COST Action CA15104
Assessment of 5G radio access techniques through experimental platforms

COST Action CA15104 (IRACON) aims to achieve scientific networking and cooperation in novel design and analysis methods for 5G, and beyond-5G, radio communication networks. In this framework, different experimental facilities are made available by institutions to IRACON participants in order to test new algorithms, techniques and protocols in real-world contexts, enabling a coordinated effort among experts of separate disciplines, as complex test beds need a variety of suitably joint and coordinated competences.

This deliverable describes the experimental facilities available in the consortium for assessing 5G and beyond radio access techniques. New waveforms, cognitive radio approaches, or massive MIMO, are possible examples.

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1. Introduction

IRACON, aims to achieve scientific breakthroughs, by introducing novel design and analysis methods for 5G, and beyond-5G, radio communication networks. IRACON aims at proposing solutions for inclusive and multidimensional communication systems with a wide variety of devices, practical constraints and real-world scenarios, addressing systems ranging from very simple transceivers and sensors, to smartphones and highly flexible cognitive radios. One of the challenges of the project is to perform experimental research on Over-the-Air (OTA) testing, IoT, localisation, tracking and radio access. These topics are addressed within four Experimental WGs (EWGs), focused on specific topics through a transversal approach.

In this framework, different experimental facilities are made available by institutions to IRACON participants in order to test new algorithms, techniques and protocols in real-world contexts, enabling a coordinated effort among experts of separate disciplines, as complex test beds need a variety of suitably joint and coordinated competences.

This deliverable describes the experimental facilities available in the EWG Radio Access.

2. EWG-RA: Radio Access

The goal of this Experimental Working Group (EWG) is to experimentally validate the many techniques that will be implemented at the PHY and MAC layers of the radio access part of 5G, especially those developed within DWG2. New waveforms, cognitive radio approaches, or massive MIMO, are possible examples.

The experimental facilities made available by partners are described below.

2.1 OpenAirInterface

OpenAirInterface[1] is an open source initiative that today provides a 3GPP compliant reference implementation of eNodeB, User Equipment (UE), and evolved packet core (EPC) that runs on general purpose computing platforms together with off-the-shelf software defined radio (SDR) cards like the ETTUS USRP, Lime SDR, and ExpressMIMO2. It allows users to set up a compliant 4G LTE network and inter-operate with commercial equipment.

The objective of OpenAirInterface is to allow experimentation with state-of-the-art cellular radio technology (4G and 5G) while preserving full compatibility with commercial 3rd party equipment. The open-source nature of the code allows experimenters to insert their own code easily. OAI uses their own open-source license, the OAI public license 1.1, which is based on Apache 2.0, but includes a clause that makes it compatible with current 3GPP licensing schemes. The

[1] http://www.openairinterface.org

OAI software alliance has been created to promote this license and to foster collaboration around OAI.

In this section we firstly describe the “classical” or “monolithic” version of OAI and the existing OAI massive MIMO testbed. Secondly we describe the recently introduced and currently being developed functional splits of OAI that will enable C-RAN deployments of OAI. Last but not least we describe the current state and vision of the C-RAN testbed at Eurecom and how we are planning to map our existing work on massive MIMO onto this new testbed.

2.1.1 Massive MIMO and LTE

Massive MIMO can also be smartly and perfectly fit into the current LTE standard. In fact, 3GPP has defined the notion of “Transmission Modes” (TMs) for different usage of MIMO in LTE such as single antenna transmission (TM1) transmit diversity (TM2), open-loop spatial multiplexing (TM3), closed-loop spatial multiplexing (TM4), etc. Different TMs use different antenna ports, which can then be mapped onto one or more physical antennas. TM 7 is defined in Release 8 and uses antenna port 5 to transmit both data and UE-specific pilots to a single user. The beamforming is thus transparent to the user and can be arbitrary. Release 9 extends TM 7 to TM 8, giving the possibility of transmitting two streams to a single user or two users, whereas in release 10, this is further extended to TM 9 where up to 8 layers for a single user transmission and up to 4 layers for multiuser transmission is supported. Release 11 adds TM 10, similar to TM 9 with up to 8 layers transmission but the transmit antennas can be physically located on different base stations. In Release 13, no new transmission mode is defined, but CSI Reference Signal (RS) has been extended to 16 ports. Moreover, the ongoing work item in release 14 on the enhancement of Full-Dimension MIMO (special case of massive MIMO in 3GPP) for LTE has defined the objective of extending the CSI-RS to 32 ports with enhancement on CSI reports and support for providing higher robustness against CSI impairments [7].

OAI currently supports TMs 1,2, and 7, and has experimental versions of TMs 3 and 4. TM 8 and 9 are currently in development. OAI does not (yet) support any CSI reference signals, but it does support sounding reference signal (SRS), which can be used in TDD together with a proper reciprocity calibration mechanism to estimate the CSIT.

The Eurecom massive MIMO testbed is based on TDD and TM 7 driving up to 64 co-located antenna elements. It uses uplink channel estimates based on the SRS and transforms them with the help of the calibration matrix (see next section) to a downlink channel estimate, which is then used to compute the beamforming weights. During our experiments we were able to establish communication with a commercial UE and achieve the maximum possible throughput for the given configuration [7].

2.1.2 Functional splits in OAI

In the massive MIMO testbed described above, all the eNB functionality was running in the same machine\footnote{using heavy parallelization to meet the real-time constraints}. In order to support a distributed antenna array built from remote radio heads, the monolithic architecture of OAI is split into several parts.

We have adopted the definitions of [1] for the software architecture of OAI. The eNB protocol stack is split in 3 different parts: the remote radio unit (RRU), which is an evolution of the classical remote radio head (RRH), the radio aggregation unit (RAU), which controls multiple RRUs potentially operating on different bands and with different coverages. As the name suggests this unit is responsible also for carrier aggregation and in the future also different radio access technologies. Last but not least the Radio Cloud Center (RCC) controls multiple RAUs. In the 3GPP 5G specifications the RCC is also called the central unit (CU) and RAU the distributed unit (DU).

The split between RRU and RAU is flexible and there are three possible options in OAI. The first two interfaces are similar to the ongoing standardization in [2].IF5 is similar to the classical BBU-RRH interface and transports baseband time domain IQ samples. IF4.5 corresponds to the split-point at the input (TX) and output (RX) of the OFDM symbol generator (i.e. frequency-domain signals) and transports resource elements in the usable channel band. Both interfaces also support optional A-law compression. Additionally to these two interfaces, OAI today also supports the small cells FAPI interface specifications P5 and P7 between the PHY and the MAC layer [4] that allows to offload the lower PHY functionality to the RRU.

The interface between RAU and RCC is currently under development and we are retro-fitting the current 5G-NR specifications [5] for the F1 interface between CU and DU to 4G.
Figure **1** summarizes the functional splits in OAI.

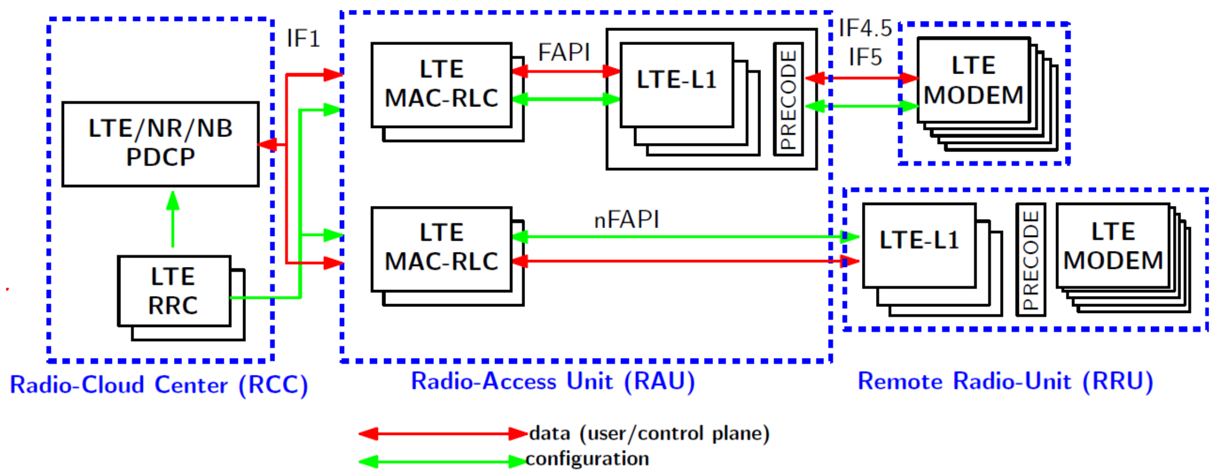

Figure 1: OAI functional splits

2.1.3 C-RAN testbed

Eurecom is currently building and deploying a C-RAN network on its premises

in Sophia-Antipolis. The platform will consist of a set of RRUs deployed on the ceilings of the corridors on levels -3 and -4 of the EURECOM building. The RRUs on each floor are connected by Gbit Ethernet to a switch which are in turn connected to a central server over optical 20Gbit Ethernet. An additional high power commercial remote radio head is connected to the C-RAN server through a CPRI gateway (see
Figure **2**).

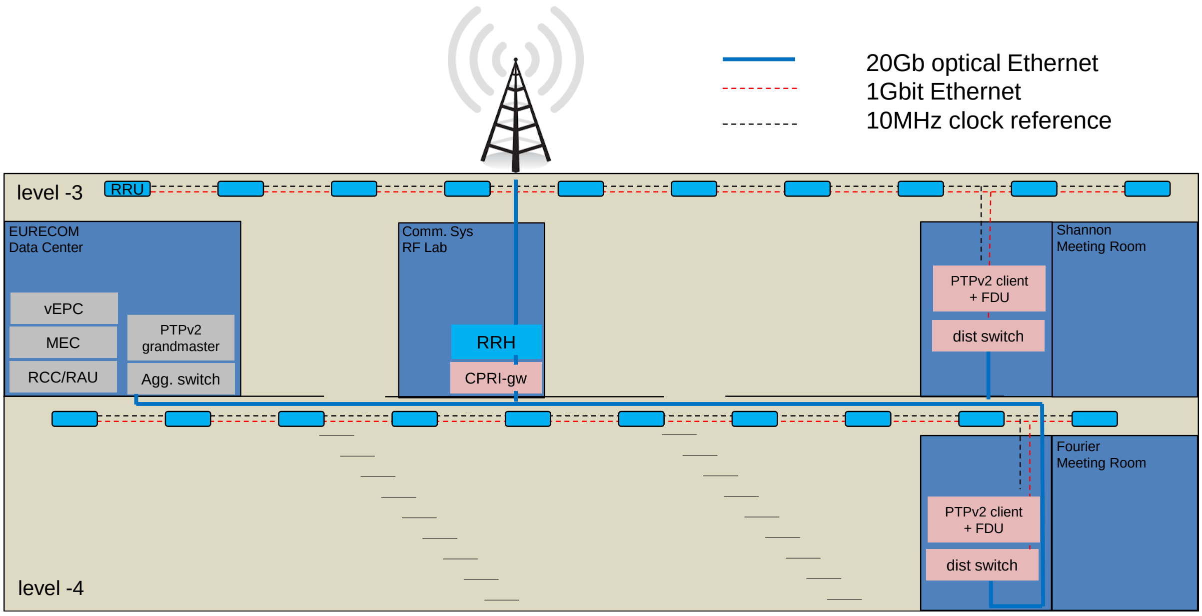

Figure 2: Floor plan of the Eurecom C-RAN deployment

Frequency synchronization is provided by a clock distribution unit which provides a 10MHz reference signal on each floor. Timing synchronization is achieved by a special protocol in the RRUs that first listens to other RRUs within its range to derive the frame number and the start of the frame. In the future, the FDUs on each floor can further be synchronized using the PTPv2 (IEEE 1588) protocol over optical fiber. For this a PTPv2 grandmaster clock will be placed in the server room and a PTPv2 client in the local server rooms.

The RRUs consist of an up-board from Intel, a B200 mini from Ettus research, a RF frontend designed by Eurecom and PoE module (see
Figure **3**). The RRUs will use Band 38 (2.5 GHz) time-division duplex (TDD) for which EURECOM has been granted a license from the French regulatory body (ARCEP) for both indoor and short-range outdoor experiments (1km radio around our building).

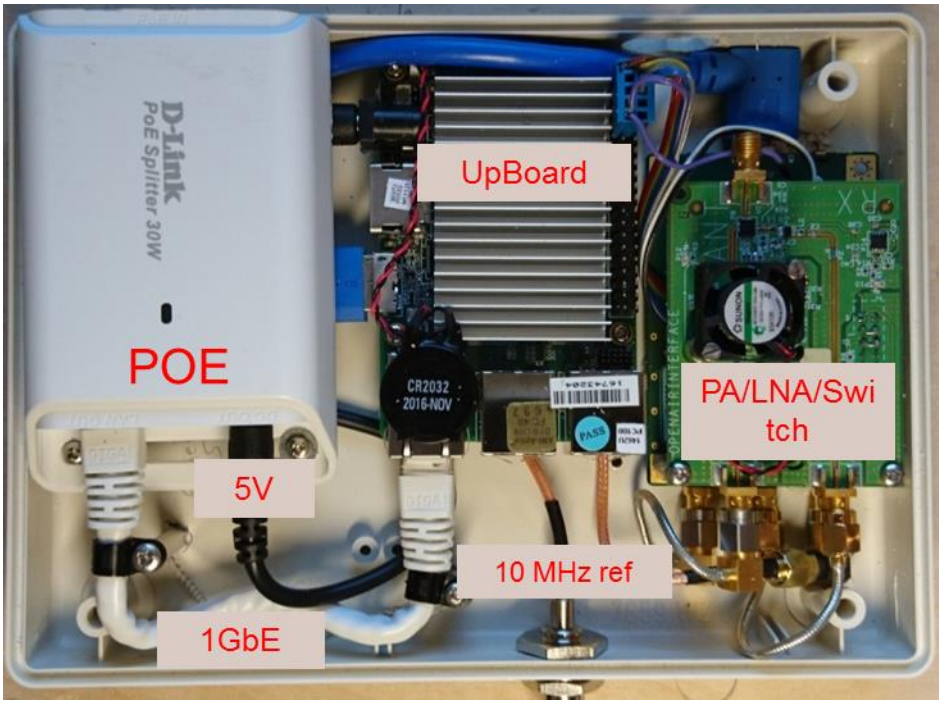

Figure 3: Remote Radio Unit (RRU) built from commodity hardware

2.1.4 Accesibility

The OAI C-RAN testbed at Eurecom is accessible for all members of IRACON. At the moment remote access is under development, but interested people are invited to Eurecom to carry out their experiments in collaboration with the Eurecom team.

The following TDs have more information on the testbed.

- TD(16)02044
- TD(17)03065
- TD(17)04002

Also see the website www.openairinterface.org for more details.

2.2 The Lund massive MIMO (LuMaMi) testbed

The Lund University Massive MIMO, LuMaMi, testbed is the world's first real time testbed for massive MIMO communication [8]. The testbed is based on Software Defined Radios (SDR) interconnected with a synchronous high capacity network and provide a flexible platform for experimental work with massive MIMO under real life conditions. A few other testbeds based on the same design principles have been assembled, e.g. the massive MIMO testbeds at the University of Bristol, Norwegian University of Science and Technology and KULeuven in Belgium. Below is a summary of the design and features of the LuMaMi testbed based on the thorough and detailed description in [9], please see this document for further details on the setup and on massive MIMO testbed requirements and designs in general.

The LuMaMi testbed can use up to 100 coherent base station antenna elements and can serve up to 12 single antenna users. OFDM is used and the transmission scheme has been made as similar to LTE as possible. The bandwidth is 20 MHz using an IFFT size of 2048, meaning 1200 active sub channels with a subcarrier spacing of 15 kHz. Basic parameters are summarized in Table 0.

Table 1. Basic parameters

Nr. of coherent RF channels	100
Nr. of users	12 single antenna users/6 dual antenna users
RF bandwidth	20 MHz
Center frequency	3.7 GHz
Output power	16 dBm per channel
Pre-coding	MRC/MRT, ZF, regularized ZF
Modulation	OFDM: 4, 16, 64, 256 QAM
Nr. of sub-carriers	1200
Sub-carrier spacing	15 kHz

The system is controlled by the host on the base station. There, operational parameters are set and operation is monitored in real time. It has an integrated Windows controller running LabView.

2.2.1 Frame Structure

The frame structure used for transmission is defined by frames of 10 ms, each divided into 10 subframes with 1 ms duration, which in turn is divided into 2 slots. Each slot of 0.5 ms, comprises 7 OFDM symbols. The first one is an uplink pilot symbol, where the 12 users simultaneously transmit on each 12th

subcarrier in an interleaved fashion to support uplink channel estimation. The system is using time division duplex, TDD. The uplink pilot symbols are used also for downlink pre-coding, based on a reciprocity calibration scheme [11]. There are also downlink embedded pilots to support channel estimation and equalization at the UE side.

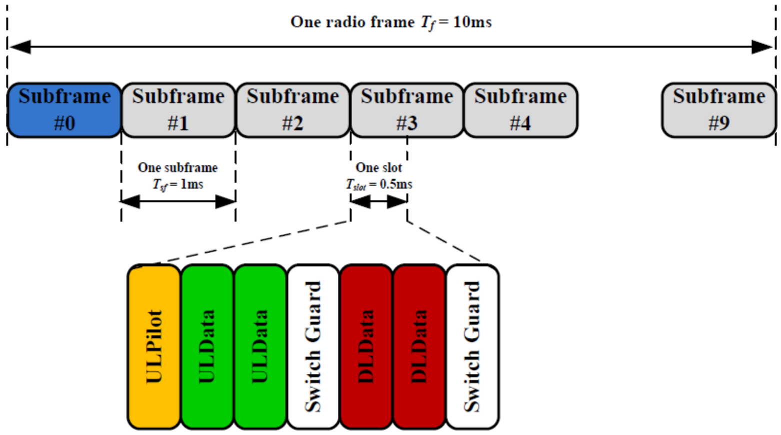

Figure 4. Frame structure

2.2.2 Mobility

As the establishment of the communication links are based on downlink pre-coding, the maximum velocity supported is determined by the time between the uplink pilots and the last downlink data symbol in the slot. With the frame structure above, a maximum Doppler frequency of 240 Hz can be supported in a straightforward manner. Given the carrier frequency typically used, 3.7 GHz, this thus corresponds to a maximum velocity of 70 km/h. A mobility test has been performed [10], showing successful operation at 50 km/h without any additional optimization.

2.2.3 Antenna Array

The base station array has 160 dual polarized patch elements spaced half a wavelength apart. It provides 320 possible antenna ports that manually can be reconfigured. Typically, for outdoor operation, a dual polarized configuration with the upper part of the T shaped antenna is used, resulting in a dual polarized 4×25 antenna configuration. For indoor operation, where the elevation spread is larger, it is possible to use a more compact array structure and then the central 5×10 dual polarized part can be used. In any case, any antenna configuration is possible and there is no restriction on maximum antenna spacing for successful massive MIMO operation.

2.2.4 User Equipment

The UEs are implemented using software defined radios (SDRs), with one or two antennas each. The SDRs are connected to laptops for user interface and logging, whereas the antennas of the UEs are connected with SMA-cables.

2.2.5 Synchronization

Synchronization is maintained internally at the base station through a star synchronization network transmitting a 10 MHz reference and 1 PPS signal to all units. The UEs are synchronizing to the base station though an over the air procedure to find the proper timing. If needed the UEs can also be disciplined by GPS reference signals to minimize frequency offsets.

2.2.6 Accessibility

The testbed is stationed in Lund, Sweden. In general, we are open to research collaboration and joint projects. Contact Fredrik Tufvesson, fredrik.tufvesson@eit.lth.se, if you have ideas to discuss. The testbed has previously been used in the EU project MAMMOET, Massive MIMO for efficient transmission (https://mammoet-project.eu), as an experimental platform for massive MIMO research.

The following TDs have used the testbed.

- TD(17)03043, Paul Harris, Steffen Malkowsky, Joao Vieira, Fredrik Tufvesson, Wael Boukley Hasan , Liang Liu, Mark Beach , Simon Armour and Ove Edfors: Temporal Analysis of Measured LOS Massive MIMO Channels with Mobility, 3rd MCM Lisbon, Portugal 2017.
- TD(17)04049, Erik L. Bengtsson, Peter C. Karlsson, Fredrik Tufvesson, Fredrik Rusek, Steffen Malkowsky, Ove Edfors: A Simulation Framework for Multiple Terminal Antennas in Massive MIMO Systems Evaluated Against Measurements, 4th MCM Lund, Sweden, 2017

2.3 Self-interference cancellation testbed for In-band Full-duplex transceiver prototyping

The Bristol self-interference cancellation (SIC) testbed is a reconfigurable hardware/software platform implementing several combinations of multi-stage SIC. The purpose of the testbed is to allow development and prototyping of adaptive RF circuit control algorithms and digital domain cancellation algorithms, and characterise cancellation performance when subject to hardware imperfections and in dynamic environments.

The cancellation performance achieved by a particular system is heavily dependent not only on the particular design, but also on implementation specific details. In the case of active RF cancellation, circuit imperfections such as phase noise and non-linearity in the Tx chain are the primary limiting factor in determining cancellation performance. Similarly, the type and placement of antennas can have a large impact on achievable isolation. Furthermore, the isolation achieved by a particular technique, and the resulting self-interference channel transfer function, have a substantial impact on the requirements and performance of further stages of cancellation.

Due to the dependence of the performance of digital cancellation techniques on the design and performance of the prior stages of cancellation, prototyping and characterisation of digital baseband cancellation algorithms can only be properly performed using a testbed which implements the preceding RF domain suppression techniques. Similarly, the performance of adaptive control algorithms for RF and digital domain cancellation loops depends heavily on the dynamics of the self-interference channel, and therefore adaptive cancellation algorithms and only be properly characterised when subject to realistic environmental conditions.

This section summarises the following reference, which documents this testbed in detail.

- C. Zhang, L. Laughlin, M. A. Beach, K. A. Morris, J. L. Haine, A Self-Interference Cancellation Testbed for Full-Duplex Transceiver Prototyping, *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2016 IEEE 27th Annual International Symposium on*, Valencia, 2016.

2.3.1 SIC techniques and testbed architecture

The testbed is based on National Instruments Vector Signal Transceivers and implements the following SIC techniques:

- Antenna separation
- Electrical balance duplexing (EBD)
- Active RF cancellation
- Linear baseband cancellation
- Non-linear digital baseband cancellation

Figure 5 : Dual antenna and electrical balance duplexer configurations of the SIC testbed. depicts the testbed architectures. The testbed implements two hardware configurations, utilizing either separate Tx and Rx antennas, or an EBD as the first stage of SI suppression. The following stage of suppression uses a reconfigurable active RF canceller, and finally the digital baseband cancellation processing is implemented in MATLAB. The system uses National Instruments VSTs as the Tx and Rx radios. Transceiver hardware control and active cancellation signal generation is implemented in LabView, along with hardware control of the EBD hardware in the EBD configuration (using a MIPI interface to control MEMS tunable capacitors in the balancing network). Baseband Tx and RX signals are exchanged between LabView and MATLAB, allowing the digital baseband cancellation process to be performed offline in MATLAB.

This testbed architecture has been chosen to provide a highly flexible platform to characterise cancellation performance across a range of system configurations. The physical layer implementation is highly reconfigurable, and allows many parameters to be easily adjusted, for example, modulation scheme, bandwidth, Tx power, subcarrier spacing and carrier frequency can all be easily changed. The use of MATLAB for the digital baseband cancellation facilitates ease of implementation and experimentation in the development of digital cancellation algorithms, leveraging the fast development cycle of MATLAB to provide rapid prototyping of digital cancellation algorithms using real self-interference signals from a fully operational reconfigurable self-interference cancelling transceiver front end. The reconfigurable nature of the testbed physical layer also allows the impact of various different hardware configurations and physical layer parameters on the performance of prototype digital cancellation algorithms to be investigated. Additional hardware can be included in this testbed, for example, an external Power Amplifier (PA) can be included in the Tx chain to increase the Tx power and degrade Tx Error Vector Magnitude (EVM), and an external Low Noise Amplifier (LNA) and/or attenuator can be included in the Rx chain in order to adjust the Rx noise figure.

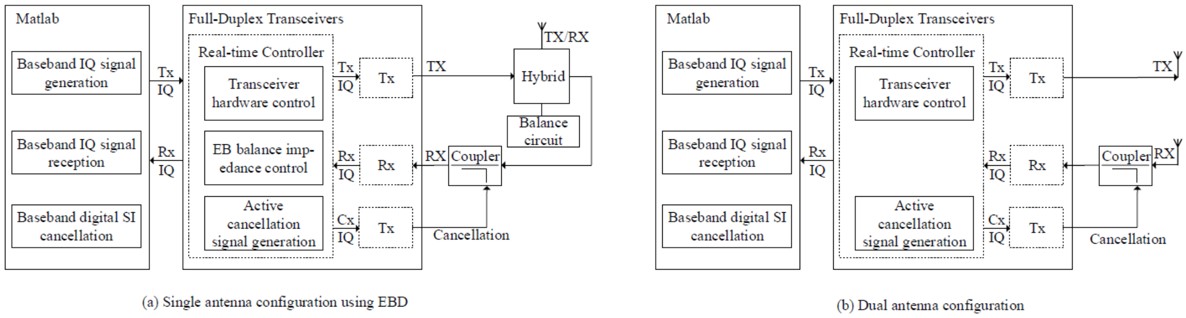

Figure 5 : Dual antenna and electrical balance duplexer configurations of the SIC testbed.

2.3.2 Physical layer

The testbed implements and LTE-like OFDM physical with subcarrier spacing of 15 KHz and bandwidth up to 120 MHz, as provided by the NI PXIe-5644R VST. However it should be noted that, for non-linear cancellation, an excess bandwidth ratio of the order of the non-linear processing is required (for example, the system can support 3rd order non-linear processing up to a 40 MHz modulation bandwidth. All baseband digital signal processing, including Quadrature Amplitude Modulation (QAM) and demodulation, OFDM sub-carrier mapping and de-mapping, the Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT), and cyclic prefix processing is implemented in LabView and runs on the controller. A state machine architecture is utilised to perform EBD balancing, SI channel estimation, and active self-interference cancellation sequentially.

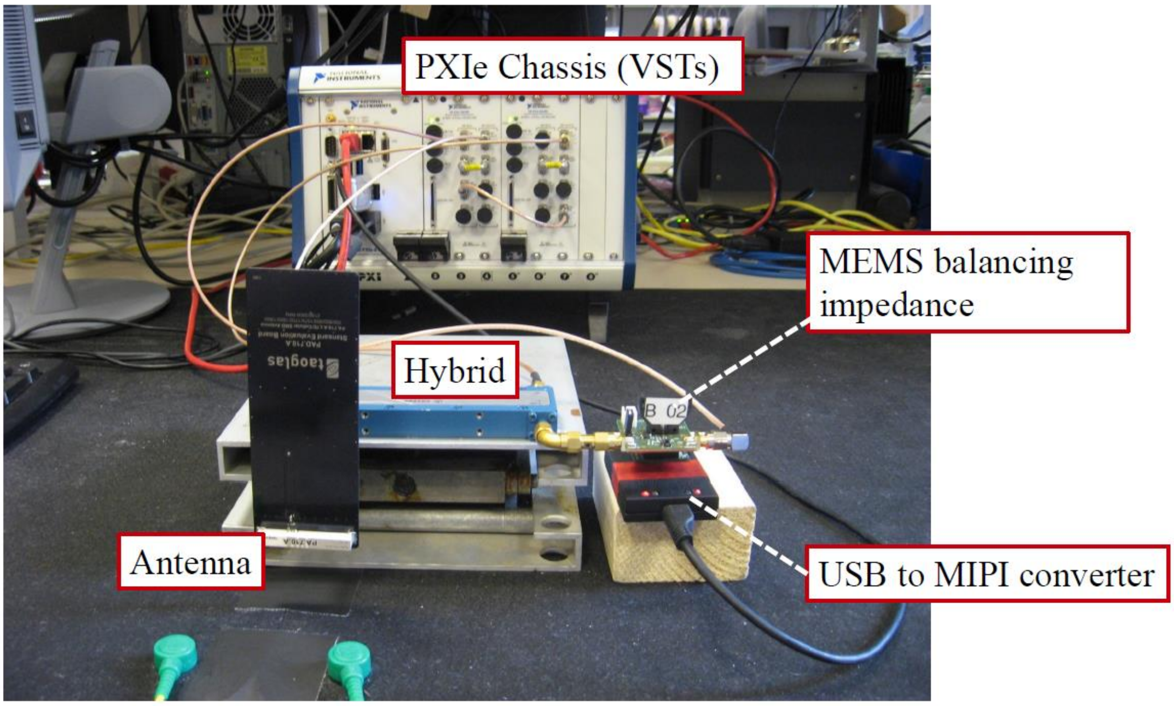

Figure 6 : Photograph of IBFD testbed in the electrical balance duplexer configuration.

2.3.3 Availability

Remote access is unavailable for this testbed, however is available for use at the University of Bristol to members of IRACON.

3. References

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[11] J. Vieira; F. Rusek; O. Edfors; S. Malkowsky; L. Liu; F. Tufvesson: Reciprocity Calibration for Massive MIMO: Proposal, Modeling, and Validation, IEEE Transactions on Wireless Communications, Year: 2017, Vol.16, Issue 5, pp 3042 - 3056, DOI: 10.1109/TWC.2017.2674659