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Performance evaluation of wireless MIMO radios

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Abstract: Next generation wireless radios demand for better spectral efficiencies and for high energy efficient (green) handhelds, and multiple-input multiple-output (MIMO) air interfaces represent a popular approach to address these challenges. In this work, spatial signal processing techniques in MIMO radios at different domains are evaluated with respect to their achievable performance, their power consumption and system sizes. Here, adaptive weighting in the analogue domain reveals several benefits compared to digital approaches. The obtained results are based on a four antennas receiver implementation in an $0.25\ \mu m$ SiGe BiCMOS process.

1. Introduction

Wireless and mobile networks will become more important than today and market analysts predict promising perspectives for such networks with data rates up to the Gbit/s range in the next years [1]. Simultaneously, better spectral efficiencies and low energy (green) reconfigurable radio implementations are required for these next generation wireless networks.

To achieve these goals, one promising concept consists of enhanced MIMO schemes with improved diversity and multiplexing gains. Especially in the last decade, MIMO wireless radios, e.g. in 802.11n or in WiMAX, have gained considerable attention due to its potential to significantly increase spectral efficiency and link reliability compared to single-input single-output (SISO) systems. Low correlation between antennas at transmitter and receiver enables transferring a MIMO channel into several parallel SISO channels [2]. Therefore, higher efficiency, better reliabilities and larger coverage ranges are achieved due to array gain, diversity gain and multiplexing gain [3].

Parallel operating antenna paths must be independently acquired and processed at the base band to exploit these gains. Consequently, the hardware costs, system size and power consumption are increased by the factor of parallel operating antennas. Despite the advantages of MIMO systems regarding capacity and reliability, those higher costs and especially a poor energy efficiency have delayed the wide scale commercial deployment of multiple-antenna wireless transceivers mainly in mobile handsets.

Nevertheless, spatial signal processing can also be performed in the analogue front-end enabling further MIMO concepts besides conventional base band MIMO [4]. All concepts show different performance properties with respect to their power consumption, system size, spatial diversity gain, and spatial multiplexing gain and these properties are traded off for each other. In this work, those MIMO concepts are analyzed

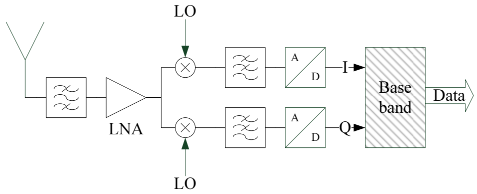


Figure 1: SISO homodyne receiver as reference system architecture

based on implementation results from a four antennas MIMO receiver with respect to those metrics. It is shown that low power consuming devices with small form factors but still retaining most of the benefits of MIMO processing are enabled by an innovative MIMO concept.

2. MIMO system concepts

The architecture of wireless radios usually differ in their concept such as homodyne or heterodyne transceivers [5] and in the number of antennas. Several antennas at transmitter and receiver enable MIMO communication[1] insofar as the channel can be accessed from spatially separated locations. Spatial signal processing can be performed at different domains, e.g., at the digital base band (BB), at the radio frequency (RF) and the intermediate frequency (IF) domain, or completely at the RF-domain.

2.1 SISO reference system

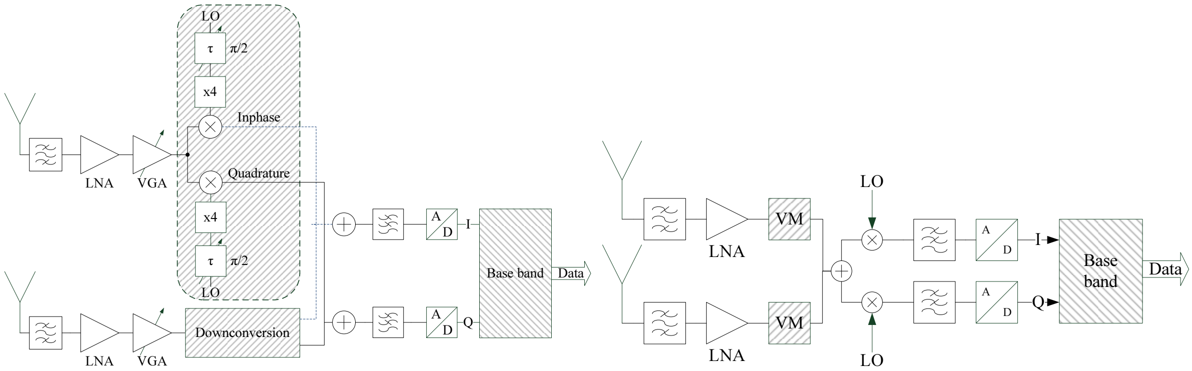
SISO systems still constitute the state-of-the-art in wireless radios, especially for mobile handhelds. Albeit different concepts for the transmitter and the receiver exist, e.g., superheterodyne, low-IF, or zero-IF [5], most of the air interfaces use a direct-conversion architecture [6]. Nevertheless, in the variety of wireless technologies each particular concept can be more or less applicable to the specific requirements of a communication standard.

Fig. 1 shows the architecture of a direct-conversion receiver. The signal is received at the antenna and a band pass filter in the RF ensures the suppression of strong interferers. After the low noise amplifier (LNA), the signal is directly converted to zero-IF by a quadrature mixer. The low-pass filter removes remaining images before quantization and signal processing at the BB. Thus, this concept provides several advantages, e.g., low cost solutions, simple frequency plan for multi standards, highly integrable systems, and no image problem.

2.2 Base band MIMO

Wireless MIMO radios use parallel operating SISO systems that are controlled by a joint digital BB. This enables splitting a serial data stream in several parallel data streams and transmitting each of them over a single SISO transmitter system. Of course, the same concept can be applied at the receiver, at which several parallel data streams are received and processed simultaneously. Thus, the architecture of a MIMO air interface consists of straight forward implementation of parallel operating SISO systems and as many SISO receivers as antennas are operating in parallel. The spatial signal processing is executed in the base band.

[1] We refer to MIMO as its basic meaning of multiple input-antennas and multiple output-antennas. In literature, MIMO is often referred to full-rate and spatial multiplexing schemes only.



(a) RF/IF spatial processing
(b) RF spatial processing

Figure 2: MIMO radios with spatial processing in the front-end

2.3 Combined RF- and IF-MIMO

Spatial diversity will be still achieved if only a single up- or down-conversion path is used in the transceiver but spatial signal processing must then be shifted to the analog front-end. Here, multiplexing gain cannot be achieved because a single up- or down-conversion path is only available.

Fig. 2(a) shows the concept for MIMO communication, in which spatial signal processing is performed in the RF- and IF-domain by adjusting amplitude and phase of the incoming signals. In contrast to base band MIMO, after the LNA the amplitude is weighted for each antenna path by a variable gain amplifier (VGA). Because spatial processing is achieved by adjusting amplitude and phase of the incoming signals relatively to the other antenna paths, the VGA must not change the phase when amplifying the signals. Otherwise, phase and amplitude cannot be adjusted independently from each other [4]. Of course, the same remarks are relevant for the phase shifter that must not change the amplitude when changing the phase.

The phase shift is performed in the IF domain[2] with the local oscillator (LO). Therefore, the requirements for the phase shifting element can be relaxed compared to phase shifters in the RF domain because for down-conversion the signal in the LO path is driven into saturation before it is fed to the mixer. Consequently, any variation in the amplitude is suppressed. The phase adjustment is preserved since the arguments of the RF and LO signals are subtracted and added during mixing [5].

Additional simplification is achieved by quadrupling the LO frequency. This allows the use of phase shifters that cover only $\pi/2$ instead of 2π. Therefore, the elements can be designed more precisely in their phase shift because the group delay is only considered for a small fraction of the frequency band [5].

2.4 RF-MIMO

A consequent extension of the concept would mean that the phase shifter also operates in the RF domain. However, adjusting phase and amplitude does not directly correspond to spatial signal processing in the base band where complex weights are usually determined by their real and imaginary parts. Logically, the same representation is also used in the RF spatial signal processing because no conversion needs to be performed.

[2]We refer to the IF domain as LO path of the mixer in Fig. 2(a). In zero-IF receivers, the IF is at DC.

Table 1: Characteristics of wireless air interfaces

Parameter	System concept		
	SISO	MIMO	RF-MIMO
Diversity gain	1	$n_\mathrm{T} n_\mathrm{R}$	$n_\mathrm{T} n_\mathrm{R}$
Multiplexing gain	1	$\min(n_\mathrm{T}, n_\mathrm{R})$	1
Received SNR [dB]	SNR	$\mathrm{SNR} + 10\log(n_\mathrm{R})$	$\mathrm{SNR} + 10\log(n_\mathrm{R})$
Complexity	$\mathcal{O}(1)$	$\mathcal{O}(\max(n_\mathrm{T}, n_\mathrm{R}))$	$\mathcal{O}(1)$

Fig. 2(b) shows the concepts of RF-MIMO for a two antennas system. Multiplication of complex numbers is achieved by a vector modulator (VM) after the LNA. These weighted signals are combined coherently and are down-converted like in SISO systems. The VM splits the incoming signal in an inphase and a quadrature component that directly correspond to real part and imaginary part. Both parts are generated by constantly shifting the phase of one signal by $\pi/2$. Each of these signals is then amplified using a VGA as in Fig. 2(a). Hence, the VGA has to provide low phase variations when changing the gain of the amplifier, as for RF/IF-MIMO. Otherwise real and imaginary part cannot be adjusted independently from each other. Thus, the weights from the base band can be directly applied at the RF front-end because they use the same representations. However, the changed architecture of the front-end, possible RF impairments and limited resolution in analog signals will affect the BB algorithms in their weight selection process [7].

3. Performance analysis

The different concepts presented in Section 2. obtain different performance characteristics regarding potential MIMO benefits, e.g., array gain, diversity gain or multiplexing gain, and important metrics such as system size and costs, area and component count, power consumption or complexity.

3.1 Wireless radio performance

Table 1 compares the properties of SISO systems, full BB-MIMO and RF-MIMO transceivers with n_T transmit and n_R receive antennas. Because RF/IF-MIMO is identical to RF-MIMO with respect to these characteristics, this concept is omitted here. The signal-to-noise-ratio (SNR) of a SISO transceiver and its complexity measured by the O-notation serve as a reference value. The complexity and component counts are analyzed in more detail in Section 3.2.

As can be concluded from Tab. 1, a BB-MIMO transceiver offers the largest flexibility and highest achievable performance regarding spatial diversity and spatial multiplexing. Nonetheless, the complexity is significantly higher, requires more components and results in larger systems and higher power consumptions compared to SISO and RF-MIMO approaches. Additionally, because of its high number of components the system costs are increased.

However, all benefits from spatial signal processing cannot be achieved by full BB-MIMO systems simultaneously because there exists a trade-off between achievable spatial diversity gain and spatial multiplexing gain [8]. As a result, the expected performance gain compared to RF-MIMO systems, in which multiplexing gain is always

Table 2: Simulated power consumption and size per component

Component	Current [mA]	Supply [V]	Power [mW]	Size [mm^2]	Component count BB	Component count RF/IF	Component count RF
LNA	3.06	3.3	10.10	0.050	4	4	4
Active balun	1.52	3.3	5.02	0.017	4	4	4
Buffer	2.19	3.3	7.23	0.008	4	4	4
passive VGA	0.54	2.5	1.35	0.044	0	4	8
I/Q splitter	3.00	3.3	9.90	0.050	0	0	4
I/Q combiner	0.00	0.0	0.00	0.050	0	0	4
RF combiner	10.00	3.3	33.00	0.650	0	0	1
IF combiner	1.00	2.5	2.50	0.050	0	1	0
Passive mixer	6.00	2.5	15.00	0.235	8	8	2
Multiplier by 4	4.00	3.3	13.20	0.050	0	8	0
LO phase shifter	5.00	2.5	12.50	0.200	0	8	0
Synthesizer	9.00	3.3	29.20	0.050	4	1	1
ADC	9.09	3.3	30.00	2.040	8	2	2

limited to one, depends on the actual channel characteristics. It can be shown that in low up to medium SNR channel conditions full BB-MIMO and RF-MIMO outperform conventional SISO approaches with respect to outage capacity and bit error rates (BER) [7]. On the contrary, the differences in BER and capacity between full BB-MIMO and RF-MIMO is negligible in these low and medium SNR conditions whereas, of course, for high SNR BB-MIMO obviously reveals its better performance over RF-MIMO [2].

SISO transceivers achieve the lowest possible system area, system costs, and power consumption, but do not profit from any spatial signal processing. As a result, RF-MIMO radios depict a good compromise between the benefits from spatial signal processing and minimum sized, low cost and low power consuming air interfaces.

3.2 RF front-end implementation

Table 2 gives an overview about the power consumption and silicon size of components that are needed for the discussed direct-conversion receiver concepts. The power consumption and system size were determined by designing these components in IHP 0.25 μm SiGe technology (SGB25VD) [9]. All designs use fully-differential architectures. The analog-to-digital-converter (ADC) have not been designed yet and a state-of-the-art design was selected [10, 11] for comparison. Considering its technology node, it can be expected that a corresponding design in the IHP technology will have larger power consumption and component size. Moreover, the amounts of components, which are needed in a four antennas receiver wireless radio, are depicted for each MIMO concept. Several components are used in all concepts, e.g., the LNA, baluns, buffers, ADCs or the synthesizer. Thus, their performance affects all MIMO concepts. Furthermore, some components can be integrated completely passive such as the I/Q combiner for the vector modulator. and, hence, they do not consume any power.

The most silicon area besides the ADC is consumed by the RF-combiner, which is needed in the RF-MIMO concept only. Fortunately, according to Fig. 2(b) only one component is needed. Furthermore, the mixer and the LO phase shifter consume significant silicon area. Consequently, BB-MIMO and RF/IF-MIMO suffer from large system areas because they need several of those components for down-conversion. Especially, for RF/IF-MIMO the number of those components is significantly high, because in every inphase and quadrature path of each antenna a mixer and a phase shifter is needed (cf. Fig. 2(a)).

The RF combiner is the most power consuming component, but fortunately it is only needed once in the RF-MIMO concept. However, this component burdens the concept with large base load regarding power consumption. The high power consumption of the RF-combiner arises from its high frequency operation that is not favorable for passive combiner structures. Moreover, the synthesizer and the ADC are significantly contributing to the power consumption and MIMO concepts using a large number of these components will suffer from large power consumption. Because in BB-MIMO parallel operating SISO receivers are used, as many ADCs and synthesizers as antennas are required. For RF/IF-MIMO it is assumed that one synthesizer drives all down-conversion paths. Nonetheless, more synthesizers might be needed to ensure enough driving capability. But, the components needed for RF/IF-MIMO like the phase shifter or the quadrupler have also significant power consumption leading to large power consumptions for this approach.

Fig. 3 shows the characteristics of each concept with respect to power consumption and system size. For comparison, the performance characteristics of a SISO radio is shown as a reference system. Full BB-MIMO transceivers result in the largest system with highest power consumption whereas RF/IF-radios obtain similar power consumption at half silicon areas. The comparable power consumption arises from the large component count, e.g., quadrupler in the LO, mixer, and phase shifter, that is needed in each inphase and quadrature path for every antenna. Nonetheless, the power consumption can be considered to be higher than BB-MIMO because it was assumed that a single synthesizer drives all down-conversion mixers. In practice, such a synthesizer would demand high currents. Thus, RF/IF-MIMO offers only an advantage of smaller systems. Because the overall wireless radio size might be determined by the antenna array and RF/IF-MIMO shows degenerated flexibility and performance compared to BB-MIMO, this concept provides no significant benefit over full BB-MIMO.

RF-MIMO transceivers achieve lowest system size and power consumption compared to the other concepts. Both quantities are halved with respect to full BB-MIMO radios. In comparison to a SISO system, the increased system size is not much of a difference, but the gain in performance of a four antennas RF-MIMO radio is significant. Simulations results show an increase by 6 bps/Hz in the outage capacity for RF-MIMO compared to SISO systems in the case of single carrier transmission [7]. However, most of the power and area is consumed by the RF combiner and the ADCs. An optimization of these components will lead to less power consumption and less system size. Consequently, RF-MIMO radios offer an attractive solution for wireless MIMO radios in handheld devices.

4. Conclusions

MIMO communication improves the spectral efficiency of wireless radios but also provides drawbacks such as high power consumption or large system sizes. These limitations make the approach less attractive for mobile devices. Nonetheless, MIMO with adaptive weighting in the analogue RF front-end is able to achieve improved

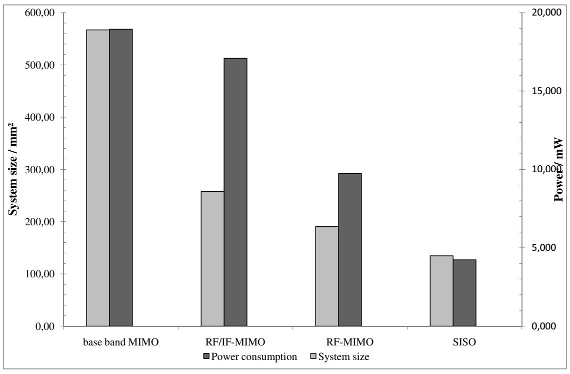


Figure 3: Power consumption and system size for the different MIMO concepts

performances like base band MIMO systems and to reduce power consumption and system size simultaneously that makes this concept attractive for handhelds. Currently a transceiver with weighting in the RF front-end is developed in 0.25 μm SiGe BiCMOS for supporting RF-MIMO in 802.11a networks.

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