Amplitude and Phase Distortions in MIMO and Diversity Systems

Christiane Kuhnert, Gerd Saala, Christian Waldschmidt, Werner Wiesbeck
Institut für Höchstfrequenztechnik und Elektronik (IHE)
Universität Karlsruhe (TH), D-76128 Karlsruhe, Germany
Phone: +49–721–608–3178, Fax: +49–721–691–865
E-mail: Christiane.Kuhnert@ihe.uka.de

***Abstract*— In this paper future wireless communication systems are investigated, which employ several antennas on one side of the link (diversity systems) or both sides of the link (multiple input multiple output, MIMO systems). A system model for the OSI physical layer including a transmitter, the propagation channel, and a receiver is presented. The emphasis lies on a realistic modelling of the radio frequency part of the system including coupling among the antenna elements, noise, and accurate models for components of the analog front end. Adverse effects may occur there leading to amplitude and phase distortions.**

Several systems with different numbers of transmit and receive antennas are compared. By simulations it is investigated how amplitude and phase distortions in the radio frequency front-end of the system affect performance of MIMO and diversity systems.

I. INTRODUCTION

In recent studies it has been shown that mobile communication systems with several antennas on one side or both sides of the link are beneficial. These diversity or multiple input multiple output (MIMO) systems make use of the spatial properties of the wave propagation channel and therewith overcome the fading problem and may even multiply the spectral efficiency of the communication system.

Most research work focusses on topics like signal processing, the propagation channel, antenna aspects, and measurement techniques assuming an ideal radio frequency (RF) front-end. The radio frequency part of the system suffers from impairments such as mutual coupling, noise, saturation and nonlinearities of analogue components. In this paper, amplitude and phase distortions due to a non-ideal RF front-end are taken into account. In addition to that, an inaccurate channel estimation adds amplitude and phase distortions. The impact of such impairments on diversity and MIMO system performance will be evaluated. This impact depends on the space-time algorithm used in the system.

The paper is organised as follows: In section II, a MIMO system model for the OSI physical layer is proposed including a realistic modelling of the RF part of the system. Section III addresses the amplitude and phase distortions and their influence on the system performance. Finally, a conclusion is drawn.

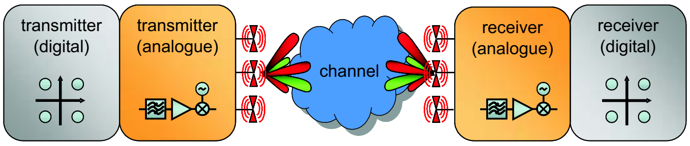

Fig. 1. Parts of a wireless communication system.

II. SYSTEM MODEL

A wireless communication link can be divided into five parts, as shown in figure 1. The first part is the digital part of the transmitter, which contains modulation, space-time coding and signal processing. Note, that for a system with multiple transmit antennas an algorithm is needed performing the mapping of the data stream onto the transmit antennas. After that, the signals are converted to analog and pass through the analog part of the transmitter. Here, the signals are upconverted to the radio frequency and amplified. The third part of the system contains the antennas and the propagation channel. The signals are sent out by the transmit antenna or transmit antenna array, respectively. Then they propagate through the air as electromagnetic waves, and are received by the receive antenna or receive antenna array, respectively. The next part of the system is the analog part of the receiver, where downconversion is performed. Finally, in the digital part of the receiver the signals are processed to recover the data. Note, that for systems with multiple receive antennas a combining scheme is needed to obtain a single data stream of all received data streams.

In this paper two examples of algorithms for MIMO and diversity are employed. The maximum ratio receive combining (MRRC) is a scheme for combining signals received by multiple receive antennas [1]. Space time block coding (STBC) is a scheme for diversity and MIMO systems with multiple transmit antennas. In this paper, the STBC proposed by Alamouti is used [2].

Five systems with different numbers of transmit and receive antennas are compared:

- SISO 1×1: a single input single output system with one transmit and one receive antenna is used as reference
- MRRC 1×2: a receive diversity system with one transmit and two receive antennas, using the MRRC scheme
- MRRC 1×4: a receive diversity system with one transmit and four receive antennas, using the MRRC scheme
- STBC 2×1: a transmit diversity system with two transmit and one receive antennas, using a STBC given by Alamouti
- STBC 2×2: a MIMO system with two transmit and two receive antennas, using the extended STBC given by Alamouti

The system model is modular, so that all systems can be incorporated basing on the same components.

In the following, the models and assumptions used in each of the five parts of the wireless communication system are discussed:

A. Digital Sub-System

The digital processing used is kept simple, because the focus of this work lies on an accurate model of the RF front-end. A block diagram of the system model describing the digital part at transmitter and receiver is given in figure 2.

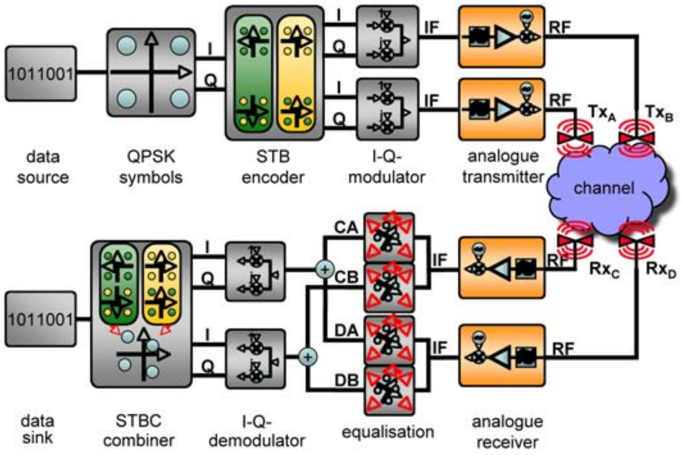

Fig. 2. Block diagram of the system model.

On the transmit side a data source provides information bits to be transmitted. It is assumed, that these bits are already coded and interleaved. Then the bits are mapped onto complex symbols using e.g. quadrature phase shift keying (QPSK) modulation. For the systems with multiple transmit antennas (STBC systems), the inphase (I) and quadrature phase (Q) symbols are encoded in a space time block encoder. The simple Alamouti algorithm proposed in [2] is used. For the systems with only one single transmit antenna, no space time block encoder is needed. The I- and Q-symbols for each transmit antenna are I-Q-modulated onto continous signals at an intermediate frequency and delivered to the analog transmit front-end.

On the receive side the continous signals at an intermediate frequency are delivered from the analog receive front-end to the digital part. The signals coming from the analog front-end at an intermediate frequency are equalised. For the STBC systems, this equaliser is STBC-specific, whereas for the other systems, it is a usual matched filter. Perfect channel knowledge is assumed under the condition that all components are ideal. The signals coming from the receive antennas are then I-Q-demodulated. There is one I-Q-demodulator per receive antenna. Then the I- and Q-symbols have to be detected. In the systems with only one receive antenna, maximum likelihood detection is carried out. In the MRRC systems, the symbols are combined according to the MRRC scheme and then the maximum likelihood detection is performed. For the STBC systems, the two I- and Q-symbols are combined in the Alamouti STBC-Combiner. Finally, for all systems the estimated symbols are converted to a bit stream. By comparison with the transmitted bit stream, the bit error rate can be calculated.

B. Analogue Sub-System

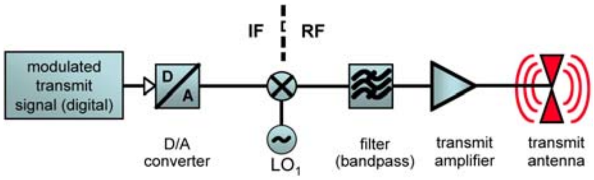

Fig. 3. Block diagram of an analogue transmitter branch.

A block diagram of one analogue transmit branch is given in figure 3. There is one transmit branch for each transmit antenna. The modulated transmit signal belonging to one antenna is converted from digital to analogue. Then the signal is upconverted from the intermediate frequency to the radio frequency. Without loss of generality the intermediate frequency is chosen to be 45 MHz for the simulations. As example and following the UMTS standard, 2 GHz was chosen as RF carrier frequency. The UMTS data rate of 384 kbit/s is related to an RF bandwidth of 192 kHz. After upconversion a bandpass filter is needed. Then the signal is amplified and transmitted by the antenna. As transmit power, 1 W is assumed. For the systems with multiple transmit antennas, the total transmit power is 1 W, allowing for a fair comparison. This total transmit power is distributed equally among the transmit antennas. The components of the analog part on the transmit side are all assumed as ideal.

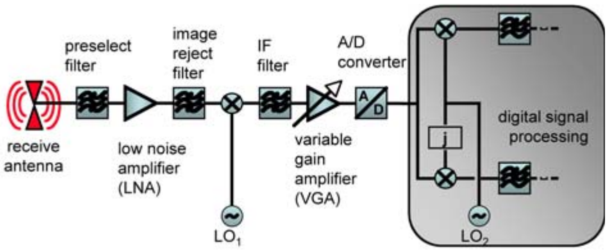

Fig. 4. Block diagram of an analogue receiver branch.

At the receiver, there is one analogue receiver branch belonging to each receive antenna. A block diagram is given in figure 4. A direct-IF-conversion receiver architecture is used for the system model. It basically consists of a low noise amplifier and one single downconversion stage. That means, the analogue-digital-conversion takes place at the intermediate frequency.

C. Antennas and Radio Channel

MIMO and diversity systems exploit the spatial characteristics of the radio channel. A channel model has to be employed which reproduces accurately this spatial structure due to multipath propagation. The antennas are adapted to the propagation channel. Therefore the antennas and the propagation channel have to be treated together. In [3] a model is introduced which treats the transmit antennas, the propagation channel, and the receive antennas together. It is based on a scattering parameter description. This model is employed here as the inner part of the system model.

As antennas, half-wavelength dipole antennas are used in the system model. Each antenna element of an array is influenced by the other elements. These mutual coupling effects among antenna elements have an impact on the performance of a MIMO or diversity system, especially if the antennas are closely spaced. Hence, the effects have to be taken into account. As single antenna element, a vertically oriented dipole antenna is used. As array of two antennas, two dipoles are arranged in parallel with a spacing of half a wavelength. As array of four antennas, four diploles were arranged in parallel with a spacing of half a wavelength between two adjacent elements. All antennas were oriented vertically; and transmitter and receiver were perfectly aligned.

The propagation channel between a transmit and a receive antenna can be described by a channel transfer function, or a channel coefficient for the flat-fading case. In general, the channel coefficients between each transmit and each receive antenna of a system employing multiple antennas can be stacked into a channel matrix $\mathbf{H}$. The number of columns of $\mathbf{H}$ equals the number of transmit antennas, while the number of rows is the number of receive antennas. For systems with only one transmit antenna, the channel matrix simplifies to a column vector, for systems with only one receive antenna to a row vector, and for SISO systems a scalar value.

As model for the propagation channel, the path-based indoor channel model given in [4] was used. 1000 realizations of the MIMO channel matrix $\mathbf{H}_\nu$, $\nu = 1 \ldots 1000$, were generated for random locations of transmitter and receiver inside an office building. Then the average $E\{\mathbf{H}_\nu\}$ of these realizations is used in the MIMO system simulation. The channel is kept constant during the transmission of all bits. Perfect channel knowledge is assumed at the receiver under the condition that all components are ideal, whereas no channel knowledge is assumed at the transmitter. The channel has also an additive white Gaussian noise component, that means the signals are corrupted with noise.

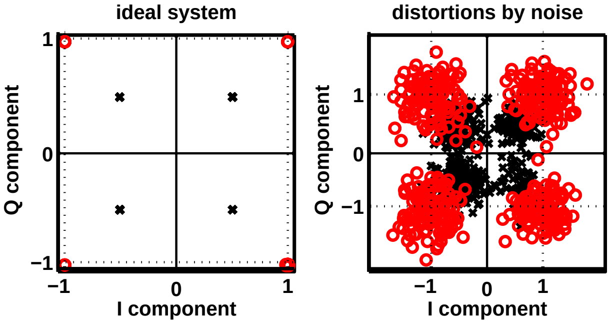

Fig. 5. Constellation diagrams of the received QPSK symbols for an ideal system (left) and a system with noise distortions (right). The signal-to-noise ratio equals 3 dB. The symbols of the 1×1 SISO system are denoted as crosses, the symbols of the 2×2 MIMO system as circles.

III. SIMULATION OF SYSTEMS INCLUDING AMPLITUDE AND PHASE DISTORTIONS

In real systems, components may be not ideal, leading to signal distortions. Especially, non-ideal components in the analogue part of the receiver have a major impact on the quality of the received signals, therefore this paper focusses on non-ideal components in the analogue part of the receiver. In order to gain insight into the influence of non-ideal components on performance of MIMO and diversity systems, the distortions caused by non-ideal components are mapped onto single effects, which are investigated separatly from one another. In the following, results for a system with ideal components in the analogue part are presented. In subsequent subsections, two single effects are addressed, namely amplitude and phase distortions.

A. Simulation of a system with ideal components

The most important effect deteriorating the received signals is noise. Noise obviously also occurs in conventional systems with one transmit and one receive antenna. In MIMO and diversity systems noise is added at all receiving antennas. The noise voltage received at each receive antenna is uncorrelated additive white Gaussian noise, e.g. n_a and n_b for two receive antennas. As mentioned in section II-C, the antenna elements are mutually coupled. Therefore noise received by antenna 1 is coupled into branch 2 belonging to antenna 2 and vice versa. This leads to the effect, that the noise in two branches at the analog front-end is partially correlated. If the mutual coupling coefficient between both antennas is S_C, then the noise n_1 and n_2 fed into the two branches at the receiver can be calculated as

$$n_1 = \sqrt{1 - |S_C|^2} n_a + S_C n_b \quad (1)$$

$$n_2 = S_C n_a + \sqrt{1 - |S_C|^2} n_b \quad . \quad (2)$$

Obviously, n_1 and n_2 are correlated. The correlation coefficient depends on the antenna coupling level S_C. For two dipole elements with half-wavelength spacing, the coupling level S_C equals approximately -13 dB.

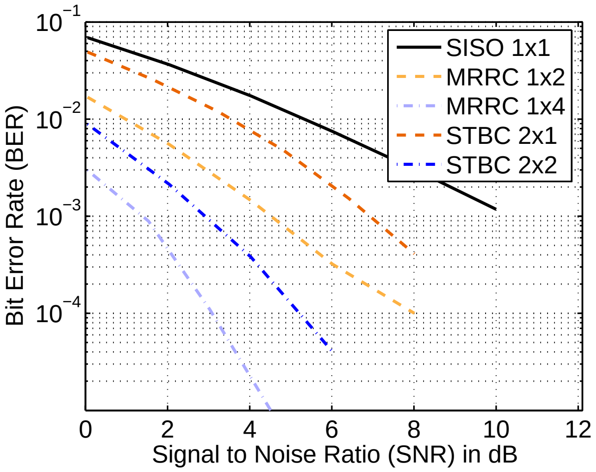

Fig. 6. Bit error rate of all systems, assuming ideal components and only distortions by noise.

The constellation diagram of the received QPSK symbols in an ideal system without noise is shown in figure 5 (left). If all components are ideal and only noise distortes the received signals, the constellation diagram of the received QPSK symbols is shown in figure 5 (right). The MIMO system has on average a larger receive power. That is why the symbols of the MIMO system are farther from the origin than the SISO symbols.

Simulation results for the bit error rate of all systems are given in figure 6, assuming ideal components and only distortions by noise. Employing diversity on one side of the link leads to a BER improvement compared to a SISO system. Due to the total transmit power constraint of 1 W, the 2×1 system cannot reach the BER performance of the 1×2 system, although these two systems have the same diversity order. This difference complies with the simulation results given in [2]. A similar effect can be seen by comparing the 2×2 system and the 1×4 system, which both have a diversity order of 4. Actually, the difference is less that 3 dB, which means that the 2×2 system can combat the noise distortions better than the 1×4 system.

B. Amplitude Distortions

One major effect influencing the received signals and therewith the bit error rate is an amplitude distortion. Amplitude fluctuations mainly occur due to fading in the propagation channel. Obviously, fading also leads to phase variations, but as stated above all effects are investigated separatly from each other. The time-variant behaviour of the propagation channel is modelled as follows: Each entry of the averaged channel matrix is multiplied with a Rayleigh-distributed random variable[1].

$$\mathbf{H} = E\{\mathbf{H}_\nu\} \odot \mathbf{R} \tag{3}$$

The elements r_{kl} of $\mathbf{R}$ are i.i.d. Rayleigh-distributed with mean 1. The speed of the channel variations is controlled by a variable ζ. With this approach, the fast fading behaviour of the mobile radio channel is taken into account regarding amplitude fluctuations. The power transmission gain is the same for both the real channel and the constructed Rayleigh-fading channel. Only the correlation properties among the elements of the channel matrix differ: in a real channel these elements are somehow correlated, while in the constructed channel the elements are completely uncorrelated.

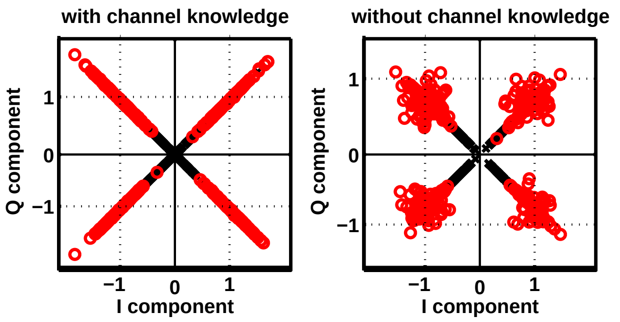

Fig. 7. Constellation diagrams of the received QPSK symbols for the SISO (crosses) and the MIMO (circles) system with amplitude variations, which are known at the receiver (left) or unknown at the receiver (right).

Usually, the receiver has perfect channel knowledge, hence amplitude variations can be compensated for. Nevertheless, it is interesting to see how a MIMO or diversity system behaves if the receiver cannot compensate for the amplitude variations, e.g. due to a lack of channel knowledge. The constellation diagrams for both cases, with and without channel knowledge, are given in figure 7. With perfect channel knowledge all symbols are on the diagonal, but the amplitude fluctuations can clearly be seen. Without channel knowledge, the symbols of the 2×2 STBC system are distributed around the diagonal. That means that the signal structure of the STBC algorithm leads to a translation of amplitude errors in phase errors.

A quantitative comparison is given in figure 8. The SISO

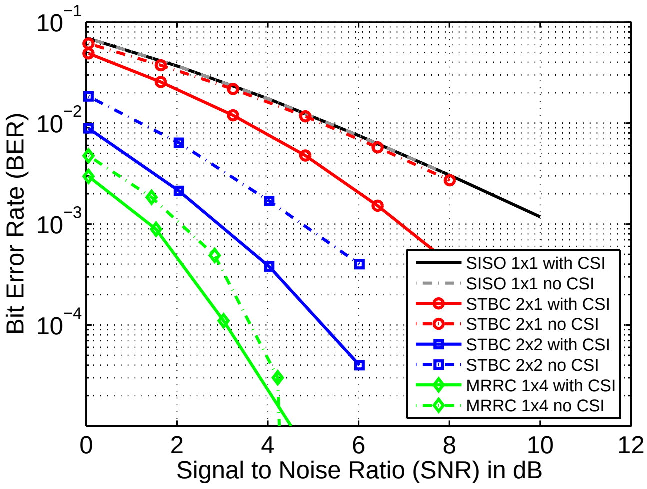

Fig. 8. Bit error rate versus SNR for various systems, if the system suffers from amplitude variations. Two cases are compared: either the receiver knows the channel (with channel state information CSI) or not (without CSI).

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[1] $\odot$ denotes element-wise multiplication of two matrices of the same size

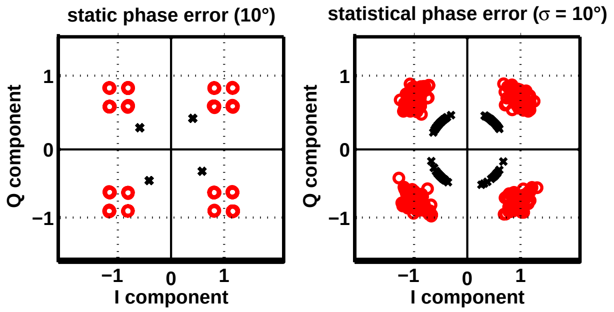

Fig. 9. Constellation diagram of the received QPSK symbols for the SISO (crosses) and the MIMO (circles) system, assuming a static phase error of 10° (left) or a zero-mean Gaussian distributed statistical phase error with standard deviation $\sigma = 10°$ (right).

system is not influenced at all by the lack of channel knowledge, whereas both STBC systems deteriorate, but do not fail completely. The performance of the MRRC system is less degraded than the performance of the STBC systems. In the STBC algorithm applied here, the signals are orthogonal at the transmitter. This orthogonality is lost due to imperfect channel knowledge.

C. Phase Distortions

There are various reasons why a phase error may occur in the receiver front-end, e.g. due to a non-ideal oscillator in the mixer stage. Phase errors may be constant over time (static phase error) or changing over time, which can be modelled by a statistical phase error. As an example, a static phase error of 10° is assumed. The statistical phase error is modelled by a zero-mean Gaussian distributed random variable with a standard deviation of 10°.

The constellation diagrams for both static and statistical phase errors are shown in figure 9. In the SISO system the symbols are simply rotated by 10°, the value of the static phase error. In the MIMO system, the symbols are rotated in both directions and an amplitude shift occurs, due to inversions of the I- and Q-component performed by the STBC algorithm. A statistical phase error leads to a random rotation of the symbols of the constellation diagram for both SISO and MIMO. In addition to this rotation, amplitude fluctuations occur in the MIMO system due to the STBC algorithm. The simulation results demonstrate that phase errors have another impact on MIMO systems than on conventional SISO systems. In SISO systems phase errors lead only to a rotation of the complex symbols in the constellation diagram. In MIMO systems these errors lead also to a scaling of the symbols in the constellation diagram similar to additive noise.

The BER performance with respect to phase errors is given in figure 10. The performance of the SISO system is degraded more by a statistical phase error that by a static phase error, because a random variable with a standard deviation of 10° allows also for realisations with a larger phase error. In the MRRC system, the multiple receiver branches lead to a compensation of statistical phase errors in each branch, therefore the performance of the MRRC system is degraded more by a static phase error than a statistical phase error. This is one of the benfits of diversity. The STBC system suffers from the translation of phase errors into amplitude errors, therefore the compensation of statistical phase errors is worse than in the MRRC system and the influence of a static and a statistical phase error is nearly the same.

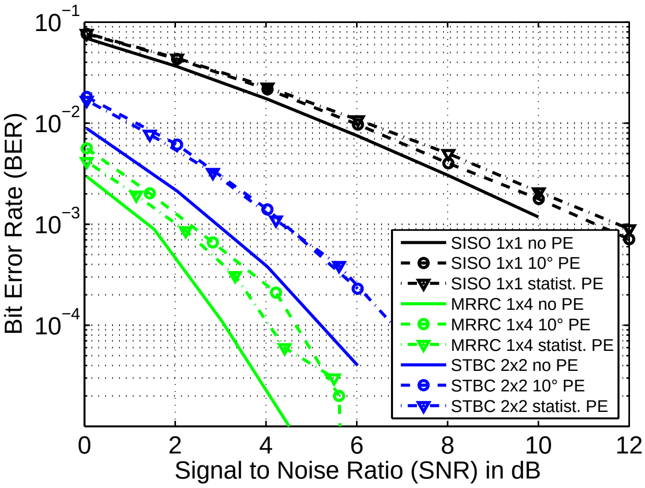

Fig. 10. Bit error rate for various systems, if phase errors (PE) occur in the system. The phase error are either static (10○) or statistical ones with a standard deviation of $\sigma = 10°$.

IV. CONCLUSION

In this contribution, a system model for wireless communications systems with multiple antennas has been presented. MIMO and diversity systems with different numbers of transmit and receive antennas have been investigated using an accurate model of the RF part. The results demonstrate how the Bit Error Rate of a MIMO or diversity system is affected by amplitude and phase distortions. Depending on the algorithm, the signal structure is different from SISO systems, resulting in another impact of distortions on the system performance than in conventional single input single output systems.

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