Multiple Antennas in Mobile Communications
Concepts and Algorithms

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Abstract: Multiple antenna systems have become very popular since the middle of the nineties. The growing demand in high data rate communications and simultaneous bandwidth restrictions emphasize the necessity of systems with high spectral efficiencies. This paper gives an overview of the application of multiple antennas at transmitter and receiver for mobile radio communications. It is explained how the channel properties and the level of channel knowledge affect the best strategy to use multiple antennas. Diversity concepts and beamforming enhancing the link reliability are discussed as well as approaches multiplying the achievable data rate by space division multiple access.

1. SYSTEM MODEL

Multiple antennas can be employed in a variety of different ways that highly depend on the properties of the physical channel and the degree of channel state information (CSI) at transmitter and receiver. For the sake of simplicity, only frequency nonselective channels are considered although the approaches can be extended to the frequency selective case. Assuming a system with M transmit and N receive antennas, the common linear signal model

$$\mathbf{y}[k] = \mathbf{H}[k]\cdot\mathbf{x}[k] + \mathbf{n}[k] = \mathbf{U}[k]\mathbf{\Sigma}[k]\mathbf{V}^H[k]\cdot\mathbf{x}[k] + \mathbf{n}[k] \tag{1}$$

is used where $\mathbf{x}[k]$ denotes the $M\times 1$ transmit vector at time instance k whose elements $x_j[k]$ are chosen from a discrete alphabet. The $N\times 1$ vectors $\mathbf{y}[k]$ and $\mathbf{n}[k]$ represent the received signal and the noise, respectively. A coefficient $h_{ij}[k]$ of the $N\times M$ channel matrix $\mathbf{H}[k]$ describes the flat channel between transmit antenna j and receive antenna i. It is generally modeled in the equivalent baseband as a complex random variable whose real and imaginary parts are statistically independent Gaussian distributed.

$\mathbf{H}[k]$ can be decomposed by the singular value decomposition (SVD) into two unitary matrices $\mathbf{U}[k]$ and $\mathbf{V}[k]$ and a diagonal matrix $\mathbf{\Sigma}[k]$. Alternatively, when only long-term statistics of the channel are known, the eigenvalue decomposition is applied to the covariance matrix $\mathbf{R}_{\mathbf{HH}} = \mathrm{E}\{\mathbf{H}[k]^H\cdot\mathbf{H}[k]\} = \bar{\mathbf{V}}\bar{\mathbf{\Lambda}}\bar{\mathbf{V}}^H$. In order to classify different multiple antenna strategies, the properties of $\mathbf{H}$ or $\mathbf{R}_{\mathbf{HH}}$ and the kind of CSI at transmitter and receiver have to be analyzed.

Mainly, two purposes are pursued: a) improving the quality of a link by diversity concepts or beamforming and b) multiplying the data rate by spatial multi-layer transmission[1]. Both strategies are described in the subsequent sections.

2. INCREASING LINK RELIABILITY

Diversity is obtained by receiving several statistically independent replicas of the same signal. Appropriate combining of the replicas reduces the impact of deep fades and leads to smaller variations of the signal-to-noise-ratio (SNR). Thereby, no channel knowledge is required at the transmitter. For proper code designs and statistically independent channel coefficients with equal average power, the achievable diversity degree equals $D = M\cdot N$. If the coefficients $h_{ij}[k]$ are correlated, i.e. there exist preferred directions of arrival or departure, $D < M\cdot N$ holds and different strategies may be preferable.

Figure 1a shows the probability density of the normalized SNR after maximum ratio combining D statistically independent replicas with equal average power. For Rayleigh fading, the SNR is chi-squared distributed with $2D$ degrees of freedom. Obviously, the variations become smaller for increasing D and vanish totally for $D\rightarrow\infty$. Figure 1b depicts the corresponding average bit error probabilities for BPSK. In the asymptotic case, the performance of an AWGN channel without fading (dashed line) is reached.

While combining the signals of multiple receive antennas is straight forward, diversity concepts for multiple transmit antennas require appropriate coding. So called Space-Time Codes (STC) perform the encoding over space and time, i.e. they map a block of temporally successive symbols onto the transmit antennas during a certain number of time slots. Generally, Space-Time Block-Codes (STBC) [1,2] and Space-Time Trellis-Codes (STTC) [3,4] are distinguished.

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1 In cellular environments, also topics like interference avoidance and interference suppression are important.

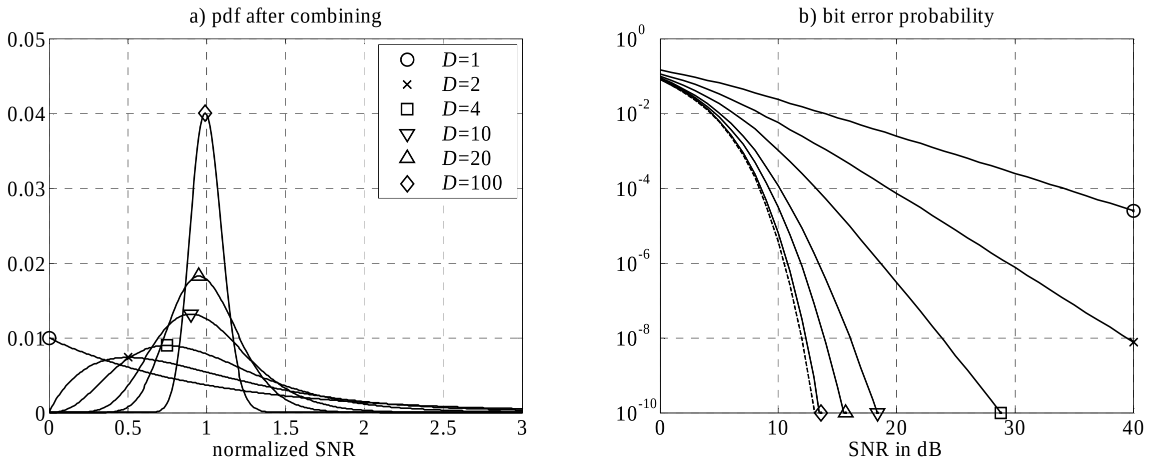

Fig. 1: PDF of normalized SNR and symbol error probability for different diversity degrees and maximum ratio combining

The most famous and simplest example for STBCs with two transmit antennas is Alamouti's scheme. Two successive symbols s_1 and s_2 are encoded such that $\mathbf{x}[1] = [s_1\ s_2]^T$ is transmitted at time instance 1 and $\mathbf{x}[2] = [-s_2^*\ s_1^*]^T$ at time instance 2. This leads to an orthogonalization of the equivalent channel matrix so that the optimal receiver simply performs a linear maximum ratio combining according to

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \cdot \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \quad \Rightarrow \quad \begin{bmatrix} \hat{s}_1 \\ \hat{s}_2 \end{bmatrix} = \begin{bmatrix} h_1^* y_1 + h_2 y_2^* \\ h_2^* y_1 - h_1 y_2^* \end{bmatrix} = \begin{bmatrix} \left(|h_1|^2 + |h_2|^2\right) s_1 + \eta_1 \\ \left(|h_1|^2 + |h_2|^2\right) s_2 + \eta_2 \end{bmatrix}. \tag{2}$$

No mutual interference between s_1 and s_2 disturbs the transmission and diversity of order 2 is achieved. The rate is $R = 1$ since two symbols are transmitted during two time slots. Orthogonal designs for higher diversity degrees and more than 2 transmit antennas exist only for $R < 1$, i.e. spectral efficiency is lost [2].

(Eigen)Beamforming: For rank deficient channel matrices $\mathbf{H}$, preferred directions of arrival or departure exist that can be exploited by beamforming. This requires knowledge of $\mathbf{H}$ or $\mathbf{R_{HH}}$ at the transmitter. Classical beamforming just exploits the eigenvector $\mathbf{v}_{\max}$ corresponding to the largest eigenvalue $\lambda_{\max}$ of $\mathbf{\Lambda}$ resulting in the transmit vector $\mathbf{x}[k] = \mathbf{v}_{\max}[k] \cdot s[k]$ (beamforming) or $\mathbf{x}[k] = \bar{\mathbf{v}}_{\max} s[k]$ (eigen-beamforming). Beamforming also allows the suppression of interference caused by other users and, therefore, the maximization the signal-to-interference-plus-noise-ratio (SINR). The question whether beamforming or diversity concepts should be preferred cannot be answered in general but depends on several conditions, e.g. the SNR, if other diversity sources such as frequency or time diversity are available, etc.

3. SPATIAL MULTIPLEXING

Instead of increasing the link reliability, multiple antennas can also be used for multiplying the data rate by spatial multiplexing. As in the case of diversity concepts, the channel knowledge at the transmitter affects the optimum transmission strategy. Without any channel state information, M independent data streams called layers are simultaneously transmitted over the channel. This approach named V-Blast (vertical Bell Labs Layered Space-Time) was first proposed in [5] and is depicted in Figure 3. Alternatively, diagonal Blast systems distribute the symbols of each layer over all antennas thereby increasing the diversity degree.

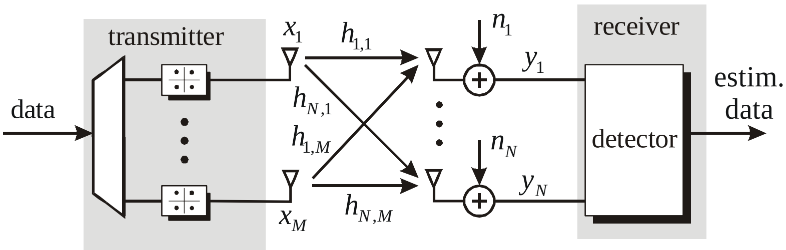

Figure 3: Structure of V-Blast for spatial multi-layer transmission

If the transmitter knows $\mathbf{H}$, the eigenmodes of the channel can be exploited. According to the waterfilling principle, the r strongest eigenmodes of $\mathbf{H}$ are used resulting in the transmit vector $\mathbf{x}[k] = \mathbf{V}_r[k] \cdot \mathbf{P}_r[k] \cdot \mathbf{s}[k]$

where the columns of $\mathbf{V}_r[k]$ are the r right singular vectors of $\mathbf{H}$, $\mathbf{P}_r[k]$ is diagonal and contains the transmit powers of r layers and $\mathbf{s}[k]$ represents the r data symbols. The number r of supported layers depends on the SNR and the distribution of the singular values of $\mathbf{H}$. The higher the SNR, the more layers can be used.

In [6], the amazing capacity of MIMO systems is analyzed. As depicted in Figures 4a, the capacity grows linearly with the antenna numbers but only logarithmically with the SNR. However, the number of antennas at transmitter and receiver has to be enlarged simultaneously because only in that case the rank of $\mathbf{H}$ grows (Fig. 4b). Fig. 4c illustrates the influence of correlated coefficients as a function of the antenna spacing d. Without CSI at the transmitter, correlations ($d = 0.5\ \lambda$) decrease capacity. However, if CSI is available, capacity can be improved and for very low SNRs, the performance is slightly better than in the uncorrelated case.

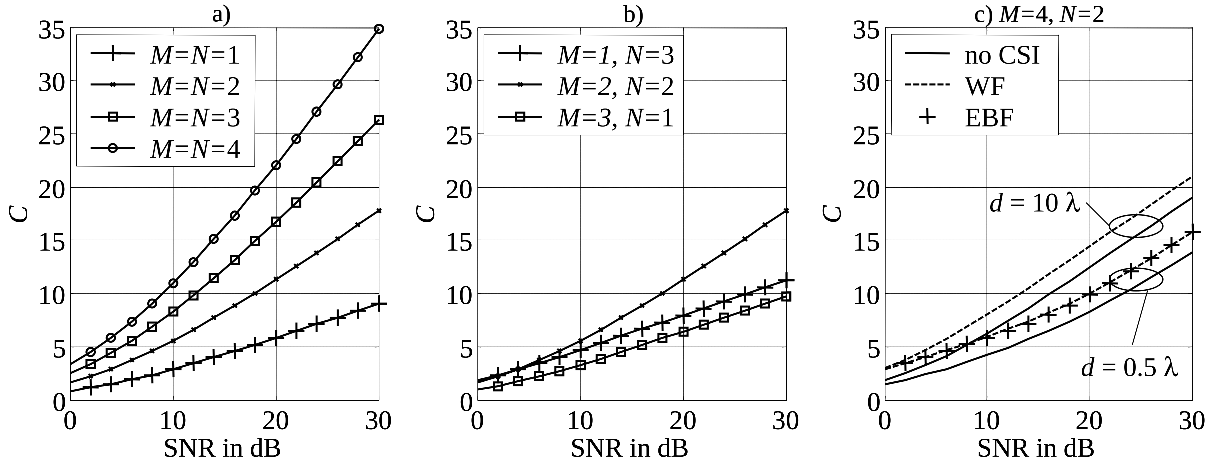

Figure 4: Capacities of MIMO channels (WF: Waterfilling, EBF: eigen-beamforming)

CONCLUDING REMARKS

It was shown that multiple antennas are a promising approach for improving mobile radio communications. Link reliability as well as throughput can be significantly increased. However, the channel properties have severe impact on the optimum strategy and the achievable gains. Moreover, the information theoretical analysis pre-assumes optimal maximum likelihood detection at the receiver. However, this is infeasible in practical systems. Instead, multi-stage receivers and turbo detection strategies are applied [7,8].

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