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IEEE 802.11N MIMO-PROTOTYPING WITH DIRTY RF USING THE HARDWARE-IN-THE-LOOP APPROACH

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ABSTRACT

Modern wireless systems employ highly integrated hardware. Especially for the processing at radio frequencies, this high integration causes many undesired effects of signal distortion and degradation that must be simulated comprehensively before finalizing the system design. However, often the model accuracy is not sufficient to obtain sound results of the simulations; and in the case of sufficiently accurate models the simulation times get immense. A way out is to use real radio frequency hardware and digital physical layer simulations together in a hardware-in-the-loop system. Short simulation times and real-world radio characteristics are the unbeatable advantage of the hardware-in-the-loop approach.

1. MOTIVATION

The physical layer (PHY) design of wireless systems has to cope with the complex interaction between analog radio frequency hardware that operates at carrier frequencies of some GHz and the digital baseband hardware which performs complex algorithms like Viterbi-decoding, filtering, and the FFT. The demand for flexibility has initiated a convergence of several wireless standards in very small portable devices. Furthermore, to keep pace with the fast changes at the market there is an ongoing evolution of the wireless standards. This means that new releases of wireless standards will become products much faster in the future than today. Therefore the wireless systems design flow can be expected to change dramatically in the near future. In this respect the evolution of the wireless local area networks (WLAN) standard is a good example. Currently, the 802.11 family includes five different PHY specifications. As soon as one PHY specification was ready the demand for new functionality was already there.

Such a fast evolution requires a proof of concept in every stage of the design flow to avoid costly re-designs. Efficient wireless system prototyping becomes more and more important and can be expected to become vital to enable a fast time-to-market of future flexible solutions for different wireless devices.

2. WIRELESS SYSTEM PROTOTYPING

The conventional wireless system design flow follows a straight roadmap in many cases consisting of the following stages:

- system concept design
- simulation
- hardware specification
- implementation
- verification and test

To cope with the risks of the complex design many companies rely on prototyping activities. However, these prototyping activies have been more like a plaster on the “open wounds” of this design flow rather than they have been an integrated part of the design flow. Moreover, building prototypes is a generally time consuming and costly task that does not belong to the core business of the companies. The increasing complexity, flexibility, and market dynamics require new concepts of prototyping [1] that enable a proof-of-concept at different stages of the wireless system design.

Hardware-in-the-Loop (HIL) simulation is a technique that is becoming more and more popular in the development and test of complex real-time embedded systems. But it is not yet widely employed in the field of wireless systems due to the lack of supporting hardware. HIL takes the most critical functionality out of the simulation into the real world and couples it with the simulation of the remaining functionality of the system. In wireless system design it is the radio channel that is the “great unknown”. Hence, wireless HIL simulation means exchanging the channel model by a real radio channel [2]. This real radio channel comprises real radio hardware and thus may comprise real hardware issues such as phase noise, frequency offset, I/Q imbalances, and clock jitter.

As soon as the wireless HIL simulation is running, more and more parts of the remaining system functionality can be moved from the simulation environment to the prototype. A software radio based prototyping system as a basis for the HIL simulation will allow for such an approach. In the end of this process a real-time prototype is running.

A wirless system design flow that comprises a systematic prototyping would be:

- wireless system simulation
- HIL simulation
- real-time wireless prototyping
- wireles product development

Measurement campains, field trials, and tests can be conducted thoughout the development. This ensures that design faults can be discovered in an early phase of the product development.

3. APPLICATION EXAMPLE: IEEE 802.11N

3.1 Introduction to the Standard IEEE 802.11n

In January 2004 the IEEE formed a new Task Group (TGn) to develop an amendment to the 802.11 standard. The raw data throughput over the PHY was defined to reach approximately 600 Mbit/s using a radio bandwidth of 40MHz. It was also projected that 802.11n should offer a better operating distance than existing networks. There was a lenghty phase in which two system proposals blocked each other. Beside some different ideas (coding, higher order modulations, space-time-coding) there has been an overwhelming agreement that the intended high throughput can only be achieved by using MIMO techniques, i.e. multiple antennas at the transmitter (Tx) as well as at the receiver (Rx). The new standard builds upon the previous 802.11a standard by adding MIMO and an extension of the radio bandwidth to 40MHz (see Fig. 1). MIMO uses multiple Tx and Rx antennas to allow for increased data throughput through spatial multiplexing and for increased range by exploiting the spatial diversity as well as through space-time coding schemes like Alamouti coding.

In 2005 the Enhanced Wireless Consortium (EWC) was formed to help accelerate the IEEE 802.11n development process and

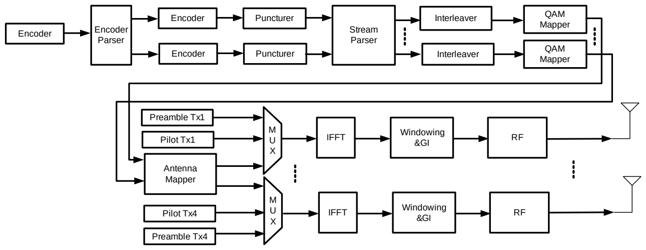


Fig. 1: Schematic of the transmit PHY of the IEEE 802.11n standard

promote a technology specification for interoperability of next-generation wireless local area networking (WLAN) products. The final standard is expected to be completed in 2006.

3.2 An IEEE 802.11n Prototyping Approach

Theoretical work on MIMO-OFDM techniques and MATLAB simulations were the first step of the development of an IEEE 802.11n prototype. The resulting bit error rate simulations as well as some capacity simulations provided a theoretical performance analysis. This initial research was followed by a complete implementation of the TGNSync proposal [3] as an executable specification in Simulink. This software model of the specification served as a reference for all of the following steps. Moreover, it was used to do first real-world trials and measurements by applying the HIL technique.

The employed HIL hardware consists of small stand-alone boxes for the Tx and the Rx that are connected to the simulation PC via USB. The setup (Fig. 2) allows the designer to transmit simulated signals over a real air-interface, to receive them, and to send them back to the MATLAB/Simulink simulation environment. The only limitations of this approach are:

- the physical layer signal processing is not done in realtime (since it is done in the simulation environment)
- the transmission is only unidirectional

However, the designer faces all problems of a real world radio channel such as channel estimation errors, RF-impairments, and the real world radio channel characteristics (e.g., fading).

Features:

- Transmission in license-free ISM bands @ 2.4 and 5.8 GHz
- bandwidth up to 60MHz
- signal sampling with up to 80 MHz
- 2 transmission/reception channels per system
- Multi antenna functionality
- Matlab®/Simulink® interface functions
- GUI for simulation and full hardware control
- Plug & Play interconnection to PC via USB 2.0

Fig. 2: Setup of Signalion's HIL system "HaLo"

The hardware of the HIL system simply replaces the channel model within the simulation. Signal bursts are periodically transmitted. Measurements of the received signals can be done on user request or automatically within a defined interval. The field tests were conducted for a system with 2 transmit and 2 receive antennas which allowed to test a subset of the TGNSync proposal.

An "easy to use" graphical user interface (GUI) enables seamless integration of the hardware into the simulation environment. A full integration into the MATLAB/Simulink simulation environment is supported by an API (application programming interface).

Fig. 3 shows the graphical user interface of the HaLo system. The panel on the right is for configuring the hardware. Beside the transmitted signals (2 subplots on the left) the GUI shows the received signals from the two antennas (upper middle subplot), the channel estimates for the four propagation paths $[h_{11}(f), h_{12}(f), h_{21}(f), h_{22}(f)]$ over frequency, and the scatter diagram of the 64-QAM signal after MIMO-equalization (the different colors represent the two layers of the MIMO transmission). The overall transmitted data rate was 108Mbit/s which is achieved by sending independent spatial streams from the two transmit antennas (spatial multiplexing).

After the real-world verification using the HIL approach the complete physical layer was transferred step by step onto the prototyping hardware. By means of a hardware extension a flexible software defined radio implementation of a complete single antenna mode of the 11n proposal was possible (Section 4.1). This system includes the full OFDM-PHY and the full 802.11-MAC-functionality. The developer can modify any of the system features that are implemented in software. The advanced hardware setup allows flexible tests of new approaches such as PHY-enhancements or MAC-modifications for future wireless systems. The combination of HIL and SDR based implementation principles is the basis for early phase prototypes that need do be adapted along with the evolution of the standard as it is the case not only within the 802.11n standardization.

3.3 The Particular Benefit of Prototyping

The MIMO capacity gain depends on the channel characteristics. However, the quality of the signal processing is as much important. Impairments of the analog signal processing in particular can destroy the MIMO capacity gain completely. Impairments such as phase noise and I/Q imbalances (also named "dirty RF" [4]) as well as issues of phase and frequency synchronicity can be observed by using real radio frequency hardware as it is used in the HIL system HaLo.

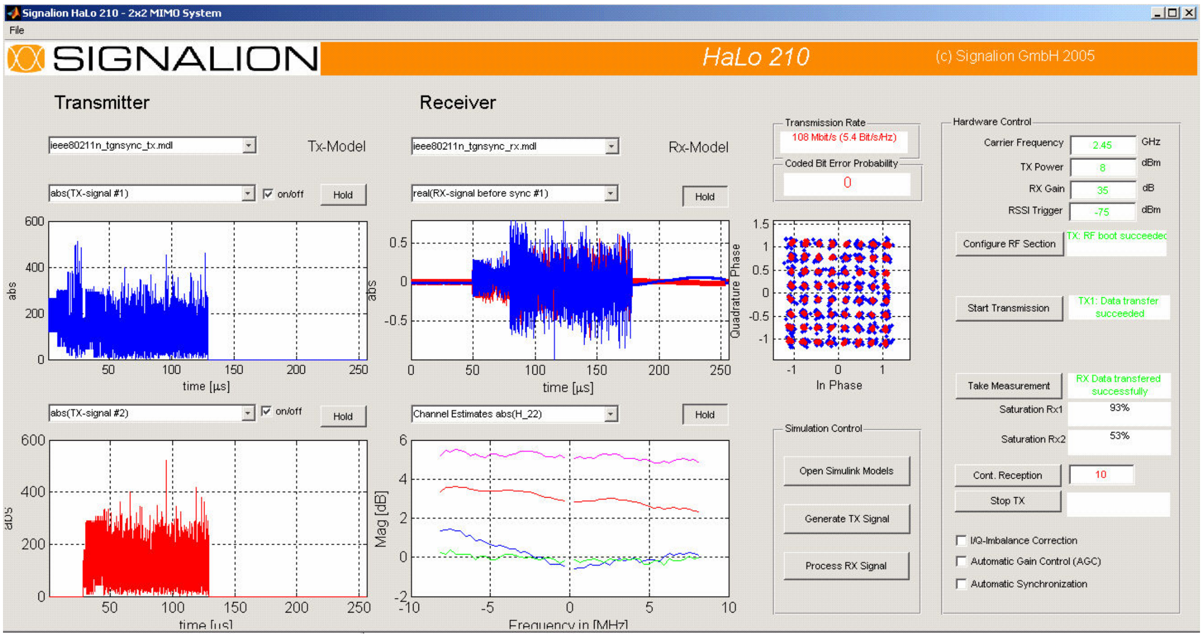
3.3.1 Phase Noise

Orthogonal frequency division multiplexing (OFDM) has been adopted as modulation technique for the WLAN standards 802.11a/g/n for its ability to provide high transmission data rates with high spectral efficiency, its robustness against frequency selective fading (typical for multi-path radio channels), and the low channel equalizer complexity required. The price paid for these advantages is (amongst others) increased sensitivity to carrier frequency offset (i.e. frequency synchronization errors) and phase noise [5].

Phase noise is an unavoidable impairment of the analog local oscillators (LO) used to up-convert the transmit signal to a radio frequency (RF) in the Tx and to down-convert the received RF signal to baseband or an intermediate frequency in the Rx. It is caused by electronic component noise (e.g., thermal noise) within the LOs which leads to a parasitic phase modulation of the theoretically ideal LO signals with time-varying (non-stationary) random phase noise processes [6, 7]

The effect of this parasitic phase modulation is a broadening of the ideally Dirac-shaped LO output spectra – free running oscillators show the typical Lorentzian-shaped output spectra [6] while PLL oscillators have output spectra that can be described as a weighted superposition of different Lorentzian spectra [7]. Multiplying an ideal OFDM transmit signal with non-ideal oscillator signals in the Tx and/or in the Rx, i.e. convolving the ideal OFDM line spectrum with the non-ideal LO output spectra, destroys the orthogonality between the OFDM sub-carriers, leading to significant performance degradation.

A detailed analysis of the effects of phase noise on the OFDM system performance and proposals for suitable compensation algo-


Signalion HaLo 210 - 2x2 MIMO System

Tx-Model: ieee80211n_tgnsync_tx.mdl

Rx-Model: ieee80211n_tgnsync_rx.mdl

abs(TX-signal #1) ☑ on/off

real(RX-signal before sync #1)

abs(TX-signal #2) ☑ on/off

Channel Estimates abs(H_22)

Transmission Rate: 108 Mbit/s (5.4 Bit/s/Hz)

Coded Bit Error Probability: 0

Carrier Frequency: 2.45 GHz

TX Power: 8 dBm

RX Gain: 35 dB

RSSI Trigger: -75 dBm

TX: RF boot succeedec

TX1: Data transfer succeeded

RX Data transfered successfully

Saturation Rx1: 93%

Saturation Rx2: 53%

Cont. Reception: 10

☐ I/Q-Imbalance Correction

☐ Automatic Gain Control (AGC)

☐ Automatic Synchronization

Fig. 3: HaLo measurement results represented in the graphical user interface

rithms have been published by several authors (see e.g. [4, 5, 8]). In principal, two different effects can be distinguished: the rotation of all demodulated sub-carriers of an OFDM symbol by a common angle, known as common phase error (CPE), and inter-carrier interference (ICI) between the OFDM sub-carriers. That is true also for MIMO-OFDM systems, even if the analytical description is much more complicated than in single antenna (SISO) systems and even if there exist additional dependencies (e.g. the influence of the number of transmit and receive antennas) [9].

Compensating the CPE by simply de-rotating all OFDM subcarriers using symbol-to-symbol CPE estimates leads to considerable performance improvements in many practical cases. In 802.11a/g/n based OFDM systems reduced complexity pilot-based CPE estimation methods are applicable [8, 10]. For very high data rate transmissions using MIMO and a higher order sub-carrier modulation up to 256-QAM as proposed in the 802.11n standard proposal [3] also phase noise induced ICI and its compensation are an issue, especially if low-quality low-cost local oscillators are used in the analog Tx/Rx front ends. ICI compensation algorithms are quite more sophisticated than the CPE compensation, since the instantaneous realizations of all significant phase noise processes (or at least some significant parameters of these processes – not only their symbol-wise time average as required for CPE correction) have to be estimated [4, 11].

For complexity reasons, the validation of MIMO-OFDM phase noise compensation algorithms by means of pure BER system simulations is feasible with simplified system models and under certain simplifying assumptions only. This becomes clear considering that the RF impairments (e.g. the time-varying random phase noise processes) of all Tx and Rx front ends, the time-varying frequency selective multi-path channels between all Tx and Rx antennas, as well as the whole digital MIMO-OFDM PHY (including synchronization) have to be simulated for a realistic system model. Hence, HIL simulations are essential for an efficient and sound validation of phase noise compensation algorithms for MIMO-OFDM.

Signalion's HIL simulation system HaLo (see Sec. 4.1) efficiently supports a step-wise development and validation of phase noise compensation algorithms for MIMO-OFDM. Starting with a cable link between one Tx and one Rx antenna allows to validate SISO algorithms in the presence of real-world RF impairments but without the effects of the multi-path radio channel. As a second step the wireless radio link can be activated by removing the cable between Tx and Rx antenna. After activating additional Tx and Rx links (including analog front ends, AD/DA interfaces, and necessary digital signal processing), a full real-world wireless MIMO-OFDM PHY is provided for algorithm validation. Since the HaLo system easily allows to switch between two different local PLL oscillators (for carrier frequencies between 2.4-2.5 GHz or 5.1-5.8 GHz) in the analog front ends, which have significantly different phase noise characteristics, and since the system further provides the possibility to adjust the PLL charge pump currents (i.e. change the filter characteristics of the PLL oscillator loop filters), a variety of phase noise scenarios can be generated and analyzed.

3.3.2 *I/Q Imbalance*

Transceiver architectures based on I/Q signal processing are of great value for reconfigurable and low-cost radio applications. Since no fixed analog image rejection filter is needed, such architectures allow cheap and highly flexible analog front-ends. In theory, an infinite image rejection is provided, if the complex analog oscillator has equal amplitudes and a phase difference of exactly 90° in the I- and the Q-branch of the signal processing path. However, a perfect match between the I- and the Q-branch is not feasible in a hardware implementation due to the limited accuracy of the analog components. These unavoidable mismatches, known as I/Q imbalance, significantly degrade the image rejection capability of any I/Q signal processing architecture.

The actual impact of the I/Q imbalance on the transmitted signal depends on several conditions, such as the chosen I/Q architecture (low-IF or zero-IF) and whether the I/Q imbalance in the Tx or in the Rx is considered. Generally speaking, a zero-IF upconversion (Tx) or downconversion (Rx) mainly causes self-interference within the frequency band of interest [12]. In contrast, the low-IF approach leads to interference between the desired and adjacent frequency bands, causing out-of-band emissions at the Tx [13] and interference by the so-called image signal at the Rx [14].

Fig. 4 exemplarily shows the impact of a zero-IF upconversion with I/Q imbalance on the transmitted OFDM signal. For visualization purposes, only a subset of the positive OFDM sub-carriers were used for the transmission. The presence of signal power at negative frequencies is a result of the insufficient image rejection due to the I/Q imbalance. In OFDM systems like IEEE 802.11a, this effect

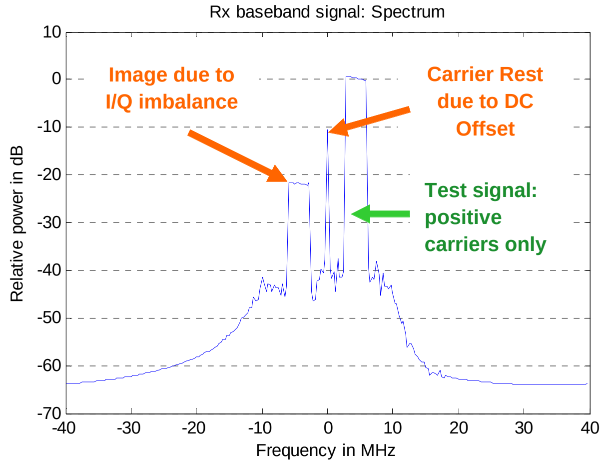


Fig. 4: I/Q imbalance and DC offset measured with HaLo 210 with a zero-IF setup at the Tx

leads to serious interferences between pairs of sub-carriers symmetric to the DC carrier [12]. MIMO applications like 802.11n impose an aggravation of the problem.

With the advent of increasing compute power available at the transceivers, the concept of a digital compensation of ”Dirty RF” has become feasible. Numerous approaches have been published in the past years. Most of them follow the concept of digital *pre*-distortion at the Tx [13] and digital *post*-correction at the Rx [12, 14]. The challenge of designing applicable digital compensation techniques is to ensure a robust I/Q imbalance compensation without adding too much complexity to the transceiver.

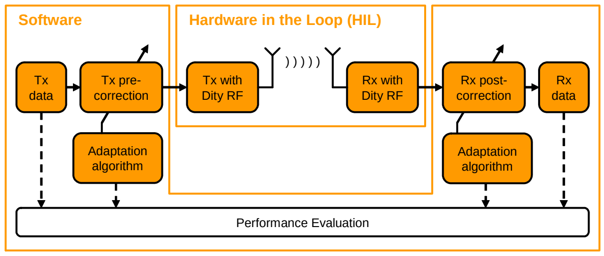


Fig. 5: Evaluation of digital I/Q imbalance compensation algorithms using the HIL approach

Signalion’s HaLo system offers a solid basis for evaluating different compensation algorithms under real-world conditions. A typical test setup is shown in Fig. 5. Both the Tx and the Rx can be run in low-IF or zero-IF mode, allowing most of today’s compensation methods to be evaluated and tuned. The possibility of selecting a low-IF as well as a zero-IF mode allows a separation of the I/Q imbalances of the Tx and the Rx. Thus, the compensation and predistortion algorithms can be designed and optimized step by step.

3.3.3 Synchronicity between the Antennas

Another issue is the synchronicity between the different MIMO antennas. Basically, there are two approaches: one common local LO for all MIMO branches or one individual LO for each of the MIMO branches. The first is required for phased arrays. But is it also required for space-time coding or spatial multiplexing? A big semiconductor manufacturer has claimed in its press release regarding a pre-802.11n RF-transceiver that all transceivers must run synchronously on a common LO. However, distributing the LO on the circuit board and feeding it into the circuits is a very critical issue. Therefore a solution with separate LOs (separate PLLs running on a common master clock) is much simpler and cheaper.

A HIL simulation with HaLo shows that two independent channels can be transmitted in a spatial multiplex manner using 64-QAM (see Fig. 3) even with the employed low-cost transceiver using separate PLLs. A comparison of both approaches will be possible with the next generation of HaLo which will provide a means to run all MIMO branches independently (frequency synchronously) or phase synchronously.

4. PROTOTYPING RESULTS

4.1 The Underlying Prototyping Hardware

The above presented prototyping approach starting with HIL and evolving step-by-step into a real-time prototype requires a scalable hardware platform. Signalion’s hardware platform consists of several components that can be connected in different ways to build HIL prototypes as well as real-time prototypes with much digital processing power. Also the number of antennas is scalable to support different requirements on MIMO prototyping.

Signalion’s HIL system HaLo has been used to obtain the results on IEEE 802.11n prototyping that are presented in this section. A block diagram of a HaLo station is shown in Fig. 6. Each HaLo station comprises one RF-card SRFC and one digital processing card SDCxC [15].

The SRFC is equipped with the WLAN transceiver IC PMB8680 by Infineon in order to provide a hardware platform as realistic as possible for WLAN prototyping. Two antennas are supported by one SRFC. A combination of several SRFC is the basis to support more than two antennas. The RF-bandwidth is adjustable; the Rx as well as the Tx can be operated in zero-IF and in low-IF modes. This feature is particularly useful for the investigation of the impacts of I/Q imbalances on the system performance. The transmission is performed in the license-free ISM bands at 2.4GHz or 5.1-5.8GHz with a maximum bandwidth of up to 60MHz where the I/Q signal sampling is done with 80MHz.

The SDCxC is used to realize the digital front-end, the AGC, and the synchronization as well as the data buffering that is necessary in HIL systems (for details see [15]).

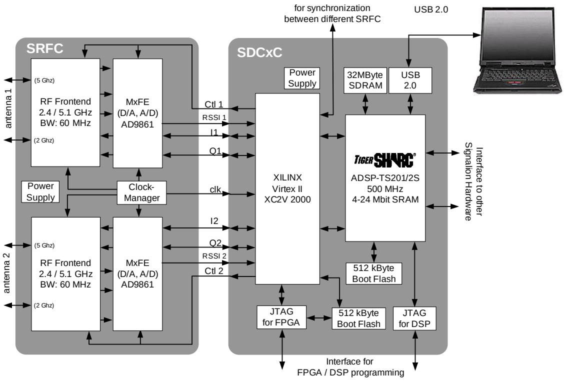


Fig. 6: Block Diagram of a Station of Signalion’s HIL System HaLo

4.2 Experiences from HIL Simulations

The MIMO system performance depends heavily on the channel characteristics. Field trials have been performed using HaLo and a MATLAB/Simulink model of the TGNSync proposal (standard-conform Tx with two spatial data streams). The main results from these field trials are summarized in the following:

MIMO Gain: In general, small roomes with many reflections from the walls enabled a stable MIMO gain. A data rate of 108Mbit/s could be reached with 64-QAM. Large and open rooms (lobbies, exhibition halls) are more critical. Only lower data rates could be achieved, e.g. 48Mbit/s with lower order modulations.

Polarization Diversity: This source of diversity is crucial for a stable performance of 2x2 antenna systems. The best performance was achieved with polarization diversity at the Tx and the Rx.

Dirty RF: MIMO-performance heavily depends on the SNR available at the Rx. Even a small degradation with respect to different dirty-RF effects (e.g., I/Q imbalances) harms a MIMO-system much more than it harms a single antenna system.

Acquisition and Synchronization: Since the transmit power is split between multiple antennas the synchronization is more critical for MIMO-systems. Simple syncronization algorithms that use only one receive signal (e.g., for complexity reasons) do not perform sufficiently well.

Burst Length: MIMO-techniques are only reasonable for long frame lengths. Otherwise the additional training overhead along with legacy training symbols for backwards compatibility lowers the effective throughput considerably.

One last example should illustrate the importance of HIL verification. An option that was discussed within the standardization was the introduction of Space-Time-Block-Codes (STBC) to the MIMO-OFDM system. Such an option provides additional spatial diversity and therfore enhances the performance and the coverage of WLAN-systems. In general there are two possibilities to introduce STBC to OFDM systems:

1. **Space-Time-Coding (STC):** This option uses two adjacent OFDM-symbols to spatially encode the signal. The most convinient way is to use the *Alamouti* scheme which allows a linear decoding at the Rx [16]. The drawback of this implementation is that the Rx needs to store two OFDM-symbols before the Space-Time-Decoding can be done which introduces some additional latency. Furthermore each frame must consist of an even number of OFDM-sysmbols which lowers the flexibility of the system.
2. **Space-Frequency-Coding (SFC):** This second option uses Alamouti-STBC over two adjacent subcarriers [17]. In this case two adjacent subcarriers are used for the coding. This approach avoids the drawbacks of the OFDM-Space-Time-Coding.

In theory both approaches have the same performance as long as it is ensured, that the channel coefficients stay constant over two consecutive OFDM-symbols (for option 1).

However, for SFC (option 2) the channel coefficients must be constant over two adjacent subcarriers. This seems to be a reasonable assumption that is valid in many scenarios. The channel estimation plot in Fig. 3 shows that it holds at least for the magnitude of the channel coefficients. However, there is one important reason, why this fundamental requirement cannot be observed in many real-world systems. Note that because of the cyclic prefix the temporal synchronization of OFDM systems is not necessarily as accurate as for other modulation schemes. Small differences in the estimated time of arrival (TOA) do not harm the system. In practical systems an additional temporal shift of a few samples compared to the estimated TOA is often used to avoid intersymbol interference (ISI) due to imprecise TOA estimates. However, this temporal shift introduces a phase shift in the frequency domain which greatly harms the SFC because the channel is not constant over two adjacent subcarriers anymore. The result is an inferior performance of SFC compared to STC. This might be one reason why STC was chosen in the standardization [3, 18] instead of SFC.

Such an effect can easily be verified with HIL simulations, but is overseen often in pure BER software simulations where synchronization is assumed to be perfect. The performance of the synchronization is analyzed in separte simulations to avoid long simulation runs. However, a HIL simulation allows to take all these effects into consideration. This clearly shows how usful HIL simulations are.

5. SUMMARY AND OUTLOOK

The system design of modern MIMO systems such as IEEE 802.11n imposes several challenges on the design flow. One of these challenges is the sufficiently accurate simulation of RF-impairments (dirty RF) as part of a complete system in a short time. Dirty RF issues in particular can be perfectly simulated and verified in a complete system by using the hardware-in-the-loop approach.

The hardware-in-the loop approach has been shown to be a very efficient step in the design flow of modern wireless systems. It helps to avoid costly design faults and re-designs. Several examples regarding dirty RF, MIMO, and other issues have proven its efficiency.

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