

Simulation of MIMO Antenna Systems in Simulink and Embedded Matlab

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Abstract—Multi-Input Multi-Output (MIMO) has emerged as a hot topic in wireless communications during the last decade. This is due to possible dramatic increases in reliability and capacity as compared to single-antenna solutions. However, much of the existing theoretical results are based on very simplistic models of the antennas and transceiver circuitry. Within the Strategic Research Center on Antenna Systems Charmant at Chalmers, we are developing a systems simulator for making more realistic studies of MIMO systems. Models of different complexity can be used for the different components. For the linear components, S-parameters are used as the interface. These can come from theoretical models, electromagnetic field simulations, or directly from measurements. For the non-linear components, simple memoryless models can be used, as existing in the RF Toolbox. However, wideband applications demand more elaborate models. We have implemented a so-called memory polynomial model, which has been found to match measurements of non-linear wideband power amplifiers well. Since RF Toolbox cannot handle multi-port scattering matrices (yet), the MIMO part is here computed in a Matlab function, and then implemented as a MIMO transfer function. The paper describes an implementation of a transceiver chain including mixers, filters, PA/LNA, matching network, MIMO antennas and channel models. The simulator can be used for a wide range of wireless communication applications.

I. INTRODUCTION

Today, hardly any hardware of some complexity is built without first performing extensive computer simulations. Communication and radar systems involving antennas is no exception. However, in almost all cases a communication (or radar) system is simulated with very crude models of the hardware and underlying physics. In contrast, the hardware (e.g. antennas) design is based on detailed electromagnetic simulation, but not taking the system aspects into account. The purpose of this paper is to describe some steps in bridging the gaps between system and hardware level simulation, based on Matlab and Simulink. The goal is to be able to directly see the effect of component design, or architecture, on system-level performance measures. The focus in this presentation is on a wireless communication system, and the performance measures are usually given in the form of bit-error rate (BER) or some other Quality-of-Service (QoS) measure. The ultimate goal of such a system-level simulator is to enable system-level optimization of components, such as material properties or

physical dimensions of antennas etc. However, in this presentation the focus is on simulation of the hardware models at radio frequency (RF). Some details regarding implementation of the signal processing part of a MIMO (Multiple Input Multiple Output) Wideband Code-Division Multiple Access (WCDMA) system, which is the 3G standard for mobile telephony, is given in the companion paper [1].

This paper is organized as follows: The next subsection gives a short introduction to MIMO communication systems, after which an overview of the architecture is given. Section II presents our implementation of the MIMO channel, whereas the antenna frontend is presented in III. This block consists of all parts of the transmitter (receiver) that are represented with physical scattering (S-parameter) models. This includes the antenna, matching network, receiver filters, and also the front-end of the amplifier. In IV, the implementation of amplifier non-linearities is discussed. Section V presents some preliminary simulation results, whereas Section VI concludes the paper.

A. MIMO in Wireless Communication

During the last 20 years or so there has been a tremendous growth in the wireless communication industry. In the beginning, the focus was only on speech, and the challenge was to allocate as many users as possible within a given bandwidth. Today, there is also an increasing demand in bitrate, to allow more advanced services such as video streaming and TV. Traditionally, the growing demand of capacity has been met by increasing the bandwidth and/or by inventing more spectrally efficient communication protocols. However, since the introduction at Bell Labs about 10 years ago (see e.g. [2]), the concept of MIMO (Multiple Input Multiple Output) has received an increasing attention. The main observation is that if both the transmitter and the receiver are equipped with n antennas, the capacity (bitrate) can be increased by up to a factor of n , depending on the richness of the wireless channel. In principle, one can form n parallel channels, which can transmit independently of one another. In general, this is not possible for line-of-sight (LOS) channels, since the multiple channels cannot be independent and will therefore interfere. However, in a rich scattering environment, the capacity can increase by a factor up to n [3]. The transmission of data in parallel streams is usually referred to as *spatial multiplexing*.

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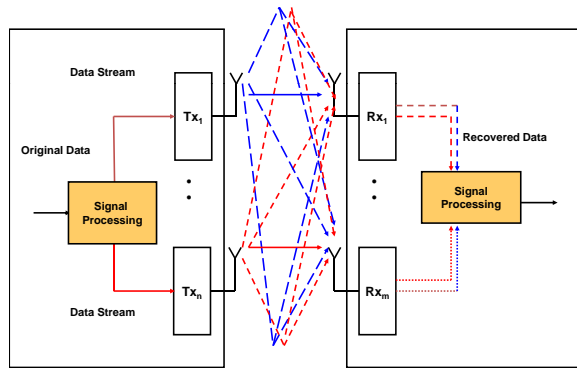


Fig. 1. Overview of a MIMO wireless communication system.

The scattering, or multipath propagation, is usually regarded as the main obstacle in wireless, as compared to wired, communication. This is because the different propagation paths will interfere constructively or destructively, depending on the position of the mobile user. This gives rise to large variations in signal level, referred to as *fading*. While spatial multiplexing can potentially bring back much of the capacity, the variations in signal level remains. An alternative way to exploit the concept of spatially separated antennas is *diversity*. The idea is that if the antennas are spaced sufficiently far apart, they fade independently. By always selecting the antenna with the best channel, or (better) combining the two with appropriate weights, the probability of a poor reception (signal outage) is dramatically reduced. Diversity increases the average signal level, which in turn improves capacity. Though the capacity increase is significantly less with diversity than if spatial multiplexing was used, it is in general more robust and can be used at lower signal-to-noise ratios. A particularly clever approach for achieving spatial diversity at the transmitter, without requiring knowledge of the channel at the transmitter, is called *space-time coding* [4].

B. MIMO System Architecture

This section describes the architecture of a MIMO wireless communication system, with focus on the transmission, channel and reception models. The implementation of the various blocks will then be described in more detail in the following sections. Figure 1 gives an overview of a system with n transmit and m receive antennas. The Signal Processing block at the transmitter represents the conversion of the source signal (e.g. speech or video) to a bit stream. This entails source and channel coding, see e.g. [5], and this part is ignored in the current presentation. The Tx_1 through Tx_n blocks represent the transmission electronics, which consist of modulation (selection of a suitable analog signal to be transmitted over the medium), amplification and filtering in the n transmission channels. The arrows between the transmitting and receiving antennas illustrate the wireless channel. The

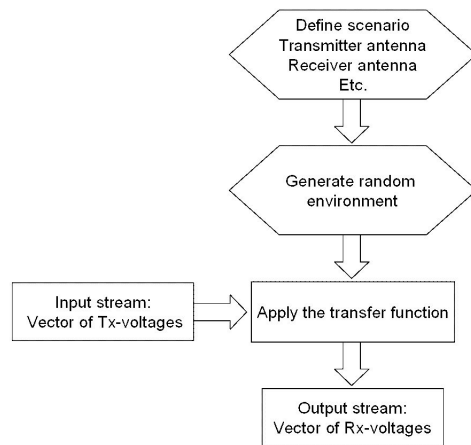


Fig. 2. Steps to generate a simulation of a MIMO wireless communication channel.

channel is generally modelled by multiple transmission paths (rays), each with its own time-delay, Direction-of-Departure (DoD) and Direction-of-Arrival (DoA) [6]. The receiving side is similar to the transmitter, but in reverse order. Thus, the Rx_1 through Rx_m blocks consist of filtering, amplification and demodulation, where the latter extract the in-phase (I) and quadrature-phase (Q) parts of the signal [5]. This results in a complex-valued received signal $I + jQ$, which is passed on to the Signal Processing block. The details of the signal processing depends on the communication protocol, but it contains in general synchronization, channel estimation, detection (estimation of the bits), channel decoding and source decoding. Also these operations are omitted herein, and the focus is on simulation of the radio frequency (RF) parts of the antenna system.

II. IMPLEMENTATION OF MIMO COMMUNICATION CHANNELS

The interaction between transmitting and receiving MIMO antennas is described by a transfer function which takes into account the radiation properties of the antennas and the propagation properties of the environment. In Figure 2, the basic steps needed to use models for the MIMO communication channel are illustrated.

The environment is assumed to consist of a finite number of scatterers, and each scatterer acts as a delay and scaling (or, more generally, an FIR-filter) for a path from the transmitter to the receiver. Any model can be used in principle, derived from measurements, electromagnetic simulations of a virtual scene, or some statistical model. We primarily use a slightly modified version of the 3GPP model [7, v6.1.0], which prescribes statistical distributions of the properties for the scatterers. (The modification is that each sub scatterer in a cluster is accounted for separately, to be able to handle Doppler due to mobile transmitter/receiver within the simulator). Random values for scattering strengths, time delays, DoD and DoA at the antennas are generated in accordance with the statistical distributions. Taking the angular and possibly polarization dependent gain

of the antennas into account, the transfer function coefficients for each pair of transmitter antenna element j , and each receiver antenna element i , is computed and stored in a three-dimensional array $H_{i,j,k}$. The transmission is via each scatterer k , and with some probability also via a direct path. The computations are done in a Matlab script, which is run before starting the simulation. Here, $H_{i,j,k}$ can be an FIR-filter of any length, but the typical case is simply a loss and a pure time delay. The number of leading zeros due to the length of the direct path is stored in a separate variable to save memory and CPU-time. If any of the antennas is moving, or if the scatterer is moving, then a Doppler shift ω_k is also included in the model. It is assumed that the Doppler shift with regard to a particular scatterer is equal for all antenna elements in an array, and that the simulation time is short enough so that the delay in number of sample periods is constant. Thus, it is enough to consider only the phase shift.

Given $H_{i,j,k}$ and transmitted signals $\{Tx_j(t)\}_{j=1}^n$, the received signal at antenna i is calculated as

$$Rx_i(t) = \sum_{j=1}^n \sum_{k=1}^K H_{i,j,k} Tx_j(t - \tau_{ijk}) e^{j\omega_k t}, \quad (1)$$

where τ_{ijk} is the time-delay of the k :th scatterer. Both t and τ_{ijk} are specified in increments of the sample time. In the FIR case, there is also a sum over delays, but this is not used in typical channel models.

The transfer function in (1) has been implemented in an embedded Matlab block, which is able to handle both sample based and frame based signals, and that automatically adjusts to the number of transmitter elements, receiver elements and scatterers. This gives a great flexibility as compared to a pure Simulink-based implementation. The radiation properties of the transmitting and receiving antennas are in this case described by embedded element patterns, so the mutual coupling between elements within each antenna is included in the analysis.

III. ANTENNA AND MATCHING NETWORK

This part of the system contains all components that are represented by physical models in terms of scattering parameters [8]. This description is used to quantify the distributed nature of microwave components, which means that for example the phase of a signal is not the same everywhere on a transmission line. At lower frequencies this effect is usually ignored. The effect is most commonly modelled in the frequency domain, using travelling waves. Thus, a transmission line, which is used to connect two components, will have one wave V^+ travelling in the forward direction and one V^- going backwards. The total voltage at any given position is given by the sum of the two. Assuming a lossless and homogenous medium, the phase of each wave will vary linearly with distance whereas the amplitude is constant. A microwave component can be represented by its (frequency-dependent) scattering parameters, which are:

S_{11} reflection coefficient

S_{21} transfer function from input to output

S_{12} backwards transfer function, from output to input

S_{22} backwards reflection coefficient

Thus, if V_{in}^\pm represents the forward and backward travelling waves at the input of a component, respectively; and V_{out}^\pm the same at the output, we have

$$\begin{bmatrix} V_{in}^- \\ V_{out}^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_{in}^+ \\ V_{out}^+ \end{bmatrix} = \mathbf{S} \begin{bmatrix} V_{in}^+ \\ V_{out}^+ \end{bmatrix}. \quad (2)$$

Note that both V_{in}^+ and V_{out}^+ represent waves going into the component by convention. Thus, the characterization is in terms of the *scattering matrix* \mathbf{S} , and the scattering parameters are often termed S-parameters. Two or more components that are interconnected can conveniently be represented by the resulting scattering matrix, which can be computed from the individual S-parameters in a straightforward way, see [8], [9] for details. Microwave components can be simulated using Matlab's RF Toolbox and Simulink's RF Blockset. The S-parameters are there referred to as *physical models*. The components can be interconnected, and also connected to *mathematical models* through physical-to-mathematical and mathematical-to-physical conversion blocks. However, a serious drawback in the MIMO context is that RF Toolbox and Blockset only deals with two-port networks, that are represented by 2×2 scattering matrices. In an antenna array, there is always interaction between the elements (mutual coupling), which means that the antennas cannot be considered in isolation. An n -element antenna array is a multi-port component, which is represented by a $2n \times 2n$ scattering matrix [9]. One possible solution is to explicitly connect all antennas to each other in RF Blockset, where the connections include the S-parameters [10]. However, for larger systems such an approach is impractical. Therefore, we have developed an alternative implementation which uses a Matlab function to compute the resulting (mathematical) transfer function for all physical components. Consider the transmission model depicted in Figure 3. Only a 2×2 system is shown for simplicity, but the principle is equally applicable to the general case. The power amplifier (PA) is split into a *mathematical* model, which contains the forward transfer characteristics only, and a *physical* part, consisting of the PA's S_{22} parameter only. The backward transmission is assumed to be negligible, which is a good approximation for most practical amplifiers. Any interactions among the PAs, other than via the connected components, are also ignored. All PAs are connected to a *matching network*, whose task is to maximize the transmission efficiency of the antenna array [11]. In short, it counteracts the effects of mutual coupling between the antennas. The matching network is connected to the different antennas, that are also split into physical and mathematical models. The physical part of the antennas represent the self-reflections of the antennas, and possibly also the mutual coupling. The mathematical part is used to model the radiation pattern of each antenna. This should be the isolated antenna pattern if the mutual coupling model is included. Alternatively, one can use the embedded element patterns and exclude the mutual coupling part. Since

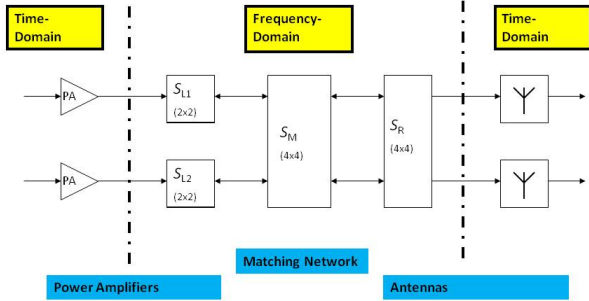


Fig. 3. Connection of amplifiers, matching network and antennas using a mixture of mathematical models (transfer functions) and physical models (S-parameters).

the antenna patterns are described by a mathematical model, we have chosen to include these in the MIMO channel model, described in Section II.

Since RF Blockset cannot handle multi-port physical components, the physical part of the transmission model in Figure 3 is implemented using a Matlab function. The function computes the overall multi-port scattering matrix from the S-parameters of a set of multi-port components along with a representation of how they are connected. The resulting block is transformed into a multi-channel mathematical model, consisting of the transfer function only. This corresponds to the resulting S_{21} parameter (matrix) of the overall scattering matrix. The mathematical representation of the entire physical part in Figure 3 is then connected to the input from the mathematical PA models and the output is feeded to the mathematical antenna models. This is done in Simulink, where multi-channel mathematical models, unlike physical models, can be connected and handled properly.

This section has only described the simulation of a multi-element transmitter. However, precisely the same procedure is used for the receiving antenna array and RF components. This results in two MIMO transfer functions (mathematical models), which are connected via the MIMO wireless channel transfer function described in Section II. The full system can then be simulated in Simulink. The characterizations of the transmitter and receiver models are done in the frequency domain, and they are entered and stored in a standard file format of choice. We have used the Touchstone format in the current project, which is supported by RF Toolbox/Blockset. Although the description is in the frequency domain, the simulation is usually done in the time domain by calculating the resulting impulse response matrix from the transfer functions by inverse Fourier transform.

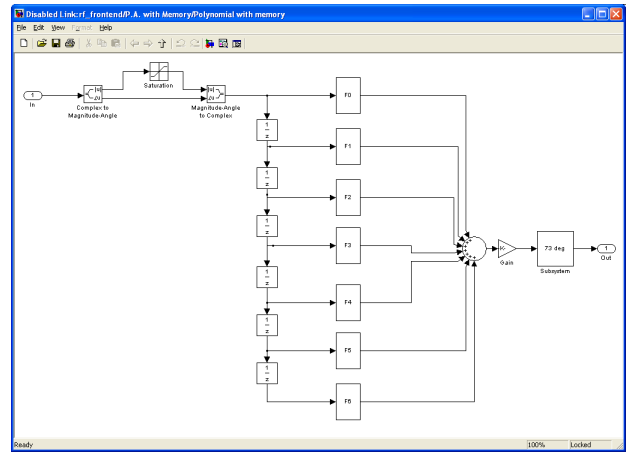


Fig. 4. The amplifier non-linearity is modeled as a memory polynomial model, implemented in Simulink.

IV. NON-LINEAR AMPLIFIER MODELING

While many components in an antenna system can be well approximated by linear models, this is in general not true for the amplifiers. In particular, power amplifiers (PAs) at the transmitter are often operated near the saturation limit to maximize the efficiency. This is because of the desire to increase the battery life time of, for example, a mobile unit. In this region, the PA can have a highly non-linear characteristic. The Communication Blockset contains standard models for memory-less amplifier models. While these are useful for narrowband systems, they are of less value for a wideband system, like 3G, Turbo-3G or the coming LTE standard. In these systems, the frequency-dependence, or the memory-effect, of the non-linearity must be taken into account to give a good representation of the true PA. Several such models are available in the literature, including for example Volterra series and neural networks. We have chosen a simple, yet efficient, model which is here referred to as the *memory polynomial* model (MPM) [12]. This is a special case of the Volterra series, where only the diagonal terms are used. The MPM can also be seen as a generalization of linear finite impulse response (FIR) filters, and it is therefore sometimes called the NFIR model. A Simulink implementation of the MPM is depicted in Figure 4. Note that the MPM is described and simulated in the time-domain, which is necessary for non-linear models. The input is first passed through a fixed saturation, which is always present in a PA. The $1/z$ elements represent a delay of one sample, whereas the $F0$ through $F6$ blocks represent individual non-linearities for each delay. Here, the non-linear blocks are modeled as polynomials, but other options are of course available. At the output, a common gain and phase shifter is applied. A useful property of the MPM is that the output is a linear function of the polynomial coefficients. Thus, the parameters of the model can easily be adjusted to experimental data by a linear least-squares fit [12]. The chosen model structure is able to approximate most amplifiers of interest with reasonable model orders. We have used up to

of techniques to tune components to optimize system-level performance measures.

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