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Smart Versus Dumb Antennas—Capacities and FEC Performance

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***Abstract*—We compare two approaches to use multiple transmit antennas in an FEC coded wireless system: Smart antennas use an antenna array to direct a beam in the direction of the dominant transmission path in order to obtain an antenna gain. Another approach is to use multiple transmit antennas for diversity using space–time block codes. Since no knowledge of the channel is required at the transmitter we denote this approach as dumb antennas. Using equivalent single-input channel models we compare smart and dumb antennas in terms of BER performance and channel capacity and discuss under which conditions it is preferable to use multiple transmit antennas for transmit diversity or for beamforming.**

***Index Terms*—FEC coding, smart antennas, space–time codes, transmit diversity.**

I. Introduction

MULTIPLE transmit antennas will play an essential part in improving the spectral efficiency of future wireless communications systems especially in the data rate demanding downlink. Possible proposals to make use of multiple transmit antennas include beamforming and diversity techniques.

The beamforming [1] approach uses an antenna array in order to direct a beam to the direction of the dominant path. Unambiguous beamforming requires that the antenna spacing is less than half a wavelength. The transmitter has to estimate the dominant direction and adapt the antenna weights. This approach is often called adaptive or *smart antennas*. Despite the term *smart antennas* is used in a wider sense we restrict ourselves to beamforming. A goal of smart antennas is to increase the system capacity of cellular systems by reducing inter-cell interference and thereby enabling a higher reuse factor. Furthermore, space-division multiple access (SDMA) can possibly be applied. Smart antennas provide antenna gain but no diversity in a flat fading environment where no multipath resolution is possible.

Another approach is to separate the antennas far enough spatially or through polarization changes to provide independent transmission paths from each transmit to each receive antenna and to use multiple transmit antennas in order to obtain diversity. A simple transmit diversity scheme for two transmit antennas was introduced by Alamouti in [2] and generalized to an arbitrary number of transmit antennas as space–time block coding by Tarokh *et al.* in [3]. In contrast to smart antennas, space–time block codes use omni-directional antennas and do not require any knowledge about the channel at the transmitter nor any antenna steering. Therefore, we denote this approach as *dumb antennas*. In [4] it was shown that a transmission scheme with n_T transmit and n_R receive antennas including the space–time block code, the flat fading multiple-input–multiple-output (MIMO) channel and the linear combining at the receiver is described by the equivalent channel model depicted in Fig. 1. The resulting channel tap is given by

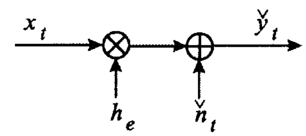

Fig. 1. Equivalent channel model for space–time block codes and linear combining at the receiver.

$$h_e = \sqrt{\frac{1}{n_T} \sum_{i=1}^{n_T} \sum_{j=1}^{n_R} \left|h^{(ij)}\right|^2}$$

where $h^{(ij)}$ is the complex Gaussian channel tap from transmit antenna i to receive antenna j. The simple space–time block code given in [2] for $n_T = 2$ transmit antennas is of rate $R_{ST} = 1$ and no bandwidth expansion takes place. However, for $n_T > 2$ the best known space–time block codes given in [3] and [5] are of rate $R_{ST} = 3/4$ for $n_T = 3$ and 4 and of rate $R_{ST} = 1/2$ for $n_T = 8$, respectively. Nevertheless, the energy combining gain of those space–time block codes exactly compensates for the rate loss and all space–time block codes are equivalent in terms of SNR per bit [4]. The disadvantage is still the bandwidth expansion by a factor of $1/R_{ST}$.

In the sequel we attempt a rough discussion of the question under which conditions it is better to use multiple transmit antennas for transmit diversity or for antenna gain using simple scenarios which can easily be treated analytically. Section II describes the scenarios used for the comparison of smart and dumb antenna systems. The comparison is done in terms of channel capacity in Section III and in terms of BER performance considering the same overall rate and bandwidth in both systems in Section IV.

II. Scenarios for Comparison of Smart and Dumb Antennas

We compare smart and dumb antennas in a coded system with the same overall rate and complexity and QPSK modulation. The two scenarios are illustrated in Figs. 2 and 3. In practice, the mobile remote units shall remain small, simple and cheap. Therefore, we restrict ourselves to the case of $n_R = 1$ receive

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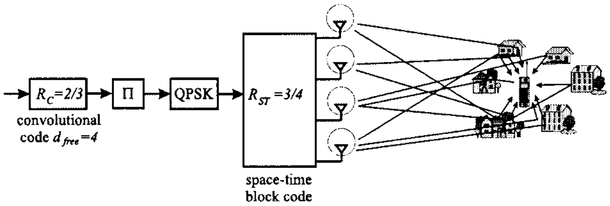

Fig. 2. Dumb antenna scenario.

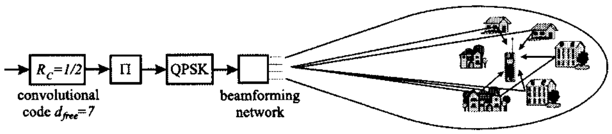

Fig. 3. Smart antenna scenario.

antenna. Since space–time block codes for $n_T > 2$ transmit antennas have a rate loss, we adapt the rate R_c of the FEC convolutional code in order to obtain the same overall rate for the smart and the dumb antenna system. More precisely, in the case of $n_T = 4$ transmit antennas, we use a rate $R_c = 1/2$ convolutional code with memory 4 for the smart antenna system. Since the space–time block code for $n_T = 4$ is of rate $R_{ST} = 3/4$, the convolutional code is punctured to rate $R_c = 2/3$ in the dumb antenna system. We assume flat Rayleigh fading which is generated by many reflections and scattering close to the receiver to which the antenna beam points (see Fig. 3). Therefore, we assume that beamforming does not alter the channel characteristics from Rayleigh fading to Rice fading. Then, the BER curve of the coded smart antenna system is that of a Rayleigh single-input–single-output (SISO) channel shifted to the left by the maximum antenna gain of $10 \log n_T$ dB. This implies that the beam is perfectly directed toward the receiver.

III. Capacities of Smart and Dumb Systems

In this section we compare smart and dumb antenna systems in terms of outage capacity. The x%-outage capacity C_x is the maximum data rate which can theoretically be transmitted error free in $(100 - x)$% of the time, i.e., we expect x% outage. For comparison we include the capacity of the underlying multiple-input–single-output (MISO) channel. If the channel taps are unknown to the transmitter but perfectly known to the receiver (e.g., due to channel estimation), the capacity for a particular realization of a complex flat fading MIMO channel is given by [6], [7]

$$C = \log_2 \left\{ \det \left(\mathbf{I_{n_R}} + \frac{E_s}{n_T N_0} \mathbf{H}\mathbf{H^H} \right) \right\} \tag{1}$$

where the $n_R \times n_T$ matrix $\mathbf{H}$ contains the channel taps and $\mathbf{I_{n_R}}$ is the $n_R \times n_R$ identity matrix. For a space–time block code of rate R_{ST}, the capacity for a block with constant channel taps $h^{(ij)}$ follows from the equivalent channel model in Fig. 1 to be

$$C_{\text{dumb}} = R_{ST} \log_2 \left(1 + \frac{E_s}{n_T N_0} \sum_{i=1}^{n_T} \sum_{j=1}^{n_R} \left| h^{(ij)} \right|^2 \right). \tag{2}$$

For $R_{ST} = 1$ and $n_R = 1$, this is equivalent to the capacity of a MISO channel according to (1). For $n_T > 2$, the rate loss of space–time block codes results in a lower asymptotic slope of the capacity curve over SNR.

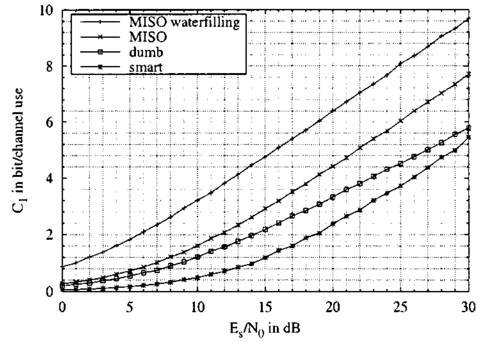

Fig. 4. 1% outage capacity, $n_T = 4$, $n_R = 1$.

If the transmitter has full knowledge of the channel coefficients $h^{(ij)}$ the channel capacity is given by

$$C_W = \sum_{i=1}^{\min\{n_R, n_T\}} \log_2 \left[\max \left\{ 1, \frac{N_0 \lambda_i^2}{\Theta} \right\} \right] \tag{3}$$

where λ_i denotes the eigenvalues of $\mathbf{H}$ and Θ is the solution of the waterfilling problem

$$\sum_{i=1}^{\min\{n_R, n_T\}} \left(\Theta - \frac{N_0}{\lambda_i^2} \right)^+ = E_s, \quad \text{where } (x)^+ = \begin{cases} x, & x \geq 0 \\ 0, & \text{else.} \end{cases} \tag{4}$$

In smart antenna systems some knowledge about the channel at the transmitter is exploited: the dominant direction. However, it is used for beamforming resulting in an antenna gain of n_T rather than waterfilling and the channel capacity of the smart antenna constellation yields

$$C_{\text{smart}} = \log_2 \left(1 + \frac{n_T E_s}{N_0} \sum_{j=1}^{n_R} \left| h^{(1j)} \right|^2 \right). \tag{5}$$

For $n_T = 2$ where the dumb antenna system exploits the full MISO capacity the outage capacity of the smart antenna system is smaller than that of the dumb antenna system in the whole range of SNR. Fig. 4 depicts the 1% outage capacities for $n_T = 4$. The rate loss of the space–time block code results in a lower asymptotic slope of the capacity curve. Consequently, the smart antenna system provides higher capacity than the dumb antenna system at very high SNR. This can be explained by the fact that for very high SNR a high rate FEC code will enable error free transmission. Therefore, we cannot compensate for the rate loss of the space–time block code by adapting the rate of the FEC code as we did in the scenarios in Section II. However, the smart antenna system does not exploit the full MISO capacity. Furthermore, the loss in terms of outage capacity compared to the optimum waterfilling solution increases with the number of transmit antennas since energy is misallocated in more dimensions. Even though smart antennas require some knowledge about the channel at the transmitter their outage capacity is lower in the relevant range of SNR than that of dumb antenna systems which require no knowledge of channel parameters at the transmitter.

IV. FEC Performance

We consider two extreme cases: In quasistatic fading the channel is constant during a coded block and changes independently from one block to the next. This implies a relatively

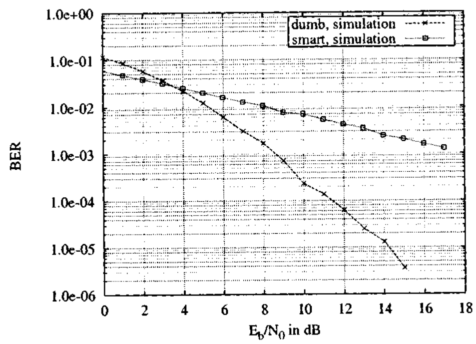

Fig. 5. Smart versus dumb antennas in quasistatic channels, $n_T = 4, n_R = 1$.

slow moving receiver and frequency hopping operating on coded blocks. On the other hand, the fast fading model assumes that the channel is varying during transmission of a coded block. Due to a sufficiently large depth of the interleaver Π, the equivalent channel faced by the FEC decoder is a fully interleaved channel which changes independently from one bit to the next.

Fig. 5 shows simulation results for quasistatic fading and $n_T = 4$. In quasistatic fading the convolutional code does not provide diversity. Therefore, irrespective of the loss in terms of free distance d_f due to puncturing, the BER curve of the dumb antenna system has a steeper slope than the smart antenna system yielding better performance in the relevant range of SNR.

In time-varying channels the convolutional code provides diversity also in the smart antenna system. Due to puncturing the free distance of the convolutional code in the dumb antenna system is decreased resulting in lower diversity provided by the convolutional code.

Some insight is gained by evaluating the asymptotic performance for large SNR. Using similar techniques as in [8] and [9] and taking the antenna gain into consideration, the asymptotic performance of the smart antenna system in fast fading can be approximated by

$$P_b^{(s)} \approx \frac{c_{d_f}}{2} \left(\frac{1}{1 + \frac{n_T R_c E_b}{N_0}} \right)^{d_f \cdot n_R} = \left(\frac{1}{1 + \frac{2E_b}{N_0}} \right)^7 \qquad (6)$$

where $R_c = 1/2$ and $c_{d_f} = 8$ is the sum of information bit errors caused by error events with Hamming weight $d_f = 7$ divided by the number of information bits per trellis transition.

For the dumb antenna system where the transmit antennas are used for diversity rather than antenna gain we obtain with $R_c = 2/3$, $d_f = 4$ and $c_{d_f} = 1.5$:

$$P_b^{(d)} \approx \frac{c_{d_f}}{2} \left(\frac{1}{1 + \frac{R_c E_b}{n_T N_0}} \right)^{d_f n_T n_R} = \frac{3}{4} \left(\frac{1}{1 + \frac{E_b}{6N_0}} \right)^{16}. \qquad (7)$$

Consequently, the dumb antenna system asymptotically outperforms the smart antenna system due to the higher overall diversity level. However, the crossover E_b/N_0 is at high SNR and low BER.

V. Conclusions and Remarks

We discussed using multiple transmit antennas to increase the diversity level (dumb antennas) or to obtain an antenna gain by beamforming (smart antennas) in a coded system. For fixed overall rate space–time block codes always outperform smart antennas asymptotically. In quasistatic fading this is true in the whole SNR range of interest. However, in fast fading the break even point is at relatively high SNR and low BER. Therefore, transmit diversity should be applied if no other source of diversity is available. In fast fading environments the FEC decoder may provide sufficient diversity and multiple transmit antennas could be used for beamforming. In terms of channel capacity smart and dumb antenna systems do not reach the capacity of the underlying MISO channel for $n_T > 2$ transmit antennas. Furthermore, for $n_T > 2$ smart antennas provide higher capacity at very high SNR due to the rate loss of the space–time block code. However, in the relevant range of SNR the outage capacity of dumb antennas is higher.

We emphasize that we gave only a rough approach to the problem assuming perfect knowledge of all parameters like channel coefficients and dominant direction. An important issue for future work is the impact of estimation errors. In fast varying channels, where we encountered advantages for smart antennas, estimation and tracking of the antenna weights as well as calibration might be difficult for smart antennas. Furthermore, the beam might be not perfectly directed to the receiver resulting in a reduced antenna gain. On the other hand, for beamforming we have to estimate less parameters (dominant direction and n_R channel coefficients) than for space–time block codes ($n_T \cdot n_R$ channel coefficients). Furthermore, based on measurements we need to characterize the channel statistics in case of beamforming. Another important issue is to investigate the impact on interference in system level simulations of a cellular system. The question is if it is preferable to observe relatively strong interfering spots caused by smart antennas—similar to shining a flashlight in a neighbors garden—or to have a lower even interference caused by dumb (omnidirectional) antennas—like glowing lights at your neighbor.

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