

A Flexible Hardware-In-the-Loop Test Platform for Physical Resource Sharing Mechanisms in Wireless Networks

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Abstract: Currently, a lot of research is being done to develop physical resource sharing mechanisms in wireless networks. These mechanisms are expected to enhance spectral efficiency, coverage, user satisfaction and operator revenue. In order to prove the feasibility of these mechanisms or to identify practical problems for mechanism optimization, a Hardware-in-The-Loop (HIL) test platform has been developed. This platform consists of multiple broadband wireless experimental devices and can be flexibly configured, allowing extensive signal transmission experiments. Furthermore, different transmission modes of the Radio-Frequency (RF) signals are available, allowing a variety of mechanism evaluation possibilities. Based on this platform, physical resource sharing mechanisms can be efficiently implemented and tested. First test results are shown in this paper.

Keywords: Resource sharing, Hardware-In-the-Loop (HIL), testbed, demonstrator platform, verification of algorithm, proof of concept

1. Introduction

As forecasted by the Wireless World Research Forum (WWRF) in 2008, future wireless communication systems are expected to provide high data rate and high quality services for a huge number of users [1]. However, most of the current wireless communication systems deploy exclusive spectrum and infrastructure allocation among operators, which is inefficient in terms of cost, spectrum utilization and energy consumption. To meet the aforementioned requirements, a lot of research has been dedicated to voluntary physical resource sharing in wireless networks. Within the European project SAPHYRE (Sharing Physical Resources - Mechanisms and Implementations for Wireless Networks), effective spectrum and infrastructure sharing mechanisms are being developed which are expected to enhance spectral efficiency, coverage, user satisfaction and operator revenue ([1-3] etc.).

As stated in [4, 5] etc., mechanisms that are designed under idealized assumptions may not work in real wireless systems, probably due to the influence of non-ideal system conditions e.g. RF impairments [6] and real wave propagation environment. An efficient and effective way to solve this problem is the Hardware-in-The-Loop (HIL) test, which can involve most of the practical system conditions. With HIL tests, practical problems and constraints can be identified in the design stage of resource sharing mechanisms,

so that they can be optimized. Furthermore, a mechanism that performs well in HIL test can be declared as feasible. In other words, HIL test provides proof-of-concept.

Several HIL test platforms have been reported in the literature ([4, 5, 7] etc). In this paper, a new HIL test platform is proposed, which is partly developed within the SAPHYRE project. This platform consists of multiple devices of a broadband wireless experimental system (with up to 250 MHz bandwidth of the communication signal) and supports HIL test of physical resource sharing scenarios with multiple independent links as well as multiple operators. Moreover, this platform is very flexible in configuration and provides extensive signal transmission and mechanism evaluation possibilities. Compared to [5, 7], this platform allows the implementation and debugging of the complete protocol stack including both Physical (PHY) layer signal processing algorithms and Medium-Access-Control (MAC) layer mechanisms. Compared to [4], higher bandwidth and more flexible network configuration are supported. Based on this platform, physical resource sharing mechanisms can be efficiently implemented and tested. The first HIL test results will be shown in this paper.

This paper is organized as follows: Section 2. describes the structure and functionalities of the HIL test platform. Section 3. describes the implementation manner of resource sharing scenarios. Section 4. provides two examples of scenario implementation and test. Section 5. concludes this paper.

2. The Hardware-In-the-Loop (HIL) Test Platform

2.1 Structure of the Platform

Fig. 1(a) shows the setup of the HIL test platform, which consists of multiple wireless experimental devices¹. Each device is equipped with two transmit (Tx) and two receive (Rx) antennas. All devices are connected together by a reference clock distribution cable, a trigger distribution, cable and Ethernet for coordinated action (see Sec. 2.3). Fig. 1(b) shows the structure of each single device, which is hosted in a high performance Personal Computer (PC) and consists of digital components, analog baseband (BB) components and RF components. The digital platform is a commercial ProcStarII FPGA board (Gidel Ltd.), where high performance FPGA devices (ALTERA Stratix II) and large sample-memories (64 MB DDR II) are located². This FPGA board exchanges configuration-, control- and transmission data with software applications (e.g. MatLab) in the host PC via PCI-X bus. A high speed signal converter board has been developed to connect the analog BB- and RF-parts with the digital platform. This converter board contains two 250 MHz 16bit IQ-DACs (Digital-to-Analog-Converter) and two 500 MHz 8bit IQ-ADCs (Analog-to-Digital-Converter) as well as power supply devices and control logic. The analog BB- and RF-components are designed as small form-factor modules that can be plugged onto the converter board. Thus, they are interchangeable to adapt the device to different RF architectures and RF frequencies. Currently, frontend components for both 1.975 ~ 2.525 GHz band and 60 GHz band are available.

¹These devices have been developed and fabricated at Fraunhofer Institute for Telecommunication (Heinrich-Hertz-Institute). Currently, three such devices are available for the SAPHYRE project. However, the working principle applies to a larger number of devices.

²For the HIL test purpose, the FPGA devices are mainly used to implement the board-controlling functionalities like sample-memory management, transmission trigger management etc.

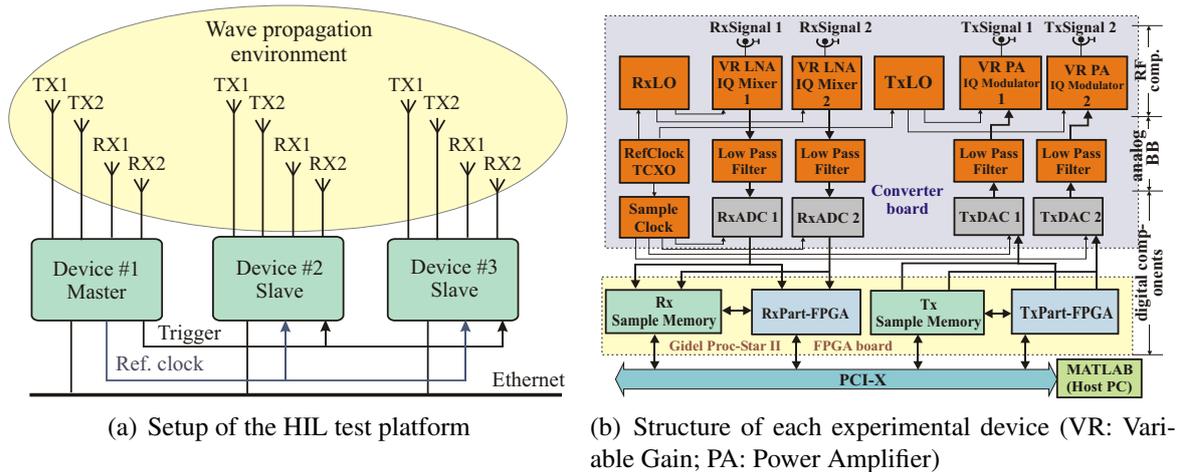


Figure 1: Setup and structure of the HIL test platform

2.2 The HIL Working Principle

First, multiple digital signal vectors (complex valued) are generated with the algorithms implemented in MatLab (see Sec. 3.1). Each of these vectors contains signal samples to be transmitted via a dedicated Tx antenna of the platform. Afterwards, each signal vector is uploaded into the Tx sample-memory of the corresponding experimental device. A global trigger signal will start the signal transmission of all the devices simultaneously, i.e. the signal samples in each Tx sample-memory are fed to the corresponding DAC and eventually transmitted through the Tx antenna to the wave propagation environment. Meanwhile, each device writes the received signal samples (from the ADC) to the Rx sample-memory. These samples are downloaded in MatLab workspace for further processing and evaluation. The burst-length of each signal transmission can be easily configured by software.

2.3 Coordination of Multiple Devices

The coordinated action of multiple experimental devices is enabled both by a synchronous global triggering mechanism and a centralized device control concept.

2.3.1 Synchronous Global Triggering

As mentioned in Sec. 2.2, the signal burst transmission of all experimental devices are started by a global trigger signal. As shown in Fig. 1(a), this trigger signal is distributed over a trigger-cable. Among all experimental devices, one of them acts as the master device, while the other act as slave devices. Within the master device, an internal trigger signal is activated by software and starts the burst transmission of this device. Meanwhile, this trigger signal is delivered (via cable) to the slave devices to start burst transmission. In order to test MIMO precoding techniques e.g. Beam-Forming (BF), a coherent transmission environment is required. Since all devices use the same reference clock (due to reference clock distribution shown in Fig. 1(b)), coherent phase of all sample clocks, Tx LO clocks and Rx LO clocks is achieved. However, jitter effect (time variation) of the trigger time exists, which could result in inconsistency of the device behavior. This problem is solved by a realtime Trigger-Synchronization-Unit (TSU), which is implemented in FPGA. The TSU aligns the trigger time of all devices

to a pre-defined time raster, whose period can be easily configured by software. With sufficiently large time raster, the trigger time jitter is compensated.

2.3.2 Centralized System Control

Efficient implementation and evaluation of PHY- and MAC layer algorithms on the HIL platform can be enabled by centralized system control, which includes distribution of Tx signal vectors, collection of the Rx signal vectors and adjustment of all device parameters (e.g. Tx/Rx attenuation value, carrier frequency). For this purpose, a common storage is established for all the devices (e.g. via Ethernet). Moreover, a controller software application (e.g. realized in MatLab) is used as the central coordinator, which also has access on the common storage. Before each burst-transmission, data files containing all transmit signal vectors and command files for parameter adjustment are generated by the controller software and placed in the common storage. In each file name, both the file type and the identity of the dedicated device is encoded. All devices always check the common storage. Once a file is detected by the dedicated device, it is loaded by this device and then deleted. After loading such files, all slave devices write an acknowledgment (ACK) file to the common storage, while the master device collects such ACK files of all the slave devices. Once all ACK files are collected, the master activates the global trigger signal, causing all the devices to transmit and receive signals. Afterwards, all devices generate files that contain the received signal vectors as well as some recorded device parameters. Finally, these files are placed on the common storage and collected by the controller software for further processing. With such a centralized system control concept, the PHY- and MAC layer algorithms can be implemented centrally and efficiently on top of the controller software.

2.4 RF Signal Transmission Modes

Three RF signal transmission modes are available: **1). RF cable mode:** The RF signals propagate through an RF cable network which connects modulators (MOD) and demodulators (DMOD). In this mode, the multi-path fading channel effect is superinduced by algorithms implemented in MatLab. **2). Channel emulator mode:** The RF signals are fed into an Elektrobit F8 channel emulator ³, which can recreate wireless channel propagation effects in a broad frequency range. The emulated wireless channels can be generated from standard channel models or measured channel realizations. Moreover, MIMO configurations of upto 4×4 are supported. **3). 60 GHz mode:** Signals are modulated to the 60 GHz band and propagate in free space.

Since the first two modes utilize isolated wave propagation environments, uncontrollable RF interference is avoided. Thus, the 2.4 GHz ISM band, which is usually severely disturbed by existing WLAN applications, can be used for these two modes. Moreover, since the wave propagation environment is under control, all the test results are reproducible. Thus, these two modes are suitable for analysis and evaluation of resource sharing mechanisms, whereas the second mode provides more configuration and channel emulation possibilities. Since there is so far no severe uncontrollable interference in the 60 GHz ISM band, the third mode is suitable for live demonstration, where real radio channel effects can be shown. Note that in all three modes, full RF functionality is utilized to investigate RF effects on the resource sharing mechanisms.

³Elektrobit System Test Ltd., Finland, www.elektrobit.com.

3. Scenario Implementation Manner on the HIL Platform

3.1 Layered Implementation Manner

A layered manner is applied to implement resource sharing scenarios on the HIL platform. Such an implementation manner allows efficient debugging and facilitates collaboration between different working groups of different development focuses. Three different layers are defined: scenario layer, signal processing layer and transmission layer. The functionalities of each layer and their interfaces are shown in Fig. 2.

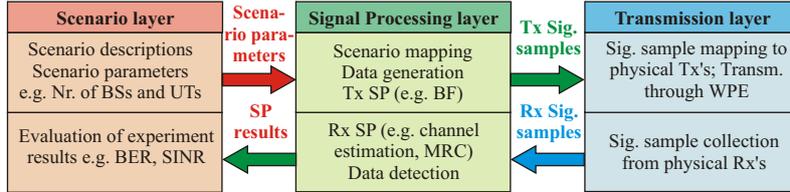


Figure 2: Illustration of the layered implementation manner (Nr.: number; BS: Base Station; UT: User Terminal; SP: Signal Processing; BF: Beam Forming; MRC: Maximum Ratio Combining; Sig.: Signal; WPE: Wave Propagation Environment)

Based on the centralized system control concept in Sec. 2.3.2, all signal processing functionalities can be implemented on top of the central controller software.

3.2 Multi-Stage Transmission Mapping

Even if the scenario under test contains more links than the existing physical links of the platform, HIL test of such a scenario is still possible. Let the Tx/Rx on the HIL platform be called Physical -Tx/-Rx (PTx/PRx), while that in the scenario to be tested is called Virtual -Tx/-Rx (VTx/VRx). The numbers of PTx, PRx, VTx and VRx are indicated as M_T , M_R , N_T and N_R , respectively. Moreover, a burst transmission process on the HIL platform is indicated as a transmission “stage”. When $N_T \leq M_T$ and $N_R \leq M_R$, single-stage mapping between VTx/VRx and PTx/PRx is possible. Otherwise, the mapping requires multiple transmission stages and is called “multi-stage mapping”. Assuming full connectivity of the wireless network in the scenario, $N_T N_R$ signal transmission links are contained. The mapping of these links onto the platform varies for two different PTx-PRx connectivity configurations: **1). Single connectivity:** The PTx’s and the PRx’s are one-to-one connected. Thus, $M_T = M_R$ separate physical links are available. In this case, $\left\lceil \frac{N_T N_R}{M_T} \right\rceil$ transmission stages are required to accomplish the signal transmission of all the virtual links. Within each stage, the Tx signals and the emulated channels should be loaded accordingly. **2). Full connectivity:** Each PTx is connected with each PRx, allowing $M_T M_R$ physical links. Thus, $\left\lceil \frac{N_T N_R}{M_T M_R} \right\rceil$ transmission stages are required. For both configurations, all received signals belonging to the same VRx are superimposed after the multi-stage transmission. Note that since controllable wave propagation environment is required, such multi-stage mapping is only possible in the 1st and 2nd RF transmission modes described in Sec. 2.4. Specifically, multi-stage mapping with the 2nd connectivity configuration is only realizable in the 2nd RF transmission mode. Finally, the multi-stage mapping is implemented on top of the central controller software (Sec. 2.3.2), while PHY- and MAC algorithms are realized on top of the multi-stage mapping.

4. Application Examples of Physical Resource Sharing Mechanisms

To illustrate the application of the HIL platform, two resource sharing scenarios are tested: 1). Spectrum sharing scenario; 2). Relay- and spectrum sharing scenario. For both scenarios, the 1st RF transmission mode in Sec. 2.4 is applied in combination with the multi-stage transmission mapping in the 1st connectivity configuration in Sec. 3.2⁴. Variation of Rx SNR is mainly achieved by adjusting the variable gain Tx- and Rx-amplifiers (see Fig. 2.1).

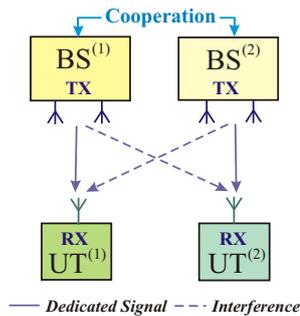


Figure 3: Spectrum sharing scenario

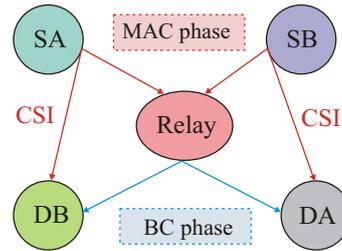


Figure 4: Relay- and Spectrum Sharing Scenario

4.1 Spectrum Sharing Scenario (Scenario A)

As shown in Fig. 3, two BSs of different operators share the same spectrum. While each BS transmits data to the dedicated UT, it also generates interference to the UT of the other operator. Thus, sophisticated signal processing techniques should be applied in the BSs and UTs to suppress the mutual interference and maximize the total throughput. In the HIL test, two such techniques are applied: Eigen-Mode Beam-Forming (EMBF) and Block-Diagonalization (BD) ([3], Sec. 2.2). We assume 2 Tx antennas at each BSs and 1 Rx antenna at each UT. OFDM is applied as the PHY technique. The total number of SubCarriers (SC) is 256, with 56 NULL SCs and Cyclic Prefix of length 32. Rayleigh channels of 24 taps are applied. Maximum-Likelihood (ML) channel estimation [8] is applied to obtain the channel state information for precoding (in Tx) and channel equalization (in Rx). No channel coding is applied. Perfect time synchronization of both operators is assumed⁵. Fig. 5 shows the HIL results in terms of sum rate of the two different techniques. As reference, a case without spectrum sharing is also included. In this case, each operator transmits in half of the available spectrum and does not suffer from interference. Moreover, each operator applies EMBF within its own spectrum. As shown in Fig. 5, the EMBF in the spectrum sharing case has much worse performance than the EMBF in the non-sharing case. The reason is that with spectrum sharing, EMBF can not effectively suppress the interference. In contrast, BD achieves the best performance due to sufficient interference suppression. Thus, the HIL test proves the sharing gain and verifies the effectiveness of BD for resource sharing.

4.2 Relay- and Spectrum Sharing Scenario (Scenario B)

As shown in Fig. 4, this scenario consists of a “butterfly” network topology, where two independent data sources, SA and SB, of different operators should transmit data to the

⁴Since a part of RF components are still under fabrication, the HIL platform is currently not fully equipped.

⁵This is enabled by the synchronous global triggering and centralized system control in Sec. 2.3

destinations DA and DB, respectively, via two-phase relaying transmission. Both relay station and spectrum are shared between operators. In the Multiple Access (MAC⁶) phase, SA and SB transmit data to the relay and to the destinations DB and DA, respectively. Note that there is no direct link between a source and its dedicated destination. The received data of DA and DB in the MAC phase are called Complementary-Side-Information (CSI, [2]). In the BroadCast (BC) phase, the relay transmits data to both destinations. The destinations decode the dedicated data based on the data from the relay and the CSI. Since both relay and spectrum are shared, the data streams of SA and SB will be superimposed at the relay and cause interference to each other. Two techniques are applied for interference suppression and capacity maximization: Hierarchical Decode and Forward (HDF, [2]) and Amplify-and-Forward with Successive Interference Cancellation (AF-SIC, [9]⁷). The HDF technique is developed within SAPHYRE project, while AF-SIC is a conventional technique. OFDM with BPSK modulation and LDPC coding of coderate $\frac{1}{2}$ is applied in PHY-layer. Both the OFDM parameters, the channels and channel estimation are the same as those in scenario A. Moreover, single antenna transmission and global time synchronization are assumed.

Fig. 6 shows the HIL results i.e. the capacity of both techniques as functions of the different SNR values. The capacity difference of both techniques is also shown. Here, we assume that the SNR in the MAC links always equals that in the BC links. As shown, full capacity SNR region of HDF is much larger than that of AF-SIC. Moreover, in the major part of the investigated SNR region (which is realistic), HDF has better performance than AF. Only with very low SNR of CSI and relatively high SNR of the MAC- and BC links, AF-SIC has considerable advantage over HDF. Thus, we can conclude that HDF is more robust than AF for the observed resource sharing scenario.

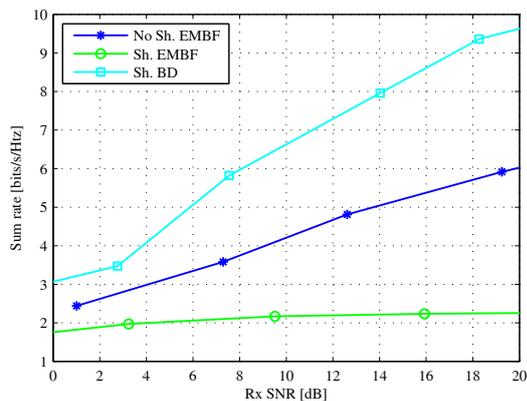


Figure 5: Scenario A: Sum rate as a function of Rx SNR

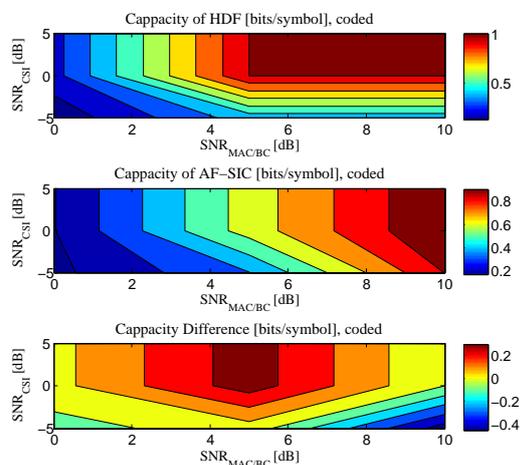


Figure 6: Scenario B: Capacity of HDF and AF as well as the difference between them in different SNR regions

⁶Only within Sec. 4.2, the abbreviation “MAC” is used to indicate “Multiple Access”.

⁷The two way relaying in [9] can be regarded as the special case that SA=DB and SB=DA, which implies perfect CSI. Thus, the 2-step scheme in [9] can be easily extended to “butterfly” network.

5. Conclusions

A HIL platform is proposed for testing physical resource sharing mechanisms in wireless networks. The proposed platform is flexible in configuration and allows different RF transmission modes, which facilitate both mechanism analysis and live demonstration. Moreover, multi-stage mapping allows to test large networks. Based on the platform and the auxiliary operation software, resource sharing mechanisms can be efficiently implemented in a layered manner. HIL test results of two resource sharing scenario have verified the benefit of sharing as well as the advantages of sophisticated sharing techniques developed in the SAPHYRE project.

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