DEVELOPING ENERGY-EFFICIENT MIMO RADIOS

Exploring and Developing New Approaches to Enhance 802.11a Short-Range Communication

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Multiple-input, multiple-output (MIMO) systems provide several benefits over single-input, single-output (SISO) air interfaces regarding spectral efficiency and reliability. An integrated wireless radio for short-range communication is developed that performs MIMO signal processing already in the analog radio frequency (RF) front-end. This concept allows using synergies in components and subsystems of the air interface leading to reduced system size, costs, and power consumption. The transceiver is developed in 0.25 μm SiGe technology for enhancing 802.11a with MIMO features. Together with a four-element antenna array, the radio is integrated on a printed circuit board (PCB) with a Personal Computer Memory Card International Association (PCMCIA) card form factor. New base band algorithms and an 802.11 medium access control (MAC) processor ensure exploiting the features of the new air interface and backward compatible operation.

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As today's computing is expected to become more and more ubiquitous oriented, decentralized mobile and wireless networks will become more important in the future. Market analysts predict promising perspectives for

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such networks with data speeds up to the Gb/s range in the next years demanding for better spectral efficiencies in existing and emerging wireless radios [1]. To achieve this goal, evolutionary and revolutionary approaches are currently explored and developed for short-range communication.

In the context of revolutionary approaches, higher data rates compared to the state-of-the-art can be achieved by exploiting the large bandwidth available at very high frequencies, e.g., at 60 GHz or above. However, the corresponding hardware is expensive, the power consumption is high, and the coverage range and reliability of these networks is rather limited that might delay the market launch of such concepts. Therefore, the success in the market of a particular revolutionary approach remains vague.

On the contrary, already existing wireless radios do not provide sufficient spectral efficiency to keep pace with the demands of the future, but their advantages consist of their matured development, their acceptance by the users and that they are already in the market and proved their success. Therefore, evolutionary approaches are restricted to maintain backward compatibility but providing better features compared to the status quo.

In the last decade, MIMO wireless radios, e.g., in 802.11n or in worldwide interoperability for microwave access (WiMAX), have gained considerable attention due to their potential to significantly increase spectral efficiency and reliability compared to SISO systems. However, to exploit the benefits from array, diversity and multiplexing gain, parallel antenna paths must be independently acquired and processed at the base band. Consequently, the hardware costs, the system size and the power consumption are multiplied by the factor of parallel operating antennas as well. Despite the numerous advantages of MIMO systems, these higher costs have delayed the wide scale commercial deployment of multiple-antenna wireless transceivers mainly in handsets or low cost terminals.

In the framework of the European project Advanced MIMO Systems for Maximum Reliability and Performance (MIMAX) [2], an evolutionary radio approach exploiting the spatial diversity offered by MIMO techniques is developed for short-range communication based on IEEE 802.11a. The developed radio frequency (RF)-MIMO transceiver mitigates the mentioned drawbacks of existing MIMO systems by shifting spatial signal processing from the digital base band to the analog RF front-end. This allows using synergies between receive or transmit paths that results in a reduction of subsystems and components in the transceiver, Therefore, the system complexity is reduced to a minimum hardware overhead of the additional antennas for the MIMO system. As a result from the reduced complexity, the power consumption and system size are reduced, now making MIMO attractive for mobile terminals.

ALTHOUGH THE MINIMIZATION OF THE MSE IS OPTIMAL IN TERMS OF BER UNDER LINEARLY PRECODED SYMBOLS AND LINEAR MMSE DETECTION, LOWER BERS CAN BE ACHIEVED BY MEANS OF CHANNEL CODING AND OPTIMAL (NONLINEAR) RECEIVERS.

RF-MIMO System Concept

Using antenna arrays at the transmitter and the receiver of a wireless radio enables MIMO communication schemes. Therefore, multiple antennas allow the use of spatial properties as an additional processing dimension. Hence, spatial diversity and spatial multiplexing can be concurrently and cooperatively used with time diversity and frequency diversity.

Spatial signal processing can be performed at different domains of the wireless radio resulting into different system concepts and air interface architectures.

The most frequently used approach performs the spatial processing that is shown in Figure 1 for a direct-conversion receiver with two antennas. Because SISO receivers operate in parallel, commercially available components and subsystems can be used that had helped to get this idea widely accepted in exiting wireless air interfaces.

The incoming signal is received by the antennas and each antenna branch is processed by independent receiver paths. After filtering interferers in the RF and the low-noise amplifier (LNA), the signals are down converted by means of a quadrature mixer, filtered, and digitized for further digital signal processing that includes temporal and spatial encoding and decoding in the base band. In the connection of spatial algorithms, this signal

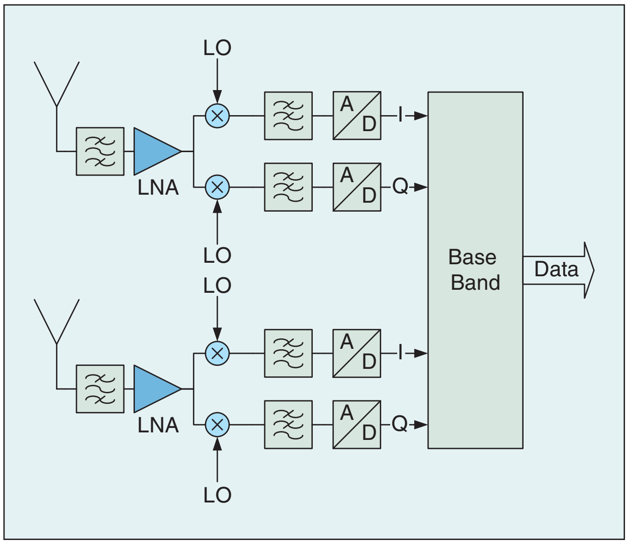

FIGURE 1 Wireless radio with spatial signal processing in the digital base band (full MIMO).

Despite the numerous advantages of MIMO systems, higher costs have delayed the wide scale commercial deployment of multiple-antenna wireless transceivers mainly in handsets or low cost terminals.

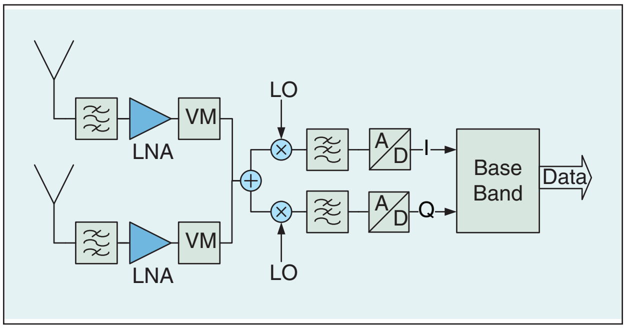

Figure 2 Wireless radio with spatial signal processing in the RF front-end (RF-MIMO).

processing can be related to weight each antenna signal by a complex number [3].

Because of the parallel operating SISO receivers, full spatial multiplexing and full diversity gain can be achieved [4] in this concept. However, it can be shown that a tradeoff exists between spatial diversity and spatial multiplexing and the maximum benefits of both properties cannot be achieved simultaneously [5].

Spatial signal processing in the RF front-end (RF-MIMO) shifts the weighting by complex numbers of the antennas paths from the digital base band to the analog domain. Particularly, this concept can be performed at different locations of the front-end depending on the transmitter and receiver architecture [6]. The concept is shown in Figure 2 for a direct-conversion receiver. Here, the spatial processing operates completely in the RF-domain. The signals received by the antennas are filtered and amplified by the LNA as for the full MIMO concept. Then, the received signals are weighted by a vector modulator (VM) that amplifies inphase and quadrature signal components independently. The weighted signals are combined coherently, down converted, and digitized for further base band processing. In contrast to full MIMO systems, the RF-MIMO base band does not require spatial processing anymore.

Both system concepts obtain different characteristics not only regarding their spatial diversity and spatial multiplexing properties, but also in the number of subsystems, in their radio complexity, in the system size, and in the power consumption.

Table 1 compares both concepts to a SISO system with respect to various performance properties. As can be concluded from Table 1, full MIMO system and RF-MIMO achieve the same spatial diversity whereas the multiplexing gain of the RF-MIMO transceiver is always limited to one because only a single down conversion path is available at the receiver. On the contrary, this single down conversion path reduces the system complexity close to the complexity of a SISO air interface. The additional overhead in hardware only consists of the additional antennas including the spatial signal processing circuits. Hence, the system size, amount of components and subsystems, system costs, and the power consumption can be kept low and are comparable to SISO air interfaces.

Consequently, the main difference between full MIMO and RF-MIMO systems consists of different spatial multiplexing gains. However, in low- and medium-signal-to-noise ratio (SNR) scenarios or for highly correlated MIMO channels, it can be shown that the performance improvement of full MIMO due to spatial multiplexing is marginal compared to RF-MIMO. For these particular scenarios, both concepts achieve a similar bit error rate (BER) and outage capacity [7]. Of course, for high SNR and rich scattering channels full MIMO reveals its benefits over RF-MIMO.

As a result, an RF-MIMO transceiver achieves similar performance such as full MIMO radios but at significant lower system complexity, system costs, and power consumption. Furthermore, the RF-MIMO approach in MIMAX is so constituted that it can be used with any wireless communication standard and in any air interface. Mainly economic factors for the network infrastructure or for the mobile handhelds rather than technological constraints determine the choice of the wireless standard. Design limitations of the RF spatial signal processing only demand for small band standards [7] compared to ultra wideband covering one or two decades of frequency bands.

Therefore, short-range communication standards for wireless personal area networks (WPANs) and wireless local area networks (WLANs) are highly attractive for the RF-MIMO concept. The 802.11a standard was chosen because it allows high transfer rates that can still be improved in low- and medium-SNR conditions of the wireless channel. Usually,

Table 1 ***Maximum achievable performance of wireless radio concepts. n_T depicts the number of transmit antennas; n_R is the number of antennas at the receiver; SNR is the received signal-to-noise-ratio of a SISO system; O is the O-notation.***

	System Concept		
Parameter	***SISO***	***MIMO***	***RF-MIMO***
Transmit antennas	1	n_T	n_T
Receive antennas	1	n_R	n_R
Diversity gain	1	$n_T \cdot n_R$	$n_T \cdot n_R$
Multiplexing gain	1	$\min(n_T, n_R)$	1
Received SNR [dB]	SNR	$\mathrm{SNR} + 10\log(n_R)$	$\mathrm{SNR} + 10\log(n_R)$
System complexity	O(1)	$O(\max(n_T, n_R))$	O(1)

users operate in such environments in their homes that decrease the maximum achievable throughput. Likewise, the frequency range of the standard together and the usually used form factors of the mobiles (personal digital assistant (PDA) or laptop form factor) allow integrating antenna arrays with low correlation not only in the base stations but also in the terminals. Specifically, users demand for energy efficient (green) handhelds for their WLANs.

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Front-End Architecture

The RF-MIMO concept imposes several changes on the analog front-end. Especially, the spatial signal processing circuitry constitutes a major design challenge because it has to operate as reliable as digital signal processing in the base band. Furthermore, the antenna array has to provide low correlation and coupling between the elements to optimally exploit the spatial properties. Both aspects omit the use of commercially available components and demand for an integrated transceiver development. The transceiver is implemented in a 0.25 μm SiGe bipolar complementary metal oxide semiconductor (BiCMOS) process from Innovations for High-Performance Microelectronics (IHP) [8].

Analog Transceiver

The transceiver is based on a direct-conversion concept and the receiver is shown in Figure 3 whereas the transmitter operates in analogy. Each antenna path is designed to be compatible to the 802.11a standard and all signals are combined coherently before down conversion to zero-intermediate frequency (IF). After filtering and digitizing the I- and Q-signals, the complex symbols can be processed by the base band.

The spatial signal processing is performed by a vector modulator (VM) that splits the incoming signal in inphase and quadrature components. Both signals are then amplified independently by a variable gain amplifier (VGA) with low-phase variation. Low-phase variation is needed because usually VGAs affect the phase when changing their gain [6], this would result in correlation between inphase and quadrature components.

This coupling causes two effects. First, the complex plane undergoes a nonlinear transformation that could mean that specific complex numbers cannot be represented by the VM. Secondly, the weights, which are determined by base band algorithms and applied to the VM, differ from the actual complex numbers realized by the analog weighting circuitry. Thereupon, calibration methods are integrated to compensate these RF impairments.

Compensation is achieved by an innovative design of the VGA [9], [10] that uses bias-point stabilized transistors in its architecture. Gain setting is achieved by driving gain stages in opposite direction but keeping the overall bias point constant. A silicon based VGA was designed that operates over a large amplitude control range of 20 dB with phase variations less than 5°. These results are significantly better than existing approaches in III/V technologies [11], [12] or silicon processes [13].

Furthermore, the VGA is calibrated by an RF control unit (compare to Figure 3). A neural network and look-up table approach are used for compensating the correlation between inphase and quadrature components. The neural network is trained to minimize the correlation between inphase and quadrature components whereas the look-up table performs a direct mapping between both values.

Moreover, the RF control unit handles the spatial code transfer from the base band to the analog front-end. The RF control unit converts the weights into corresponding control values for each VM and send these values to the

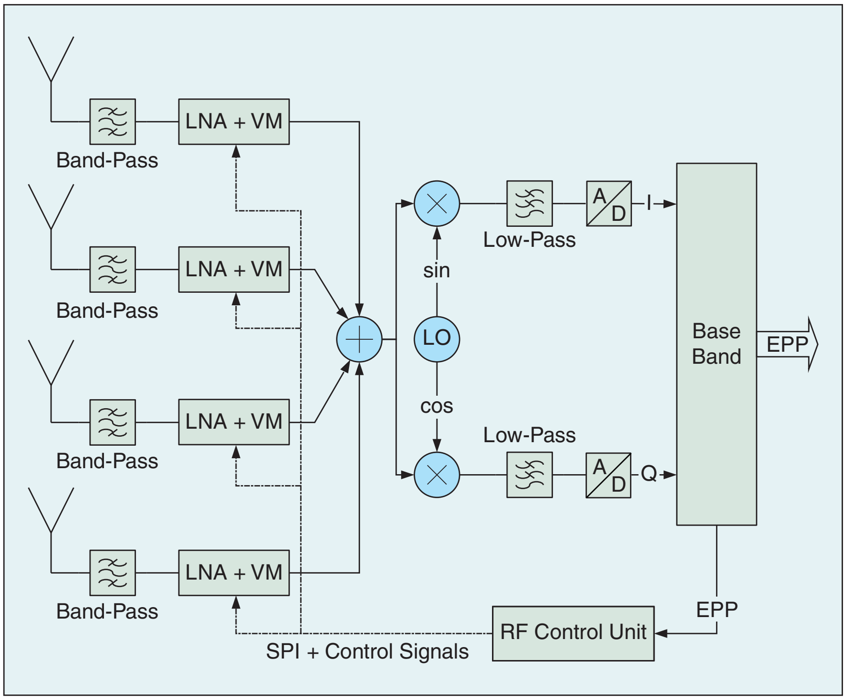

FIGURE 3 Direct-conversion receiver for RF-MIMO in MIMAX.

AS A RESULT FROM THE REDUCED COMPLEXITY, THE POWER CONSUMPTION AND SYSTEM SIZE ARE REDUCED, NOW MAKING MIMO ATTRACTIVE FOR MOBILE TERMINALS.

front-end. Furthermore, several weights can be stored in the analog front-end that allows a fast mode change of the VM for channel estimation, and it reduces the communication overhead between base band and analog front-end.

Antenna Array

Besides the analog circuitry, compact and low-cost antenna arrays are designed and optimized for the WLAN 802.11a standard. Several types of planar printed antennas, inverted-F antennas, bow tie antennas, and Vivaldi elements, are investigated with respect to their correlation coefficient and diversity gain for a PCMCIA card form factor.

To reduce the correlation between the received signals in the antenna array, various forms of diversity are exploited that arise due to the availability of multiple antennas, like space diversity, pattern diversity, and polarization diversity. Previous researches revealed benefits of pattern diversity over space diversity but the latter is limited in small system sizes.

The current development revealed that for PCMCIA card up to four radiating elements with a directive or omnidirectional radiation pattern and with a broadside or end-fire radiation pattern can be used with acceptable coupling. This is beyond the state-of-the-art where most solutions deal with two elements in this form factor. However, PCMCIA card form factor does not allow many flexible configurations because the proximity of antennas results in high mutual coupling with low effective diversity gain (EDG). The higher the number of radiating elements, the higher the value of diversity gain. The closer the elements, the less the EDG with respect to the ideal case. During the development, it was revealed that reducing the spacing between two antennas to less than 0.4 wavelengths is not worthwhile.

To improve the RF-MIMO system performance, polarization diversity is further used and dual linearly polarized antennas are implemented to exploit the advantage of several linearly polarized multipath signals at the receiver. These dual polarized antennas theoretically have a better chance of receiving higher signal power compared to a single linearly polarized antenna.

Figure 4 shows a developed four-element array configuration using inverted-F and bow tie antennas. Each individual radiating element is matched (S11 better than −10 dB) in the 5.470−5.725 GHz band. The worst mutual coupling value between two antennas was measured smaller than −13 dB whereas the best coupling values are about −20 dB. The main problem of small distances between two antennas is the change in the radiation pattern of each individual element. This produces a degradation in the EDG, which is caused by two factors: the correlation and the mean effective gain.

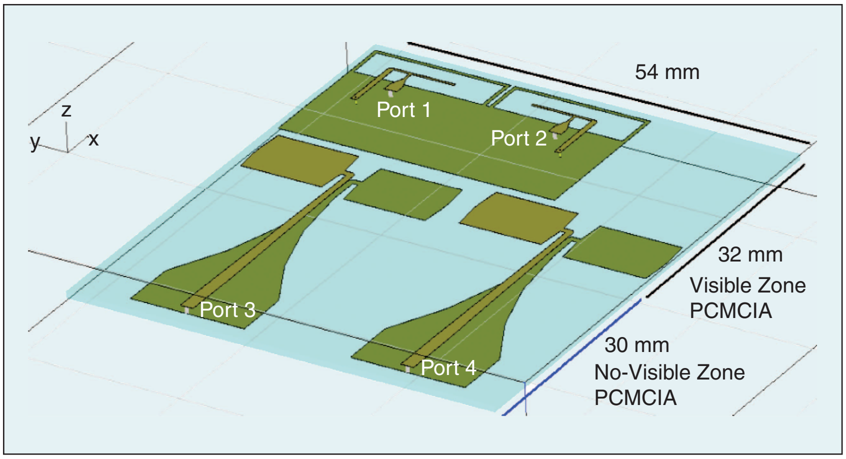

FIGURE 4 Four-antenna array configuration with two inverted-F antennas and two bow tie dipoles.

Base Band Algorithms

The concept of RF spatial signal processing requires new base band algorithms reacting to the changed properties of the spatial signal processing. Compared to full MIMO systems, the time and spatial encoders/decoders can operate at different time scales. Typically, the time encoder works at the symbol rate whereas the spatial (RF) encoder works at a slower rate (e.g., the settling time of the RF circuitry is at least 200 ns).

Moreover, 802.11a transmissions are based on orthogonal frequency division multiplexing (OFDM). For multicarrier modulations, the same RF weights have to be used for all OFDM subcarriers for RF-MIMO radios whereas each subcarrier can be weighted independently from the others in a conventional base band MIMO scheme. Finally, impairments and the limited resolution of the analog circuits demand for robust and reliable algorithms.

MIMO Algorithms for Multicarrier Transmission

Different criteria for optimal RF spatial encoding are developed that are based on different optimization goals for the weight selection. In particular, they rely on maximizing the SNR, minimizing the mean square error (MSE) or maximizing the link capacity. These algorithms are integrated in a new base band processor, which supports and is backward compatible to conventional 802.11a communication but is enhanced with MIMO features such as spatial encoding and MIMO channel estimation.

The developed algorithms are able to achieve full spatial diversity of the MIMO channel as well as to increase the received SNR through array gain. The optimal design of the RF spatial encoder and the time encoder for RF-MIMO is developed assuming perfect channel state information (CSI) at the transmitter and receiver sides. The different optimization criteria result in coupled eigenvalue problems that are solved by iterative gradient descent algorithms.

Maximum SNR Criterion

Previous research efforts on pre-discrete Fourier transform (DFT) schemes (i.e., schemes that combine the received signals before the fast Fourier transform (FFT) as imposed by MIMAX) have been focused on maximizing the received SNR (Max-SNR). For this criterion, the optimal solution amounts to maximizing the added energy of all the equivalent flat-fading SISO channels per subcarrier. These equivalent SISO channels are generated by the pre- and post multiplying the spatial MIMO channel per subcarrier by the receiving and transmitting RF weights, respectively [15].

For frequency selective channels, no closed solution does exist for this optimization problem. Therefore, iterative algorithms, which are based on gradient descent techniques, were developed to solve the resulting pair of coupled eigenvalue problems. These algorithms are able to solve also the optimization problems for other objective functions proposed in the following because all underlying eigenvalue problems can be formulated equivalently [15].

Minimum MSE Criterion

Although the Max-SNR is a sensible criterion for the weight selection, a more relevant performance measure is given by the symbol error rate (SER) or BER. To simplify the problem a linear minimum MSE (MMSE) detector is considered at the receiver. For this particular case, it is possible to obtain a lower bound for the SER [4] that depends on the signal power, the signal constellation and the MSE in each subcarrier.

This lower bound is attained if and only if the symbols are linearly precoded with an orthogonal matrix with all constant modulus entries, e.g., with the FFT matrix [4]. Under these assumptions, minimizing SER is equivalent to minimizing the average MSE across the subcarriers. Therefore, this criterion minimizes the MSE of each particular subcarrier, which depends on the SISO channels determined by transmit and receive weight selection [15].

ALTHOUGH THE MAX-SNR IS A SENSIBLE CRITERION FOR THE WEIGHT SELECTION, A MORE RELEVANT PERFORMANCE MEASURE IS GIVEN BY THE (SER) OR BER.

If both criteria, Max-SNR and Min-MSE, are compared to each other, the minimum MSE criterion tries improving the performance of the worst subcarriers, whereas the maximization of the SNR treats all subcarriers equally. It can be shown that for low SNR regimes both criteria are equivalent because noise dominates and the MSE associated to each subcarrier is basically identical.

Maximum Capacity Criterion

Although the minimization of the MSE is optimal in terms of BER under linearly precoded symbols and linear MMSE detection, lower BERs can be achieved by means of channel coding and optimal (nonlinear) receivers. Thus, a further optimization criterion was developed that maximizes the capacity of the equivalent SISO channel [15].

For 802.11a systems, which must use a given punctured convolutional encoder defined by the standard, this criterion does not translate into an increased spectral efficiency of the system, but only into a reduced outage probability for a given transmission rate.

Again, by applying the method of Lagrange multipliers a pair of coupled eigenvalue problems results, which can be solved by the iterative gradient descent algorithm.

Figure 5 presents the results for linearly precoded OFDM quadrature phase shift keying (QPSK) symbols transmitted over a 4x4 Rayleigh MIMO channel with

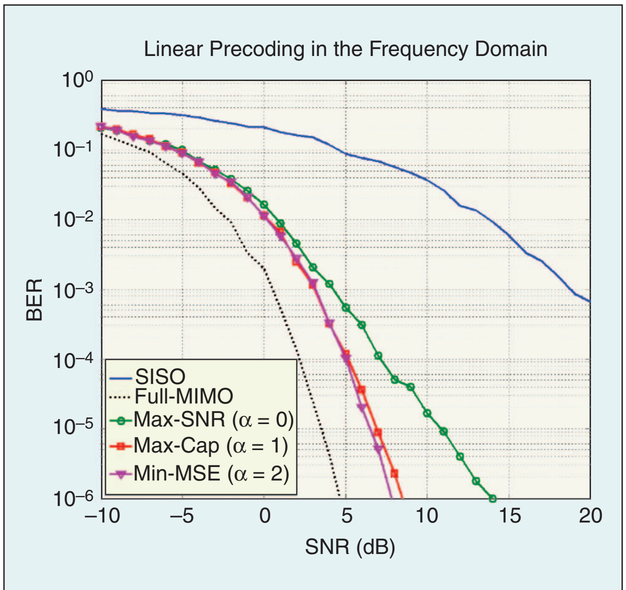

FIGURE 5 BER for linearly precoded OFDM symbols [15].

exponential power delay profiles. As a conclusion from Figure 5, the minimization of the MSE and the maximization of the capacity behave similarly in terms of BER for all SNR conditions. Both objective functions achieve better performance than the Max-SNR criterion in high SNR scenarios. In comparison to SISO systems, the MIMO algorithms for the RF-MIMO transceiver achieve significant better BER that are close to the performance of full MIMO systems.

Channel Estimation

In contrast to 802.11a, the base band algorithms employ a MIMO channel matrix for determining the optimum weights according to the different optimization criteria. Therefore, the MIMO channel has to be estimated within the 802.11a operation mode. This is achieved by transmitting special designed data frames that are compatible with the 802.11a frame format but they are only processed by MIMAX devices and dropped by conventional 802.11a stations.

In MIMAX, the channel estimation procedure comprises two phases for determining the full channel matrix. First, a MIMAX device transmits a known OFDM pilot symbol several times, but using a different combination of orthogonal weights at the transmitting and the receiving device for each OFDM symbol. The second MIMAX terminal receives these OFDM symbols, estimates the MIMO channel and computes the optimum spatial code based on the implemented channel estimation algorithms. Algorithms were developed that operate either in the time or frequency domain.

Now, only a SIMO channel in the backward-direction has to be estimated. Thus, the former receiving device transmits a known OFDM pilot symbol several times using the optimal RF weights. The initial transmitting device receives these OFDM symbols through its orthogonal weights and SIMO channel can be estimated.

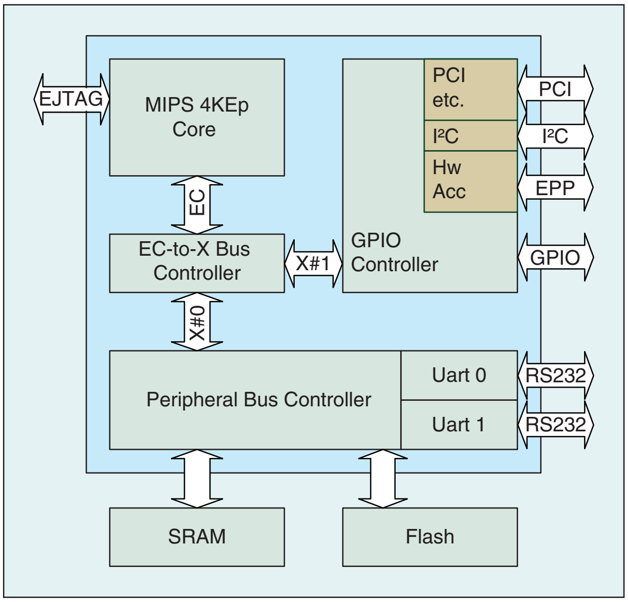

FIGURE 6 SoC implementation of the 802.11 MAC processor [14].

MAC Functionality

For the MAC processor, an IEEE 802.11 compliant system is implemented with the new base band processor. For the data link layer, the standard IEEE 802.2 link layer control is used on top of the 802.11 MAC. Nonetheless, the new functionalities of the MIMAX base band processor impose some changes on the MAC processor, e.g., knowledge of the configuration of the transceiver including the number of antennas or a database of active and available users in the network (MAC addresses, number of antennas at the user, last optimum weights, etc.).

The MAC processor manages the data and control flow to the base band processor depending on the communication scheme. Not only transmission of data and the last optimum weights to the base band are initialized by the MAC processor, but also transferring weights for channel estimation to the base band processor.

The MAC processor is developed as a flexible design using state machines in software (SDL or C). Time critical and software inefficient functions are swapped to dedicated hardware [14]. The main core of the MAC processor consists of a MIPS 4kEp RISC processor (32-b) core with additional 802.11 hardware accelerators.

Hardware accelerators for the transmit direction include a buffer for the next frames, the generation of cyclical redundancy check (CRC) and an encrypt option. For the receive direction, the CRC check, a decryption module, frame address filter, and the generation of acknowledgments (ACKs) are integrated in hardware.

Furthermore, tracking channel state (busy/idle) including back-off for sending frames, 16 timers (32 b), system timers (64 b) and several interfaces are implemented in hardware. The interfaces include an enhanced parallel port (EPP) interface to the physical layer, a CardBus interface to a host PC, a serial RS232 interface and general purpose input-output (I/Os) (GPIOs). A simplified architecture of the MAC processor is shown in Figure 6.

The MAC processor inherently uses the new features of the base band processor and the RF front-end. Therefore, the new operation modes are transparent for higher layers in the International Standards Organization Open Systems Interconnection (ISO/OSI) reference model. Consequently, users, mobile applications and wireless services can use their existing transmission control protocol (TCP)/Internet protocol (IP) solutions without any change or adjustment in the application software.

Conclusions

Shifting spatial signal processing in multiantenna systems from the digital base band to the RF front-end allows the development of energy efficient (green) MIMO radios. An integrated transceiver using RF-MIMO is designed in 0.25 μm SiGe technology together with a four-element antenna array. Low correlation between the antennas was achieved by using different diversity techniques and by optimizing the array configuration. Moreover, a base band processor with new MIMO algorithms and an 802.11 MAC processor were developed as a system-on-a-chip (SoC) design. The superior performance of the developed MIMO algorithms was demonstrated by Monte Carlo simulations. The size of the complete system was designed for a PCMCIA card form factor. This allows enhancing 802.11a WLAN with MIMO features and still guaranteeing backward compatibility of the transceiver to the adopted 802.11 standard.

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Laura González received her degree in physics and electronics from the University of Cantabria, Spain, in 1997. She joined the Department of TEISA as an R&D engineer. Since 1999 she has been working as an antennas engineer at TTI Norte in Santander. Her present work is focused on the design and investigation of broadband printed antennas and phase scan arrays for broadband mobile communications. She has participated in and led several R&D projects for the EC and the European Space Agency.

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