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Architecture of an Analog Combining MIMO System Compliant to IEEE802.11a

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Abstract: The paper describes the MIMAX system requirements and the MIMAX baseband and MAC architectures. It presents the channel estimation and weights selection algorithms as well as the comparative simulation results. The rest of the paper presents description of the MAC protocol extensions compared to a standard IEEE802.11a MAC and MAC processor itself.

Keywords: IEEE802.11a, MIMO, baseband, channel estimation, simulation, MAC

1. Introduction

One of the most promising approaches for future wireless technologies comprises the use of enhanced multiple-input multiple-output (MIMO) schemes with improved diversity and coding gains compared to those in existing systems. We develop an advanced MIMO system for maximum reliability and performance (MIMAX) that introduces spatial coding already in the analogue RF front-end and uses the wireless radio of IEEE802.11a standard [1], [2]. The developments are performed on the physical medium dependent (PMD) layer that demands for changes in the physical layer convergence (PLC) protocol and the medium access control (MAC) protocol to optimally exploit the benefits from the new RF front-end [3]. The IEEE802.2 standard is used for the logical link control (LLC). Applications can be developed by the use of TCP/IP protocol for data exchange. However, this approach needs a cross layer optimization that is shown in Figure 1.

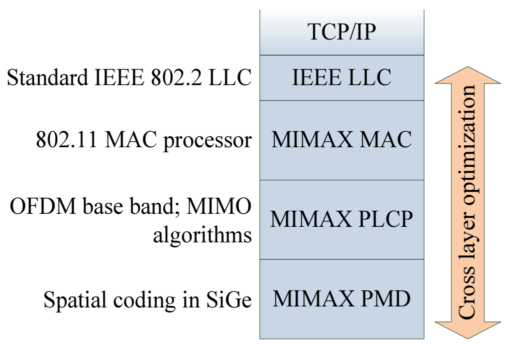

Figure 1: Layers addressed in MIMAX

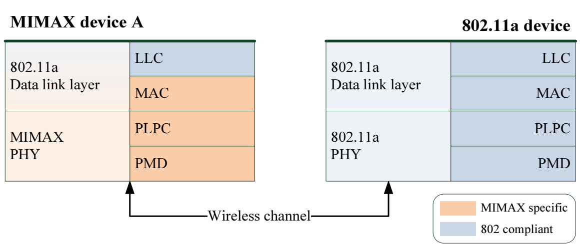

Figure 2: Communication between a MIMAX device and an IEEE802.11a device

Adjustments of the layers are performed in such a way that a MIMAX device can operate with other MIMAX and IEEE802.11a devices simultaneously without affecting neither the performance enhancements of the first nor the standard performance of the second. The communication scheme between a MIMAX device and an IEEE802.11a device is depicted in Figure 2. Modifications in the PLCP and MAC of the MIMAX device have to be provided for ensuring compatibility to the IEEE802.11a standard. The PMD is not affected by amendments because each receive and transmit path is designed for an IEEE802.11a link budget.

2. PLCP and Baseband Architecture

The PLCP baseband pursues mapping MAC protocol data units in PMD layer compliant frame formats. This task is common for all communication schemes defined by the IEEE802.11. Furthermore, in MIMAX the spatial diversity must be exploited, possible impairments in the RF spatial processing have to be compensated and the MIMO channel has to be estimated. Particularly, these tasks are not needed in the IEEE802.11a scheme, which is specified for SISO communication.

The MIMO RF front-end needs new algorithms to exploit the available spatial diversity of the IEEE802.11a communication schemes. Several challenges are addressed in the PLCP. First the impairments of the RF front-end are considered in the baseband processor. The algorithms must operate reliably and robustly with respect to the limited resolution of the RF front-end. Moreover, these algorithms must determine and select the weights for each antenna under different communication situations and channel conditions. Different optimization goals are used when determining the weights for the transmission. The maximization of the signal-to-noise-ratio (SNR) and the minimization of the symbol error rate (SER) and maximization of the capacity are used as objective functions in single-carrier and multi-carrier transmissions. The different constraints at the transmitter and receiver (Figure 3) include:

- Perfect channel state information at the transmitter (CSIT) and the receiver (CSIR),
- Perfect CSIR only and channel distribution information at the transmitter (CDIT),
- Perfect CSIT only, and
- Neither CSIT nor CSIR.

There are several differences between the MIMAX and the full multiplexing MIMO approach. In the MIMAX, the same weight is used for all subcarriers in OFDM transmissions whereas it is possible to weight each subcarrier independently from the others in the other transmission scheme.

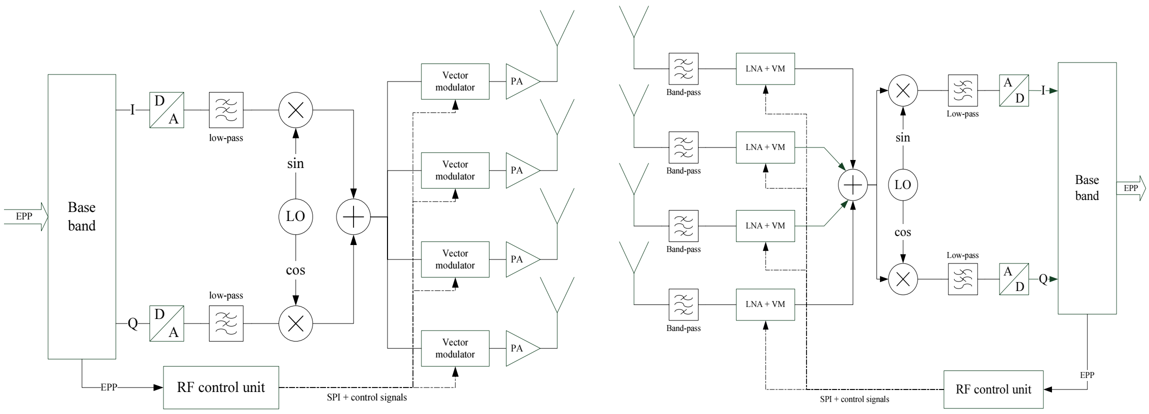

Figure 3: MIMAX transmitter and receiver

Integrating signal processing in analogue circuits is limited in the maximum achievable resolution because of noise processes, process variations or nonlinear behavior of the devices. Therefore, the signal processing has to be calibrated by the baseband to adapt to the RF impairments. This mainly considers the correlation between real and imaginary parts of the vector modulator approach. Compensation is achieved by a calibration performed by the RF control unit in Figure 3. The characteristics of the vector modulator are analyzed by this module and stored in an internal memory. The weights provided by the baseband are then transferred into corresponding values of the vector modulator using the previously determined relationship and these new weights control the vector modulator. Integrating additional calibration options in the RF front-end and the RF control unit allow an internal adaptation to impairments of the fabrication process and a feedback to the baseband processing. These techniques are based on look-up tables or neural network approaches. The interface between the baseband and the RF control unit consists of an enhanced parallel port (EPP) and the vector modulator is connected to the RF control unit by a serial peripheral interface (SPI).

2.1 Baseband processor

The basic architecture and functional blocks of the baseband processor are shown in Figure 4. We focus on the new blocks to be developed, mainly the MIMAX channel estimation block and the MIMAX RF weights selection block. Furthermore, we consider the modifications needed in the IEEE802.11a frame format to add the new MIMO functionalities. We have also developed different transmission strategies depending on the CSI information available at both sides. However, it was decided to focus on the case CSIT and CSIR, where a perfect CSI is available at the TX and RX. The reasons behind this decision are the following: a) it is the scenario providing the best performance for MIMAX; b) it is particularly well suited for TDD WLAN systems; and c) it permits to ensure backward compatibility with standard IEEE802.11a terminals with only minor modifications on the PHY and MAC layers. Despite this decision, other transmission schemes can be considered if needed.

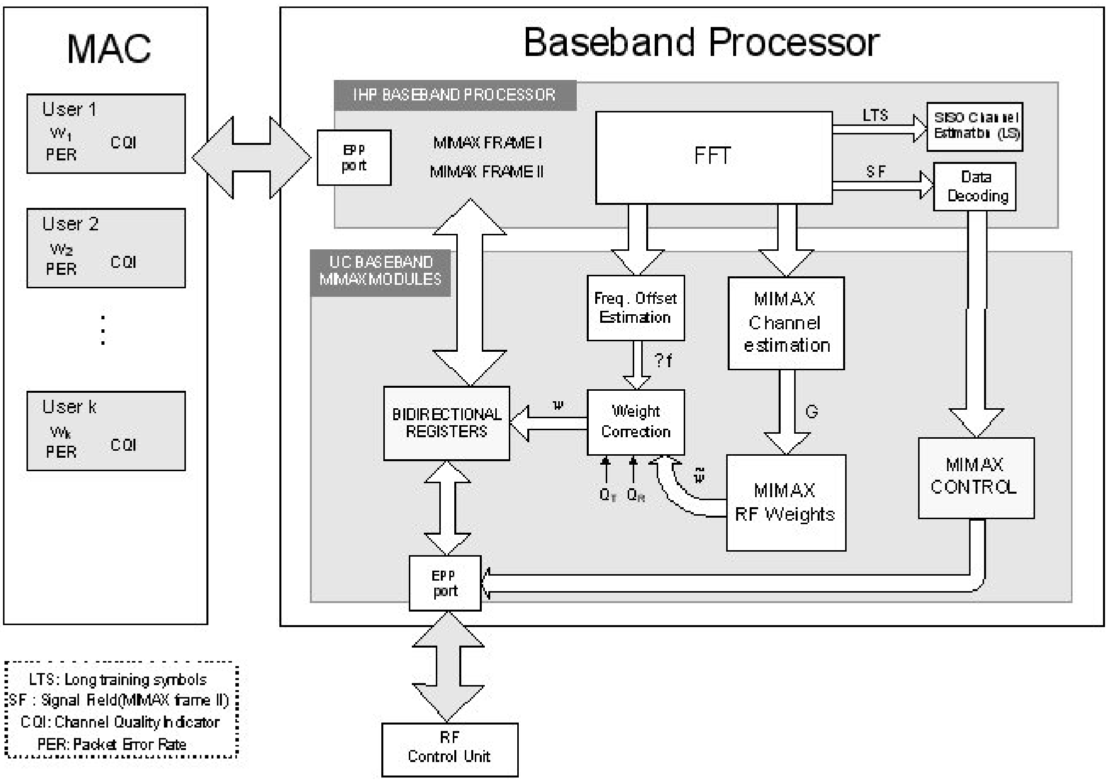

Figure 4: Baseband processor architecture

2.2 Channel Estimation

In the IEEE802.11a, broadband SISO channel estimation is needed. For the MIMAX system model, the broadband MIMO channel has to be estimated to allow the algorithms selecting the optimal weights.

In MIMAX, the MIMO channel estimation and weights setting is a two-way procedure as illustrated in Figure 5. Assuming that the number of antennas at the terminals T1 and T2 are n_1 and n_2, respectively, the procedure is as follows: In the first phase, T1 transmits a known pilot OFDM symbol n_1 n_2 times. These symbols are transmitted (by T1) and received (by T2) using different combinations of prescribed orthogonal weights vectors. Then, T2 receives the n_1 n_2 symbols, estimates the broadband MIMO channel and sets the corresponding optimal weights. In the second phase, T2 transmits a known OFDM symbol n_2 times using the optimal weights previously calculated. T1 receives n_2 the symbols using different combinations of prescribed orthogonal weights vectors and estimates the SIMO channel. Finally, T1 calculates and sets the optimal weights. Note that we assume channel reciprocity so the optimal weights in transmission and reception are identical for any transceiver.

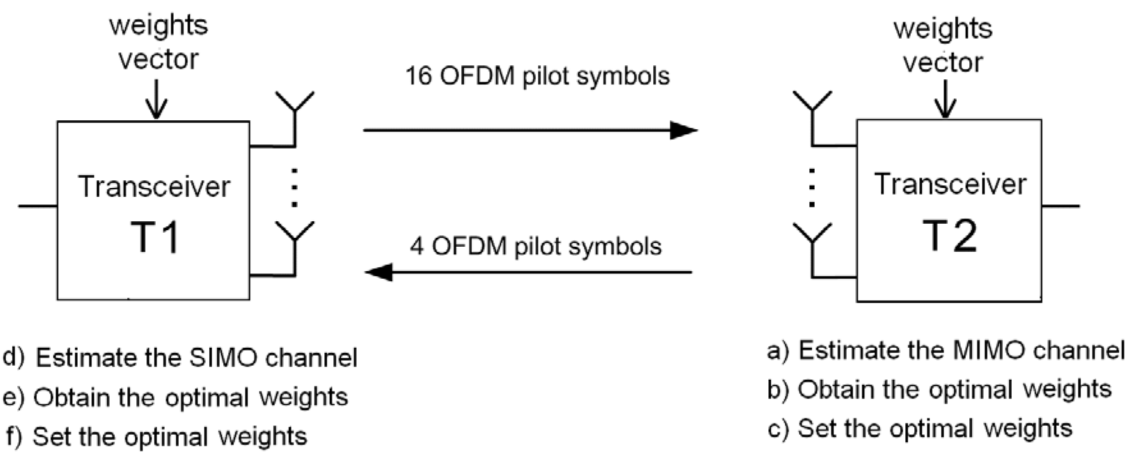

Figure 5: Channel estimation and weights setting procedure in a 4x4 MIMAX system

The optimal weights at each transceiver should be transferred to the MAC processor for storage. They remain fixed while the quality of the equivalent SISO channel, measured through the CQI (channel quality indicator) or the PER (packet error loss), is higher than a prescribed level, otherwise the procedure starts again.

To estimate the MIMO (or SISO) channel a frequency-domain LS (least squares) based algorithm is used. Let us consider the first phase of the channel estimation procedure. When the pilot OFDM symbol $\boldsymbol{x}$ is transmitted using weights vectors $\mathbf{w}_1$ and $\boldsymbol{w}_2$, the resulting signal $\boldsymbol{v}$ at T2 can be expressed as follows:

$$\mathbf{v} = \mathbf{XH\theta} + \mathbf{n},$$

where $\boldsymbol{v}$ is a $N_c \times 1$ vector being N_c the number of OFDM subcarriers, $\mathbf{X} = \text{diag}(\mathbf{x})$, $\boldsymbol{\theta}$ is the Kronecker product of the weights vectors $\boldsymbol{\theta} = \mathbf{w}_T \otimes \mathbf{w}_R$, $\mathbf{H}$ is a $N_c \times n_1 n_2$ matrix representing the MIMO channel responses at each subcarrier and $\mathbf{n}$ is a $N_c \times 1$ vector representing noise. The n_1 n_2 received symbols can be grouped in a matrix $\mathbf{V}$ as follows:

$$\mathbf{V} = \mathbf{XH\Theta} + \mathbf{N},$$

where $\boldsymbol{\Theta} = [\boldsymbol{\theta}_1 \cdots \boldsymbol{\theta}_{n1n2}]$ is an orthogonal matrix and $\mathbf{N}$ is a noise matrix. Then, the LS estimate of the channel response is

$$\hat{\mathbf{H}} = \mathbf{X}^{-1}\mathbf{V}\boldsymbol{\Theta}^{-1}.$$

The LS estimate can be refined by taking into account the maximum length of the channel impulse response. The maximum length assumed by the IEEE802.11a is $L_c = 16$ taps (accordingly the cyclic prefix is set to 16 symbols). Then, the LS estimate can be filtered in the frequency domain by premultiplying by $\mathbf{F}_r \mathbf{F}_r^+$, where the superscript $^+$ denotes the Moore-Penrose pseudoinverse of a matrix and $\mathbf{F}_r$ is a submatrix of the Fourier matrix $\mathbf{F}$ given by $\mathbf{F}_r = \mathbf{F}(\text{used subcarriers}, 1 : L_c)$

2.3 Weights Selection

After fixing the TX and RX beamformers (weights), the equivalent SISO channel is

$$h_k = \boldsymbol{w}_R^H \boldsymbol{H}_k \boldsymbol{w}_T \qquad k = 1, \ldots, N_c;$$

where $\boldsymbol{H}_k$ represents the physical MIMO channel for the k-th subcarrier, and $\boldsymbol{w}_T, \boldsymbol{w}_R$ represent the TX and RX beamformers.

In order to find the optimal pair of beamformers, different performance measures can be used, such as the maximization of the system capacity [4]. Here, we adopt the criterion in [5], which amounts to minimize the mean square error (MSE) of the optimal linear receiver, i.e., our optimization problem is

$$\underset{\mathbf{w}_T, \mathbf{w}_R}{\text{mimize}} \quad \sum_{k=1}^{N_c} \text{MSE}_k = \sum_{k=1}^{N_c} \frac{1}{\gamma |h_k|^2 + 1} \qquad \text{subject to} \qquad \|\mathbf{w}_T\| = \|\mathbf{w}_R\| = 1,$$

where MSE_k denotes the mean square error associated to the k-th subcarrier, and γ is the signal to noise ratio.

The optimal pair of beamformers is found by means of the gradient search algorithm proposed in [5]. Interestingly, the algorithm converges very fast to the optimal solution and it is very robust to errors in the estimate of the SNR, which is illustrated by means of simulation examples in the next section.

2.4 Simulation Results

In this section we evaluate the performance of a 4x4 MIMAX architecture by means of the channel estimation simulations. The MIMAX architecture is compared to a conventional IEEE802.11a SISO system and a 4x4 full MIMO system with maximum ratio transmission (MRT) and maximum ratio combining (MRC) which can be considered as an upper bound for the performance of any analog antenna combining system.

The MIMO channel is modeled as i.i.d. Rayleigh with exponential power delay profile, i.e. the power associated to the n-th tap of the impulse response is

$$E\left[\|\boldsymbol{H}[n]\|^2\right] \propto \rho^n,$$

where we have selected $\rho = 0.7$.

We have evaluated the performance of the idealized systems, i.e., assuming perfect knowledge of the channel and SNR, and without taking into account RF impairments or any other implementation issue. Additionally, we have also evaluated the performance of a realistic MIMAX system, which includes the LS channel estimation procedure, quantization (6 bits) of the RF weights, and other practical problems such as an assumed SNR of 10 dB for the selection of the beamformers, and a limitation to 5 iterations of the beamformer algorithm proposed in [5].

The simulation results for the transmission rates of 12 Mbps (QPSK signaling and ½ convolutional encoder) and 54 Mbps (64QAM signaling and ¾ convolutional encoder) defined in the IEEE802.11a standard are shown in Figure 6 and Figure 7. As can be seen, the proposed architecture greatly outperforms the conventional IEEE802.11a SISO system, and the SNR degradation due to RF impairments and other practical problems is not greater than 3 dB. Furthermore, we have verified that the gap with respect to the optimal MIMO system decreases for less frequency selective channels. Thus, since $\rho = 0.7$ provides a power delay profile close to the limit imposed by the IEEE802.11a cyclic prefix, we can conclude that the performance degradation of a realistic MIMAX system with respect to an idealized MIMO system never exceeds 10 dB.

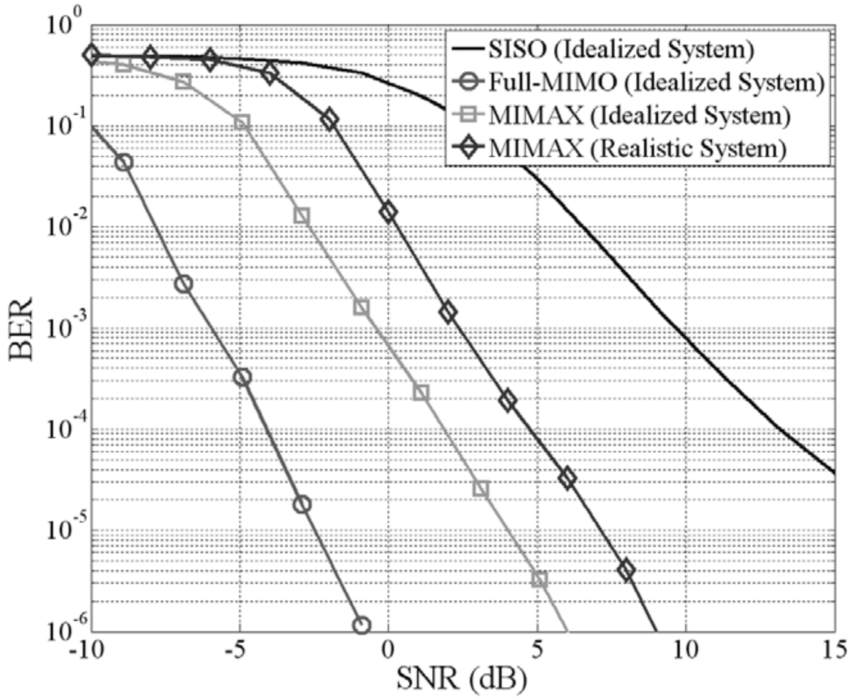

Figure 6: BER performance for a data rate of 12 Mbps

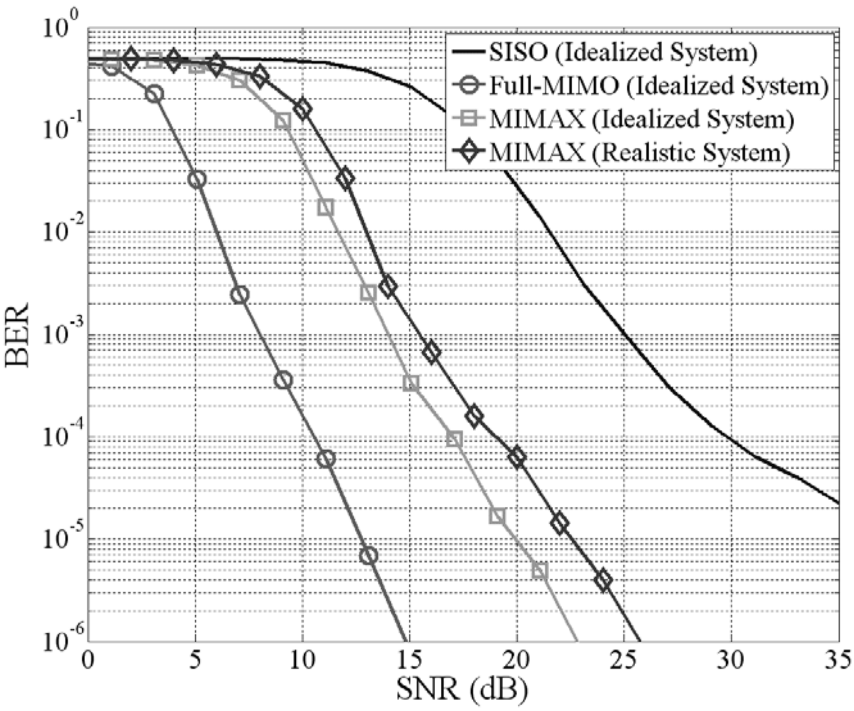

Figure 7: BER performance for a data rate of 54 Mbps

3. MAC and LLC

For the data link layer, the standard IEEE 802.2 LLC is used on top of the IEEE802.11a MAC. The new functionalities of the MIMAX baseband processor impose some changes on the MAC processor, e.g. knowledge of the configuration of the transceiver including the number of antennas for RX and TX or a database of active and available users (MAC addresses, number of antennas at the user, last optimum weights, etc.). These tasks and the storage are related to the MAC because no memory is available at the PLCP baseband processor.

The MIMAX MAC protocol has the following general extensions compared to a standard IEEE 802.11a MAC:

1. The MAC processor has to store and administer MIMO baseband parameters like the number of available antennas and their optimal weight coefficients for particular connections. It shall configure the baseband processor appropriately before a transmission or reception starts.
2. A station in an IEEE802.11 network under DCF (distributed coordination function) does normally not know from which peer station it will receive the next frame. Thus, it cannot set the receiver's optimal weight coefficients in advance. Special action is required to find them out. The MIMAX solution is a short frame exchange sequence like RTS/CTS (Request-To-Send/Clear-To-Send) before any data frame transfer. This allows identifying the peer station from the RTS frame and to set the weight coefficients for the data frame itself accordingly.
   Broadcast and multicast frames will be preceded by an RTS only. There is no CTS because of the unknown number of stations potentially responding to a multicast frame.
3. In certain time intervals and/or under certain conditions (e.g. increasing frame error rate), the MIMO weight coefficients have to be re-calibrated by exchanging special training frames between pairs of stations. The MAC protocol has to be capable of controlling those operations. It shall update its MIMO parameter tables from the measured optimal weight coefficients.

The MAC processor is developed as a flexible hardware-software co-design using state machines in software (SDL or C). Time critical or software inefficient functions are swapped to dedicated hardware. The main core of the MAC processor consists of a 32-bit RISC processor core with additional IEEE802.11a hardware accelerators [6]. Hardware accelerator functionality for the transmit direction includes a buffer for the next frames, the generation of cyclic redundancy checks (CRC) and an encrypt option. For the receive direction, the CRC check, a decryption module, a frame address filter, and the generation of acknowledgements are integrated in hardware.

Furthermore, tracking channel state (busy/idle) including back-off for sending frames, 16 timers (32 bit), a system time unit (64 bit) and several interfaces are provided as hardware modules. The interfaces include a parallel port interface to the physical layer, a CardBus interface to a host PC, a serial RS232 interface for firmware download and general purpose I/Os (GPIO) [7]. A simplified architecture of the MAC processor is shown in Figure 8.

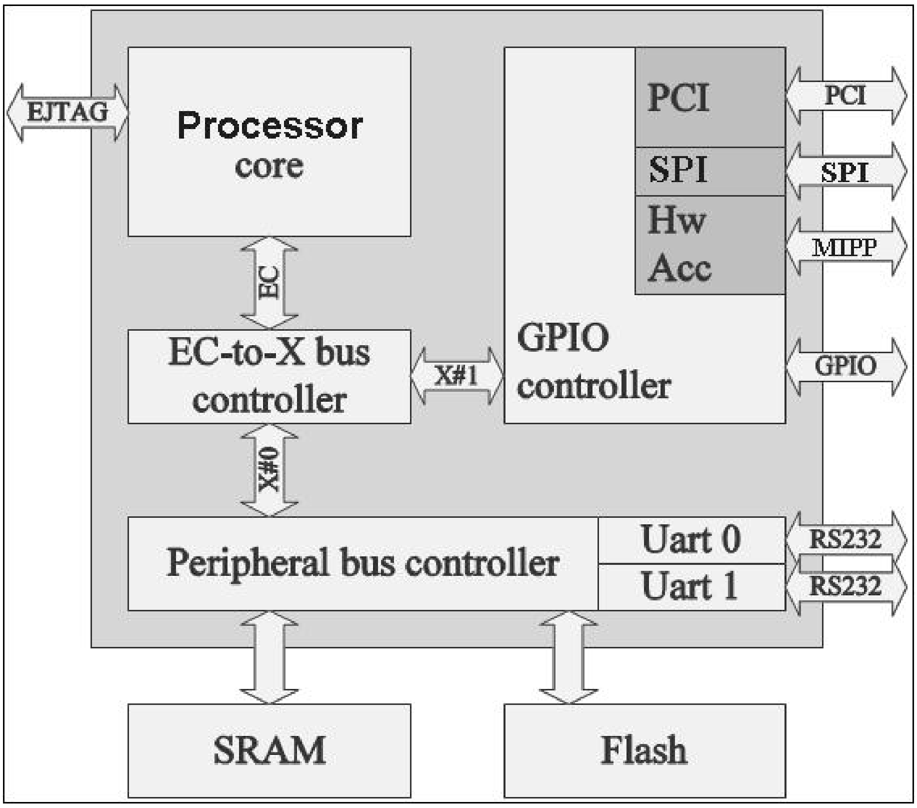

Figure 8: MAC processor architecture

4. Conclusions

We have presented the architecture of the MIMAX system and described the necessary changes in its baseband and MAC protocols. The MIMAX architecture is compared to a conventional IEEE802.11a SISO system and a 4x4 full MIMO system using the channel estimation simulations. The simulation results show a significant optimization gain of the MIMAX approach.

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