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SDR DESIGN AND IMPLEMENTATION OF DIFFERENTIAL STBC TRANSMISSION

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Abstract: Multiple-input-multiple-output (MIMO) technology uses multiple antennas and advanced signal processing to increase the communication system capacity, reliability and data rate without sacrificing energy consumption or RF bandwidth. In some scenarios, the MIMO communication system need to be designed without knowledge of the channel state information. One possible solution is differential space–time block coding (DSTBC). Ettus USRPs (Universal Software Radio Peripherals) are used in this research work to prototype a DSTBC-based 2 × 1 MISO (multiple-input-single-output) communication system. The signal processing is performed by software with MATLAB. This software defined radio (SDR) approach allows a reconfigurable implementation of the Differential STBC algorithm with tuneable parameters.

Keywords: software defined radio (SDR), Universal Software Radio Peripheral (USRP), multiple-in-multiple-out (MIMO), 5G, space time block code (STBC)

I. INTRODUCTION

In the context of high data rate wireless communication networks like for instance 5G networks, channel fading is an important issue. Multiple antenna technology, often referred as multiple-inputmultiple-output (MIMO), exploits the diversity in the space domain to enhance robustness against fading effects. It can also improve reliability and channel capacity without increasing transmitted power and RF bandwidth [1]. MIMO has led to a need of new encoders/decoders design for wireless communication system. The coherent two-antenna space time block code (STBC), also called Alamouti scheme, was invented in 1998 and is today implemented in many modern wireless communication systems. It has a low decoding complexity and achieves full-diversity, full-rate transmission [2]. In other words,Alamouti STBC can achieve full diversity gain without sacrificingdata rate. This technique was also generalized to more than two transmit antennas [3]. Later, several classes of space-time block codes (STBCs) have been proposed to exploit the spatial diversity in MIMO systems, most notably Orthogonal STBCs (OSTBCs) [4]. The Alamouti scheme can be seen as a special case (two transmit antennas) of OSTBC. All the transmitting antennas send their signal on the same frequency at the same time. A space-time block code ensures that the receiver can distinguish between the incoming signals.STBC transmission techniques require channel state information (CSI) at the receiver. The CSI can be estimated with training symbols if channel variations are slower than baseband signal variations. Assuming perfect channel estimation, a maximum-likelihood decoder was originally suggested for the Alamouti scheme. In practice, channel estimation is much more difficult for MIMO systems than single-input single-output (SISO) systems. Different decoder architectures were proposed for imperfect MIMO channel estimation, most notably the MMSE linear detector [5].

However, some scenarios require a scheme without CSI at the receiver:

- For in-vehicle high-speed data networks, large Doppler spreads lead to short coherence times. When the fading channel changes quickly, the channel conditions are significantly different from burst to burst. A training sequence is therefore required at every burst. This channel estimation overhead makes coherent detection of space time block codes inefficient.Moreover, for very fast time-varying scenarios, channel estimation might be impossible [6].
- In Ultrawideband (UWB) impulse radio communication, MIMO UWB system decoders require channel state information (CSI) and a rake receiver. The UWB channel is characterized by a dense multipath. Consequently, realization of coherent MIMO UWB system is difficult and costly [7].
- In many 5G networks use cases, massive MIMO [8] has shown up as a promising technology. Considering the large number of antennas, the associated CSI to be handled is an overhead and implies a significant reduction in terms of throughput. Non-coherent strategies are therefore receiving renewed interest.

In light of the above, non-coherent space time coding methods have been devised to dispense with training symbols in MIMO communication systems, notably differential orthogonal space–time block codes.

In the experimental area, someAlamouti STBC based systems have been implemented on SDR (Software Defined Radio) test beds and they are presented in [9]. Most of them were programmed with LabVIEW. SDR systems allow to prototype new communications techniques at low cost. One or several RF front ends are typically connected to a computer, allowing much of the signal processing to be done via software. However, the evaluation of the performance of differential STBC (DSTBC) schemes over real scenarios is not well established.

The remaining of the paper is organized as follows: Section II covers the analytical model and theoretical performance of the conventional DSTBC, which is based on the Alamouti scheme. The implementation of a DSTBC-based 2 × 1 MISO communication system using two USRPs is discussed in section III. SectionIV gives results and a discussion about performance trade-offs. Finally, in section V, a conclusion and future works are described.

II. ANALYTICAL MODEL OF DSTBC

Tarokh and Jafarkhani developed a differential STBC [10] for a slow Rayleigh fading channel with two transmit antennas. In this scheme, referred as the conventional DSTBC, neither the transmitters nor the receiver know the CSI. Like Alamouti scheme [2], the conventional DSTBC has a relatively low complexity and can achieve a full diversity gain. It also shows higher tolerance to the effects of time-variant channels than the original coherent STBC. However, the conventional DSTBC performs 3 dB poorer than the coherent STBC and its SNR (signal to noise ratio) versus BER (bit error rate) characteristic is degraded [11]. Tarokh and Jafarkhani generalized the differential detection for STBC to more than two transmit antennas [12], but the rate is not optimal anymore. In this paper we focus on differential orthogonal space–time block codes with two transmit antennas, which give full rate.

The Alamouti STBC is the optimum STBC for two transmit antennas and one receive antenna only. For more than one receiving antenna, it still achieves full diversity but there is a space-time correlation on the channel matrix. The mutual information between the received and the transmit signal vectors is not preserved. Consequently, it suffers capacity loss. The conventional DSTBC scheme used in this work is based on the Alamouti scheme and therefore inherits the properties mentioned above. The choice of using one receiving antenna is motivated by the full capacity order property.

The encoding procedure for DSTBC is similar to the one originally proposed by Alamouti: two successive symbols are encoded in an orthogonal 2×2 matrix. The input data are differentially encoded in blocks. In other words, the input vector

$$\mathbf{s}(t) = [s(2t), \quad s(2t+1)]^T \tag{1}$$

is mapped into differential coefficients:

$$\mathbf{c}(t) = [c_0(t), \quad c_1(t)]^T \tag{2}$$

where t denotes a block number, one block consisting of two time slots. BPSK or QPSK mapping is often used. Then, the new data$\mathbf{x}(t)$ is calculated from$\mathbf{x}(t-1)$, transmitted in previous block t - 1with the following equation:

$$\mathbf{x}(t) = \mathbf{M}\{\mathbf{x}(t-1)\}\mathbf{c}(t) \tag{3}$$

Where$\mathbf{M}$is a unitary matrix with vector parameter

$$\mathbf{x} = [x_0, \quad x_1]^T \tag{4}$$

and defined by

$$\mathbf{M}(\mathbf{x}) = \begin{bmatrix} x_0 & -x_1^* \\ x_1 & x_0^* \end{bmatrix} \tag{5}$$

The first column of $\mathbf{M}$is $\{x_0, x_1\}$ transmitted at time slot 2t.More precisely, $x_0$is transmitted from antennaTX_0, while x_1 is transmitted from antenna TX_1. The second column is transmitted at 2t + 1 the same way: $-x_1^*$is transmitted from antennaTX_0, while x_0^* is transmitted from antennaTX_1.

The decoding procedure for DSTBC consists in calculating the following estimated coefficient vector:

$$\tilde{\mathbf{c}}(t) = \mathbf{\Omega}^H\{\mathbf{r}(t-1)\}\mathbf{r}(t) \tag{6}$$

where the received data is

$$\mathbf{r}(t) = [r(2t), \quad r(2t+1)]^T \tag{7}$$

and

$$\mathbf{\Omega}(\mathbf{x}) = \begin{bmatrix} x_0 & x_1 \\ x_1^* & -x_0^* \end{bmatrix} \tag{8}$$

Then the coefficient vector$\hat{\mathbf{c}}(t)$ is determined by hard-decision using$\tilde{\mathbf{c}}(t)$. Finally, $\hat{\mathbf{c}}(t)$is de-mapped to get the received symbol.

III. DSTBC TRANSMISSION PROTOTYPING

The conventional DSTBC algorithm has already been simulated with MATLAB in [13]. Authors in [14] have built a homebrew SDR platform with Agilent ESG signal generators to feed their DSTBC-based encoder with real data. However, the USRP-based SDR implementation presented in this paper is a novelty. Two Ettus B210 USRPs (Universal Software Radio Peripherals) are used to prototype a DSTBC-based 2 × 1 MISO communication system.

The Ettus USRP is a computer-hosted RF transceiver. Most of the signal processing is therefore done by software. This software defined radio (SDR) platform is often used in communications education and research as a testbed for experimental validation of communication algorithms, using a programming environment like Gnu Radio, LabVIEW, MATLAB or Simulink. The Ettus USRP platform can transmit and receive radio-frequency signals in several bands using two antennas, which allows rapid and reconfigurable prototyping of MIMO communication systems. It allows to experiment with real-world signals and real time conditions, which is not possible with simulation tools.

MATLAB was chosen for this research work because it provides powerful programming techniques for signal processing and algorithm design. Moreover, the MATLAB Communications Toolbox offers customizable software for the modulation and demodulation of signals streaming to and from USRP hardware. It also provides software solutions for common issues in wireless communication system, such as phase offset, timing offset and frame synchronization. As of writing, MATLAB does not provide a MIMO application framework for SDR prototyping. MIMO coding libraries, such as comm.OSTBCEncoder are available for simulation only. The Alamouti code has to be programmed from scratch. This is probably the reason why LabVIEW, which provides a features-rich MIMO application framework, is used in most research works related to MIMO SDR [9].

The host computer communicates with the USRP radio using the SDRu transmitter System object, provided by the MATLAB Communications Toolbox. A real QPSK-based transmission-reception environment is implemented in MATLAB using SDRu System objects. The transmitter and the receiver are based on QPSK Transmitter and QPSK Receiver System object respectively. These System objects, originally intended for SISO prototyping, were modified to enable multi antenna transmission and custom MIMO coding. The test bed operates at the 900 MHz band, which is typically used in Low-Band 5G.

The QPSK Transmitter generates an ASCII message, converts the characters to bits and prepends a Barker code that will be used for frame synchronization at the receiver. Then, the complex baseband signal is modulated using QPSK. The Alamouti STBC encoder is programmed from scratch using the formulas presented in the previous section. It was not possible to use the comm.OSTBCEncoder object, available in the MATLAB Communications Toolbox, because it requires channel knowledge at the receiver, which is not suitable for the DSTBC transmission implemented in this work. Pulse shaping is applied to the modulated symbols via software to improve spectral efficiency.The encoded symbols are filtered with a square root raised cosine filter provided by MATLAB's QPSK TransmitterSystem object. Finally, the filtered QPSK symbols are transmitted over the air using the USRP hardware. The entire transmission process is illustrated on fig.1.

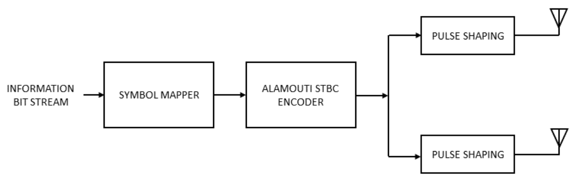

Figure 1. Block diagram of the transmitter.

The SDRuReceiver System object receives data corrupted by the transmission over the air and outputs complex baseband signals. The receiver includes correlation-based coarse frequency compensation, PLL-based fine frequency compensation and timing recovery. Fig. 2 shows the receiver block diagram.

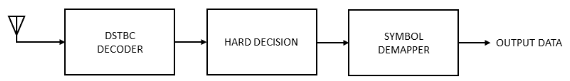

Figure 2. Block diagram of the receiver.

The DSTBC decoder is programmed from scratch using the formulas presented in the previous section. Then, the decoded symbols are demodulated by the QPSK Receiver system object. The frame synchronization occurs right after. The bit stream is thereafterconverted back into characters and the message is printed to the MATLAB command line.

IV. RESULT AND DISCUSSION

The data decoder compares this regenerated message with the transmitted one and calculates the BER, which is used to measure the system performance. The calculated BER for QPSK transmission at 900 MHz is 0.1. The bit-error performance of the Alamouti scheme was initially studied at the simulation level with coherent binary phase-shift keying (BPSK) modulation in 1998 [2]. This digital modulation process has been reused in many MIMO research works.However, in this research work, the transmitter relies on the comm.QPSKModulator object, which cannot have a modulation order different than 4. Consequently, BPSK transmission is not possible with this set-up. Nevertheless, QPSK has a better spectral efficiency and is used in many SDR test beds [9, 15]. It is important to note that the conventional OSTBC scheme [4] only gives full-rate for real constellation such as BPSK. For complex constellation such as QPSK, using more than two transmitting antennas implies a rate loss.

The main advantage of 2×1 MISO systemsis the full capacity order. Nevertheless, according to authors in [15] and [16], 2×2 MIMO has some advantages over 2×1 MISO. The diversity gain is double because the number of different paths is double. In addition, their simulations show that the BER is lower at same value of SNR, assuming perfect CSI knowledge at the receiver. One can infer that a DSTBC-based 2×2 MIMO scheme outperforms a DSTBC-based2×1 MISO scheme in term of BER.

V. CONCLUSION AND FUTURE WORKS

In this research work, Ettus USRP B210 SDRs and MATLAB software were used to implement a full-rate DSTBC-based 2×1 MISO communication system. This SDR testbed fulfills specific scenarios requirement of no CSI knowledge at the receiver by using non-coherent detection of space time block codes. Better performance could be achieved by increasing the number of transmitting and receiving antennas. But this requires more SDR devices. In addition, STBC theory shows that using more than two transmitting antennas will give a non-optimal rate order. Using more than one receiving antenna implies a capacity loss. Hence, trade-offs will have to be chosen.

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