Multi-User MIMO and Carrier Aggregation in 4G Systems: the SAMURAI Approach

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***Abstract*—The market success of broadband multimedia-enabled devices such as smart phones, tablets, and laptops is increasing the demand for wireless data capacity in mobile cellular systems. In order to meet such requirements, the introduction of advanced techniques for increasing the efficiency in spectrum usage was required. Multi User -Multiple Input Multiple Output (MU-MIMO) and Carrier Aggregation (CA) are two important techniques addressed by 3GPP for LTE and LTE-Advanced. The aim of the EU FP7 project on "Spectrum Aggregation and Multi-user-MIMO: real-World Impact" (SAMURAI) is to investigate innovative techniques in the area of MU-MIMO and CA with particular focus on the practical, real-life, implementation and system deployment aspects. In the present paper, we provided an overview of the up-to-date SAMURAI contributions together with a description of the SAMURAI demonstrators developed as core part of the project.**

I. Introduction

The recent market success of devices at the border of communication and multimedia such as smart phones, tablets, and mobile broadband enabled laptops is driving the operator revenues from voice centric models to data models and is increasing the demand for data communication capacity on mobile cellular systems. This new application scenario pushed both regulatory and standardization bodies to define new requirements for the communication technologies to come. For instance, the International Telecommunication Union (ITU), in the framework of International Mobile Telecommunications - Advanced (IMT-A) systems has defined a downlink target of 1Gbit/s for low mobility and 100Mbit/s for high mobility for mobile wireless communication scenarios [1]. These characteristics are commonly used to define the fourth generation (4G) communication technologies. In order to meet such requirements, the introduction of advanced techniques for increasing the efficiency in spectrum usage was required. Efficiency means both high spectral efficiency reachable by the air interface, and flexibility in how the spectrum is managed by the network. Multi User -Multiple Input Multiple Output (MU-MIMO) and Carrier Aggregation (CA) are two important examples of such techniques. While the former improves the spectral efficiency playing with the spatial dimension and smart scheduling, the latter aggregates multiple chunks of bands available in the spectrum to provide wireless system with larger bandwidth, raising the need of access and management of multi-band, multi-bandwidth systems. The Long Term Evolution (LTE) system and its evolution, LTE-Advanced [2] is one of the 4G technologies as defined by the ITU. Its first version, known as Release 8 (Rel'8) starts to be deployed, while Release 10 (Rel'10) is being finalized in the standardization process. From Rel'10 is foreseen the introduction into the standard of both MU-MIMO and CA, making the feasibility and implementability of these techniques extremely crucial. The "Spectrum Aggreagtion and Multi-user-MIMO: real-World Impact" (SAMURAI) project started with the intention of making techniques, that are vital for meeting the 4G requirements set by ITU practical and feasible, but also for allowing the end users to have positive experiences with the heavily demanding multimedia applications.

II. Approaches in Standardization

A. Multi-User MIMO

In (downlink) MU-MIMO, the transmissions to several terminals are overlapped in the same time-frequency resources by exploiting the spatial diversity of the propagation channel. The first release of LTE Rel'8 was aimed at defining the new OFDMA based air-interface and introduced advanced single-user (SU) MIMO transmission schemes. Only one transmission mode, the *Transmission Mode (TM) 5* (TM5), allows MU-MIMO operation. However, as the channel feedback information scheme was optimized for single-user operation, only marginal gains have been reported [3].

In LTE-Advanced (Rel'10), a special attention has been given to the signaling needed for more advanced SU/MU-MIMO schemes. In particular, a new transmission mode, *TM9*, has been defined which now includes both SU-MIMO and MU-MIMO transmission capabilities without the need for the User Equipments (UEs) to be re-configured via higher layer signaling when switching between SU and MU transmission / reception on the shared data channel [4].

B. Spectrum Aggregation

Spectrum Aggregation or CA consists in aggregating several (and possibly) fragmented spectrum bands to a (virtual) single larger band. The benefit of CA relies in higher offered data rates, but it requires more complex and expensive transceivers. Furthermore, CA can also be used to achieve better resource utilization and spectrum efficiency by means of joint resource allocation and load balancing across the carriers. CA was first introduced in the downlink of 3G systems. Dual Cell (DC)-HSDPA was standardized in December 2008 (3GPP UMTS release 8 [5]) and as its name indicates, it features the aggregation of two bands in the downlink. The scheme is already part of commercial networks with main objective of doubling the data rates and competing with 4G systems.

In LTE, 3GPP introduced CA both for downlink and uplink as essential part of LTE-Advanced (Rel'10) [6]. Component Carriers (CCs) are aggregated to support wider transmission bandwidths. It requires enhancements at Physical (PHY), Medium Access Control (MAC) and Radio Resource Control (RRC) protocol layers with respect to earlier releases. However, a key feature is the backward compatibility: each CC appears as a Rel'8 carrier hence is also compatible with Rel'8 UE categories. Initially, 12 scenarios were being studied, but due to complexity and limited time Rel'10 has just three scenarios (2 Frequency Division Duplex (FDD) (non-contiguous) and 1 Time Division Duplex (TDD) (contiguous)). In March 2011, 10 more combinations were agreed for Release 11 (Rel'11).

III. The SAMURAI Project

The aim of SAMURAI project [7] is to investigate innovative techniques in the area of MU-MIMO and CA. The main novelty of the approach adopted in SAMURAI is to pay a particular attention to the practical implementation and deployment aspects. The project, that started in 2010 and has a 2,5 years duration, is carried out by an industrially focused consortium composed of a telecommunication network equipment maker, chipset vendors, test equipment vendor and universities. The presence in the consortium of telco industrial partners stresses the effort of studying and developing techniques that are feasible and ready to be implemented in communication products. The 3GPP LTE and LTE-Advanced standards have been considered project-wise as the reference technology for future mobile communications, and all the investigations directly refer to them for both Rel'8 and Rel'10.

The more promising outcome expected from the SAMURAI project still relies on the number of Proof-of-Concept (PoC) testbeds that will be used to asses the feasibility and the impact of the MU-MIMO and CA techniques at several levels of the radio access protocol stack. As a matter of fact, the main contributions in the testbed domain will be:

- prove the gain that novel receiver architectures can bring to standardized MU-MIMO transmission modalities;
- prove the possibility of autonomously exploit the flexibility provided by the multi-carrier transmissions.

The SAMURAI project has already contributed to the literature with several theoretical/simulation contributions that prove the potential gain of the investigated MU-MIMO and CA techniques. In the following, a brief overview of the proposed methodologies will be presented. The PoC testbeds still remain the major peculiarity of the project and for this reason a deeper explanation will be also provided.

IV. Multi-User MIMO

There are two fundamental practical challenges of MU-MIMO systems: a) design practical transceiver structures, including low complexity precoding schemes achieving high data rates and receiver structures that can tackle multi-user interference and b) design of accurate and efficient Channel State Information (CSI) feedback techniques to ensure high throughput and full multiplexing gain. These practical and deployment aspects of MU-MIMO systems are investigated in SAMURAI project as explained in [3]. In next subsection a brief summary of SAMURAI transceiver design is given. More detailed description can be found in [3]

A. SAMURAI MU-MIMO Transceiver Design

At the transmitter side, Rel'8 TM5 has been adopted with few changes as explained in Section VI-A3). At the receiver side, it has been decided to apply an Interference Aware (IA) receiver that cancel out the MU interference (MUI) [8]. Further, a measurement campaign was carried out to evaluate the performance of the IA receiver.

1) Interference Aware Receiver: To handle the residual MUI, the low-complexity IA receiver proposed in [8] has been designed and investigated in SAMURAI project. The receiver is based on an approximation of a maximum likelihood receiver which exploits the structure of the residual interference rather than assuming it to be Gaussian in the detection process. In addition to this exploitation, this receiver reduces the system detection complexity by one complex dimension and is thus also applicable to single antenna UEs, which do not possess spatial degrees of freedom to cancel or attenuate the interference via Zero Forcing or Minimum Mean Squared Error filters. This low complexity receiver being based on the Matched Filter (MF) outputs and devoid of any division operation is suitable for implementation in the existing hardware. The performance-complexity trade off of low complexity IA receiver is demonstrated in Figure 1. Conventional Max-Log-MAP (MLM) receiver, MF and Interference Rejection Combiner (IRC) have been compared with the IA receiver in 4×2 channel. The performance of the receivers is evaluated by the required Signal-to-Noise Ratio (SNR) at Block Error Rate BLER=0.01. The complexity of the receivers is evaluated by the number of required real-valued multiplication for getting logarithm of the likelihood ratio values in one subcarrier. As it can be seen from Figure 1 the IA receiver outperforms both MF and MLM receiver in terms of performance as well as complexity. For low modulation orders, the IA receiver has the similar complexity and performance as the IRC receiver, i.e. Channel Quality Indicator CQI= 4. When the CQI value

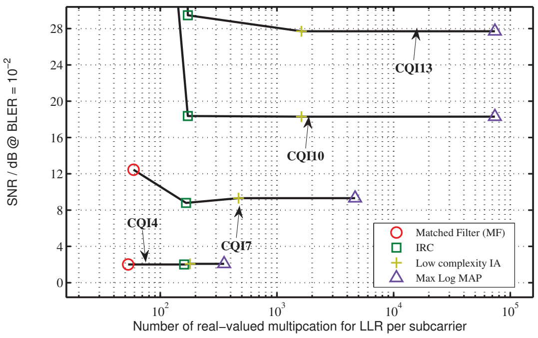

Figure 1. Performance-complexity trade off among receivers applicable in MU-MIMO

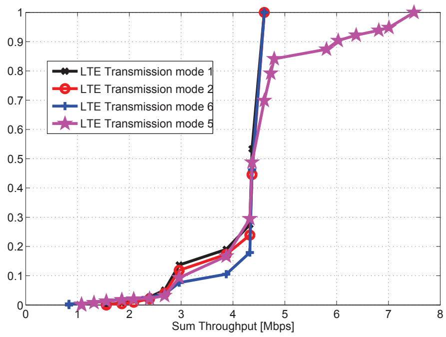

Figure 2. CDF comparison of sum throughput of the system with 2 single antenna UEs and eNB equipped with two antennas for different LTE TMs using 16 QAM

increases, i.e. large modulation order is applied, the complexity of the IA receiver increases but the performance improves comparing to the IRC receiver. Thus, the IA receiver is a good choice for MU-MIMO transmission when a performance improvement is desired. In order to evaluate the benefits of MU-MIMO with the IA receiver, a measurement campaign was conducted in the south-west region of France using Eurecom's OpenAirInterface (OAI) testbed (cf. Section VI-A2). The purpose of the measurement campaign was to calculate the modem throughput achievable by an LTE Rel'8 nomadic terminal for 5MHz bandwidth in a rural area. Along with the modem output the real life MIMO channel estimates were stored during the measurement campaign with the help of which the effectiveness of different LTE TMs was compared using PHY abstraction [9]. To evaluate the performance of TM5, the measurement traces were divided in two, and each trace was interpreted as a different user. The scheduler only scheduled the two UEs simultaneously only if both of the UEs have asked for the opposite Precoding Matrix Indicators (PMIs) during that particular sub-band otherwise it selected the best UE in terms of the received SNR and used single-layer transmit-precoding for it. To calculate the throughput of LTE TM5 abstraction for IA receiver presented in section IV-A1 was used [9]. Figure 2 compares the cumulative distribution function of the sum throughput for the TMs 1, 2, 6, and the modified 5 with two single antenna UEs present in a system served by a dual antenna enhanced Node B (eNB). These are the results for 16QAM modulation and for MU-MIMO the interference is also coming from 16QAM. It is very clear from the results that doing MU-MIMO with IA receiver is beneficial for high outage rates, i.e., the peak throughput. However, for low outage rates the throughput of MU-MIMO is less favorable.

B. *MU-MIMO Channel Model*

The effectiveness of MU-MIMO techniques relies on the channel properties. Hence, it is important to understand the multi-user characteristics of real-world channels. To this end we have investigated the correlation properties of the measured MU channel samples obtained in the Eurecom measurement campaign, and extracted various metrics from the measured data. In particular, Correlation Matrix Distance (CMD) is commonly used to characterize the similarity of MU-MIMO channels. Having investigated the narrow-band CMDs averaged over the measurement bandwidth, we have found the CMD to follow a beta distribution. Although the exact parameters of the distribution vary between different UE pairs, the distribution itself fits well irrespective of the specific scenario. In some instances, the lognormal fit has proven slightly better, but the beta fit was still acceptable. We use the extracted values to parametrize MU channel models.

V. Spectrum Aggregation

A. *Carrier Aggregation at lower layers*

Enabling carrier aggregation in a UE device, such as a handset, raises numerous challenges both at the base-band and at the Radio Frequency (RF) front end. Depending on the CA scenario (intra or inter-band, contiguous or non-contiguous), multiple transceiver architectures can be envisaged. Figure 3 shows a simplified version of UE architecture with two receiver chains. A similar description for various possible UE transmitter architectures has also been provided in the 3GPP technical report [10]. In the case of *intra-band contiguous CA*, theoretically it should be possible to use a single transmitter/receiver chain while providing backward compatibility to the LTE system. The RF front-end and the baseband in this case should provide support for a wider bandwidth of two or more CCs. Thus the individual component cost may run high due to the higher specification requirements in order to support the wider bandwidth. In the case of *inter-band non-contiguous CA*, the user equipment consists of multiple IFFTs/FFTs and RF chains each designed to operate at various bands. Typically a multi-band multi-mode RF front end is stacked together and commuted alternatively, based on the band and standard in use. Such architectures although simple with low individual component cost, are however not optimized in terms of integration and the simultaneous usage of different bands. In order to have a well-optimized architecture, the state-of-the-art approach typically consists of aggregating multiple RF Integrated Circuits (RFICs) or RF front-ends. The design

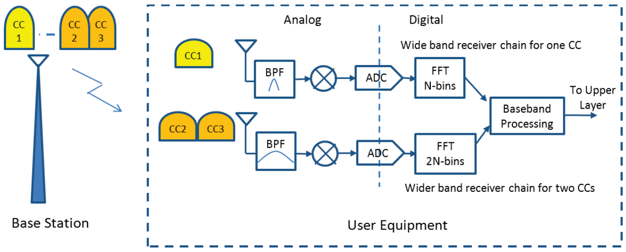

Figure 3. User equipment with multiple receiver chains

challenges in this case may increase further when there is a requirement for additional MIMO support (in theory up to 8x8 for Rel'10), as this also results in implementation of additional RF front-ends. The current trend by operators is to deploy the inter-band CA in order to optimally utilize the fragmented spectrum. However due to terminal constraints, the deployment of inter-band CA is typically limited to 2 CCs in downlink and finally no CA in uplink.

B. Multi layer and Network Impact

For backwards comparability reason, in LTE it has been decided to build the CA in LTE-Advanced based on the existing LTE Rel'8 structures. This means each CC has an independent Layer 1 transmission including the Hybrid Automatic Repeat Request (HARQ) and Link Adaptation (LA) functionalities according to Rel'8 assumptions [11]. The Layer 2 packet scheduling, which consists of time domain (TD) packet scheduling and frequency domain (FD) packet scheduling, is responsible for scheduling the UEs assigned at each CC. The assignment of the CC to the UEs is done at Layer 3 where different load balancing mechanisms can be deployed. Single or multiple CCs will be assigned to the connected UEs based on their capabilities, traffic requirements, Quality of Service (QoS) settings, the overall load in the cell etc. In general, this transmission framework is applied for both uplink and downlink CA. Both the inter-band and intra-band CA types give more flexibility in the utilization and allocation of the available radio resources. The research challenge is how to configure and utilize the available bandwidth efficiently under the constrains of RF chain capability, signaling overhead, UEs' states as well as traffic load conditions. For example, with inter-band CA systems, it is possible to optimized both the coverage and the cell performance by allocating cell-edge UEs to the lower band CCs and cell-center UEs to the higher band CCs. In general, by retaining more bandwidth for transmission CA will increase the experienced average user throughput [12],[11].

The use of CA can be extended beyond the typical SA described above. In the future Rel'11 it is already envisioned to employ CA transmission schemes for another purpose as well: enhanced Inter-Cell Interference Coordination (eICIC) [13],[14]. This means that each cell is assumed to be able to configure two or more CCs for all its served UEs and to de/activate them adaptively in order to minimize the inter-cell interference levels. This CA-based eICIC procedure would complement the TD eICIC transmission modes standardized already in LTE-Advanced. One typical application for the CA-based eICIC scheme is in large-scale small node deployments, such as Femto eNB densely deployed in residential area (similar to today's WiFi access points). In SAMURAI we have investigated the practicalities related to this deployment scenario based on an earlier proposal for CC selection algorithm: the Autonomous Component Carrier Selection (ACCS) [15]. Section VI-B describes the SAMURAI ACCS PoC implementation and current results.

VI. The SAMURAI Demonstration Approach

Since the SAMURAI project has a strong focus on practical aspects a large part of the project is devoted to development and demonstration activities. In this section we describe the two planned demonstrations in SAMURAI, one for MU-MIMO and one for ACCS, whose implementation started at the beginning of 2011.

A. Multi-User MIMO Demonstration

1) Scenario and purpose of the demonstration: The purpose of the MU-MIMO demonstration is to show the benefits of the IA aware receiver. It was shown in simulation studies [8] that this receiver can improve the system performance for LTE Rel'8 TM5 when two transmit antennas are used at the eNb and one receive antenna at the UEs. The SAMURAI MU-MIMO demo will show these gains in real life, using the OpenAirInterface demonstration platform described in the next section. The baseline comparison is LTE Rel'8 TM6. The key performance indicator for the MU-MIMO PoC will be the PHY throughput.

2) The OpenAirInterface demonstration platform: OAI is an experimental real-time, open-source hardware and software platform for experimentation in signal processing and wireless networks mainly developed by Eurecom. OAI features an open-source implementation of an LTE Rel'8 software modem for UE and eNB [16], [17], [18]. The software is written in C language and can be used either for extensive computer simulations using different channel models or it can be used for real-time operation. In the latter case, it is run under the control of the Real-Time Application Interface (RTAI) which is an extension of the Linux operating system. In OAI there are two different hardware modules available: CardBus MIMO 1 (CBMIMO1) and Express MIMO. A third platform, Express MIMO 2, is under development. The CBMIMO1 board (see Fig. 4) comprises two TDD RF chains operating at 1.9GHz with 5MHz channels and 21 dBm transmit power per antenna for an orthogonal frequency division modulated (OFDM) waveform. Express MIMO (see Fig. 4) is a baseband processing board, which provides significantly more processing power and bandwidth than CBMIMO1. It is connected to an external RF frontend. Also shown in Fig. 4 are the UE antennas and the eNB antennas with the power amplifiers. In SAMURAI the CBMIMO1 cards can be used for both UEs and eNBs. This scenario will be used for indoor demonstrations, since the output power of these cards is limited to 21 dBm.

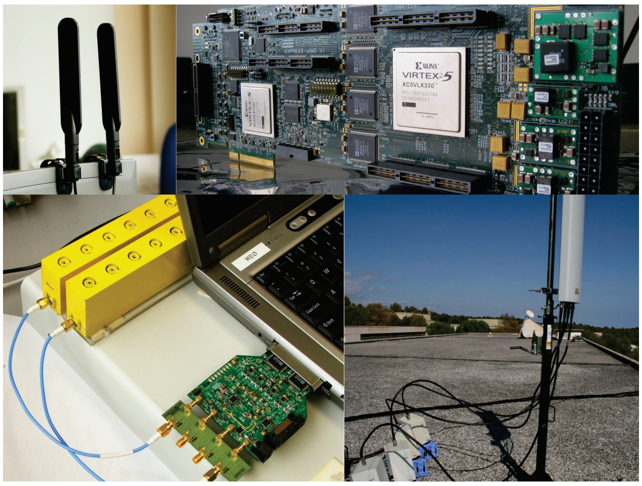

Figure 4. Hardware modules of the OpenAirInterface: CBMIMO1 card (bottom left) and Express MIMO card (top right), UE antennas (top left) and BS antennas with power amplifiers (bottom right)

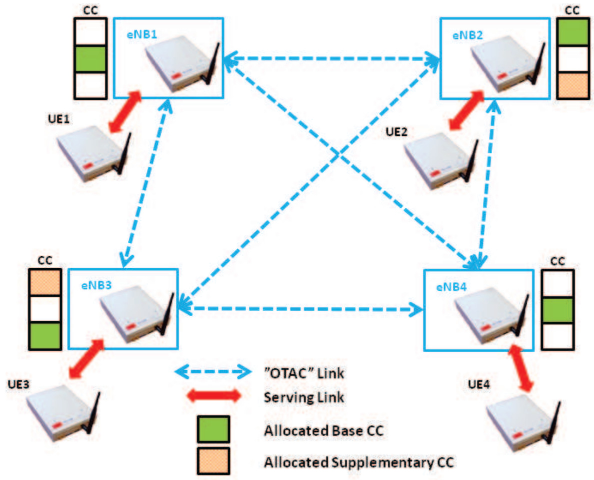

Figure 5. ACCS PoC scenario: the CCs will be occupied by Serving links, measured by the UE. The UE will also report via WiFi to its eNB the measured Reference Signal Received Powers. Finally the OTAC control channel will be emulated through WiFi and a demo server that will properly route the received packets.

For outdoor experimentations we will use the Express MIMO cards with an external RF and power amplifiers, which can amplify the signal up to 30 dBm.

3) MU-MIMO scheduling: For the performance evaluation of MU-MIMO it was also decided to make a few modifications compared to the standard. Originally, TM5 uses feedback mode 3-1 (higher layer configured feedback), which feeds back sub-band CQI and wideband PMI. Since precoding is usually based on PMI feedback, the same precoder is usually applied to the whole bandwidth. However, in a recent measurement campaign [9] it was observed that the PMI can change significantly over the whole bandwidth. Using one PMI for the whole bandwidth will thus significantly decrease the performance. Therefore it was decided in SAMURAI to make a few adoptions to TM5:

- Use of feedback mode 1-2 in order to exploit sub-band PMI feedback.
- Use of a custom Downlink Channel Information (DCI) format 2D, in order to signal the sub-band precoders to the UE. This new DCI format is based on the DCI format 2 (usually used for TM4 - closed loop MIMO) but includes one further bit for the downlink power offset like DCI format 1D (usually used for TM5 - MU-MIMO). This way we can signal the user that pre-coding was performed according to the latest PMI report on Physical Uplink Shared Channel and thus allowing for a finer granularity of PMIs.

Both of these adjustments can be seen as an intermediate step towards LTE-Advanced, where a new TM9 has been defined that basically allows the two adjustments described above. However, TM9 uses UE-specific Demodulation Reference symbols (DM-RS) and thus different to the original MU-MIMO scheme in Rel'8. The finer granularity of PMIs now allows us to schedule users on every sub-band rather than scheduling over entire bandwidth. For every sub-band, the two users will be scheduled in MU-MIMO mode 5, if they report orthogonal PMIs in that sub-band. This has been shown to be the optimal solution given to LTE low resolution precoders [8]. In a large group of users, the probability of finding a pair of users with orthogonal PMIs in sub-band is higher as compared to that of wideband PMI. Basically with this kind of scheduler, two scenarios can be seen: a pair of users with orthogonal PMIs can be obtained as described and in the second scenario, in case of no compatible pair of users, SU-MIMO transmission is enabled. This distinction between MU-MIMO and SU-MIMO mode is made by the downlink power offset bit in DCI. Therefore with this customized DCI format 2D, we can switch between MU-MIMO and SU-MIMO mode for every sub-band.

B. Autonomous Component Carrier Selection

1) Scenario and purpose of the demonstration: The starting assumption of the demonstrator is the presence of multiple eNBs in the same geographical area. In the final PoC demonstrator there will be four eNBs, each one with one affiliated UE. The goal of the PoC Demonstrator (Demo) is to verify the performances of a smart and autonomous selection of the used component carriers by each eNB. The main challenge of the proposed scenario consists in a severe spectral overcrowding, due to a number of eNBs, each one potentially using two component carriers, greater than the number of available component carriers. In Figure 5 the PoC scenario is shown.

2) The ASGARD demonstration platform: The demonstrator is a software radio based on Universal Software Radio Peripheral version 2 and above (USRP2, N200) front ends and general purpose processor-powered commercial off-the-shelf (COTS) computers. The USRP serves as RF-front-end that performs high-speed general purpose operations like digital up and down conversion, decimation and interpolation on the on board FPGA. All the waveform-specific processing like modulation and demodulation are performed in software on the host computer. In order to demonstrate the potential gain and the feasibility of the ACCS algorithms, a specific C++ software platform has been developed by Aalborg University within the SAMURAI project: the Application-oriented Software on General-purpose processors for Advanced Radio Development (ASGARD)[19]. ASGARD is substantially a processing framework that allow the development and the interconnection in single- or multi-threading mode of general processing blocks. As a matter of fact, the same framework can be used to develop PHY, MAC, Radio Resource Managment, and protocol blocks. ASGARD is designed to run in the user-space of common Linux machines, allowing the exploitation of the object-oriented features of the C++ programming language. Despite the software complexity of the framework, ASGARD has been designed following the principle of Domain Driven Development. The goal is to make the software usable by telecoms engineers (the domain experts) with limited software expertise.

3) PoC Implementation of ACCS: In order to fast-prototype the ACCS system several simplifications have been applied in the development of the software features. First of all, the PHY has been reduced to the transmission of simple pilot patterns. It is then possible to measure the transmitted power of each eNB and identify the transmitting cell. The Over-The-Air-Communication (OTAC) channel is emulated via WiFi, with the help of a demo server that act as a router for the ACCS information. The server also acts as a synchronizing entity that maintain the synchronization at the ACCS frame level. With this simplification has been possible to already prove the autonomicity of the system within the selection of the Base CC. The dynamic activation of the Supplementary CC is the following step for effectively prove the potential gain that such autonomous techniques can provide, if LTE-A has to cope with complex deployment scenarios such as the Heterogeneous Network ones. Another important result that the PoC provided is related to the implementation feasibility of ACCS. Running the ASGARD-based ACCS implementation on COTS quad-core machines, the ACCS related process are not even detectable in an accurate analysis of the CPU usage, given the simplicity of the algorithms themselves. Experimental results prove that, non surprisingly, the most demanding module in the architecture is the signal processing at the receiver [20]. Besides to the pure software implementation, experimental results for the ACCS concept are expected for the beginning of 2012.

VII. Conclusion

This paper presented the goals, investigations and current results of the EU FP7 SAMURAI project. The main focus of the project is to address the real-life system implementation constraints when deploying LTE MU-MIMO and LTE-Advanced CA transmission schemes. Complementing the in-depth theoretical and simulation studies carried out for the evaluation of the RF, PHY, baseband, L2-L3 RRM solutions, the SAMURAI project is also building proof-of-concept demonstrator platforms for validating the proposed MU-MIMO and CA building blocks. Our RF and baseband studies have shown the main challenges when implementing and testing CA support in real-life terminals. The MU-MIMO demonstrator platform is using an LTE compliant numerology and provides the ability to design and evaluate advanced receiver structures in real-life transmission conditions. The CA demonstrator platform is aimed at proving the potential of autonomous CA-based interference mitigations schemes in dense small-cell deployment scenarios. The remaining period of the project will be used to finalize and showcase these demonstrator platforms. These main recommendations and findings will help direct future research in the addressed areas and to advance the state-of-art in hardware-software platform implementation.

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