the channel coefficients between Tx_i and Rx_j, expressed as a scattering parameter, are

$$S_{ij} = \sqrt{\left(\frac{\lambda}{4\pi}\right)^2 \frac{\Re(Z_j)}{\Re(Z_i)} G_i G_j} \sum_{paths} C_j T C_i \qquad (1)$$

where $C_{i/j}$ is the complex polarimetric pattern, $G_{i/j}$ is the effective gain and $Z_{i/j}$ the input impedance of the Tx_i and Rx_j antennas. T is the polarimetric channel transfer matrix, given by the channel model [8]. Note, that if mutual coupling is taken into account, $C_{i/j}$ are

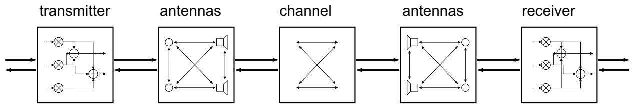

Fig. 1. System model of the complete radio frequency transmission chain. All elements are described by N-port scattering matrices.

the patterns of the antenna system with coupling, connected to the Tx/Rx load network. With the above simplification, the model is reduced to three elements: Tx, modified channel, Rx. The modified channel is characterized by a scattering matrix, that contains (as submatrices) the input impedance matrix of the Tx and Rx antennas and the channel matrix, whose elements are given by equation (1).

III. Capacity of 2x2 MIMO systems

The antenna arrays used for the simulation consist of two half-wavelength dipoles, arranged in parallel. The pattern, effective gain and mutual coupling impedances were calculated by a standard tool, based on method of moments (FEKO), for each antenna spacing. The MIMO system is equipped with the same arrays at the Tx and Rx. The channel model provides channels with a uniform power azimuth spectrum, corresponding to an indoor scenario. The incident field is randomly oriented to the antennas. For the simulation given here the arrays are perfectly matched and the transmit power is kept constant for all antenna spacings.

Figure 2 shows the capacity of the MIMO system based on multiplex transmission with no channel knowledge at the transmitter, thus the transmit power is equally distributed among all Tx antennas. For small antenna spacings the capacity drops dramatically due to a decreasing SNR and correlated channel coefficients. Note that the SNR decreases due to mutual coupling though the antennas are perfectly matched.

Figure 3 presents a comparison of the capacity of the MIMO system for beamforming and optimum multiplex transmission, called waterfilling (in contrast to figure 2 the channel has to be known at the TX). For very small antenna spacings waterfilling merges into beamforming since here the second subchannel gets very weak.

The gray lines in both figures present the results for a channel matrix H, that is normalized by a Frobenius norm to make it independent of the SNR, as done in many former studies. In that case, the beamforming capacity even increases for small antenna spacings, which makes the necessity of an accurate and more realistic modeling evident. In the realistic model, where H and the SNR are not independent from one another, the beamforming capacity decreases.

IV. Conclusion

In this paper it is shown, that it is necessary to analyze SNR and H together for comparison of different antennas or investigations on compact antenna arrays. The degradation of the SNR for small antenna spacings strongly influences the capability of an antenna setup for MIMO.

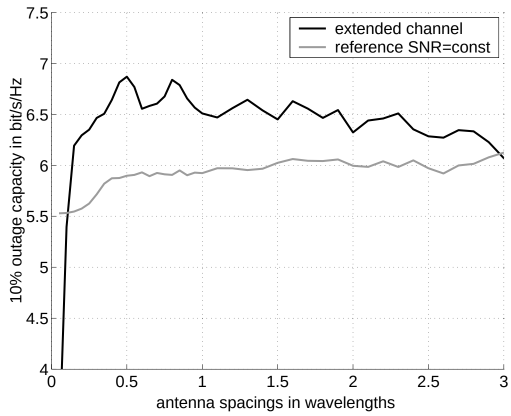

Fig. 2. 10 % outage capacity vs antenna spacings for equally distributed transmit power. For the gray curve the SNR is constant, whereas the SNR variations due to coupling are considered in the extended channel.

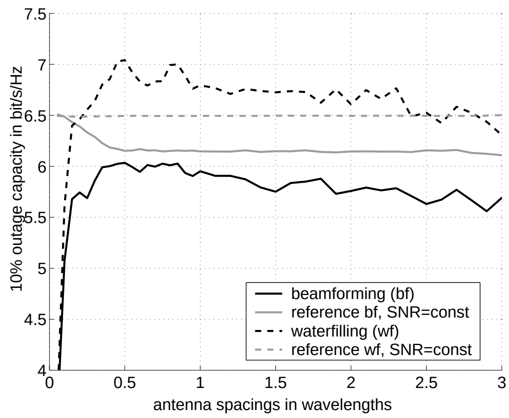

Fig. 3. If the channel is known at the Tx, beamforming or optimal multiplex transmission called waterfilling are options for the MIMO system. Both curves merge into one another for very small antenna spacings.

References

[1] G.J. Foschini and M.J. Gans. On limits of wireless communications in a fading environment when using multiple antennas. *Wireless Personal Communications*, 6:311–335, 1998.

[2] C. Chuah, D.N.C. Tse, J. M. Kahn, and R.A. Valenzuela. Capacity Scaling in MIMO Wireless Systems Under Correlated Fading. *IEEE Transactions on Information Theory*, 48:637–650, 2002.

[3] M.T. Ivrlac and J.A. Nossek. MIMO eigenbeamforming in correlated fading. *IEEE Proceedings of Circuits and Systems for Communications Conference*, pages 212–215, 2002.

[4] N. Geng, I. Viering, and M. Kiessling. Multi-user MIMO-OFDM cell throughput under real-world propagation conditions. *IEEE Proceedings of the Vehicular Technology Conference*, 2:879–883, 2002.

[5] C. Waldschmidt J. v. Hagen and W. Wiesbeck. Influence and Modelling of Mutual Coupling in MIMO and Diversity Systems. *IEEE International Symposium on Antennas and Propagation AP-S, San Antonio, Texas*, 3:190–193, 2002.

[6] T. Svantesson. Mutual coupling effects on the capacity of multielement antenna systems. *IEEE Proceedings of Acoustics, Speech, and Signal Processing Conference*, 2:2485–2488, 2001.

[7] J. W. Wallace and M. A. Jensen. The capacity of MIMO wireless systems with mutual coupling. *IEEE Proceedings of the Vehicular Technology Conference*, 2:696–700, 2002.

[8] T. Zwick, C. Fischer, and W. Wiesbeck. A stochastic multipath channel model including path directions for indoor environments. *IEEE Journal on Selected Areas in Communications*, 20:1178–1192, 2002.