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 Communications - 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 standardisation 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 SAMURAI project started with the intention of making practical and feasible such techniques, that are vital for meeting the 4G requirements set by ITU, 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 (Release 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 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 (Release 10), a special attention has been given to the signaling needed for more advanced SU/MU-MIMO schemes. In particular, a new transmission mode has been defined which now includes both SU-MIMO and MU-MIMO transmission capabilities without the need for the UEs to be re-configured via higher layer signaling when switching between SU and MU transmission / reception on the shared data channel [4]. This is transmission mode 9 (TM9).

B. Spectrum Aggregation

Spectrum Aggregation (SA) or Carrier Aggregation (CA) consists in aggregating several (and possibly) fragmented spectrum bands to yield to a (virtual) single larger band. The
price being more complex thus more expensive transceivers. The obvious benefit being the possibility to offer increased data rates. Furthermore, SA can also be used to achieve better resource utilization and spectrum efficiency by means of joint resource allocation and load balancing across the carriers.

SA was first introduced in the downlink of 3G systems. Dual Cell (DC)-HSUPA 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 carrier aggregation both for downlink and uplink as essential part of LTE-Advanced (Release 10) [6]. Component carriers (CC) are aggregated to support wider transmission bandwidths. It requires enhancements at PHY, MAC and RRC protocol layers with respect to earlier releases. However, a key feature is the backward compatibility: each CC appears as a Release 8 carrier hence is also compatible with Release 8 UE categories. Initially, 12 scenarios were being studied, but due to complexity and limited time Rel-10 has just three scenarios (2FDD (non-contiguous) and 1 TDD (contiguous)). In March 11, 10 more combinations were agreed for 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 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-A 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 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 advanced receivers 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 multi-user 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 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 the transmitter side, Release 8 Transmission Mode 5 has been adopted with few changes as explained in Section VI A 3). At the receiver side, it has been decided to apply an interference aware (IA) receiver that cancel out the multi-user interference [8]. Further, a measurement campaign was carried out to evaluate the performance of the IA receiver.

1) Interference Aware Receiver: To handle the residual multi-user interference, the low-complexity IA receiver proposed in [8] has been designed and investigated in SAMURAI project. The receiver is based 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 ZF or MMSE filters. This low complexity receiver being based on the MF outputs and devoid of any division operation is suitable for implementation in the existing hardware.

The performance-complexity tradeoff of low complexity IA receiver is demonstrated in Figure 1. Conventional Max-Log-MAP receiver, matched filter (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 SNR at BLER=0.01. The complexity of the receivers is evaluated by the number of required real-valued multiplication for getting LLR values in one subcarrier. As it can be seen from Figure 1 the IA receiver outperforms both MR and conventional max log MAP 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. CQI = 4. When the CQI value 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 southwest region of France using Eurecom’s OpenAirInterface testbed (cf. Section VI-A2). The purpose of the measurement campaign was to calculate the modem throughput achievable by an LTE release 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 transmission modes 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 PMIs during that particular subband 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 CDF of the sum throughput for the TMs 1, 2, 5, and 6 with two single antenna UEs present in a system served by a dual antenna 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 user equipment device, such as a handset, raises numerous challenges. Challenges at the base band, challenges at the RF/Front end level. These challenges come in addition to the requirement of supporting additional MIMO modes (in theory up to 8x8 for Release 10), which has two main impacts: the need to implement 8 antennas in a small device providing good decorrelation properties; the need to develop a powerful baseband (and interface!) able to support very high throughput (more than 1Gbit/s for LTE UE category 8).

Depending on the CA scenario (intra or inter band, contiguous or non-contiguous), multiple transceiver architectures could be imagined. In theory, it should be possible to use a single IFFT/IFFT module and a single RF chain to achieve contiguous CA, while providing backward compatibility to the LTE system. An inter and intra band non-contiguous CA case may require multiple FFT/IFFTs followed by a single or multiple RF chain. Typically the choice between single or multiple FFT/IFFTs and RF chain comes down to the comparison of power consumption, cost, size, signal quality and flexibility for the support of different aggregation schemes. In a MIMO scenario additional FFT/IFFTs and RF chains will be needed in combination with different aggregation schemes. At last, in theory, multiple antenna should be also provisioned, assuming that for inter-band CA, a single antenna could not perfectly match in the various bands. In a typical multi-band multi-mode RF front end multiple specific RF front ends are stacked together and commuted alternatively, based on the band/standard in use. Such architectures, although simple, are not optimized in terms of integration and do not allow simultaneous use of different bands. For simultaneous usage
of multiple bands, the state-of-the-art approach consists in aggregating multiple RF Integrated Circuits (RFIC) or RF front-ends.

Because of these challenges, and mainly due to operator traction, the trend in carrier aggregation moved from intraband towards inter-band. Actually, intra-band was mostly used to increase the communication bandwidth to reach high data rate while inter-band is seen by most operators as a tool to optimize their fragmented spectrum. As a result, the current traction in carrier aggregation goes towards inter-band CA, with limited number of component carriers, e.g., 2 in downlink and finally no CA in uplink because of terminal constraints.

B. Multi layer and Network Impact

For backwards comparability reason, in 3GPP LTE it has been decided to build the CA in LTE-A based on the existing LTE Release 8 structures. This means each CC has have an independent layer 1 transmission including the Hybrid automatic repeat request (HARQ) and Link Adaptation (LA) functionalities according to LTE-Release 8 assumptions [10]. The layer 2 packet scheduling, which consists of time domain (TD) packet scheduling and frequency packet (FD) 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, signalling overhead, UEs’ states as well as traffic load conditions [11]. 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 [11],[10].

The use of CA can be extended beyond the typical spectrum aggregation described above. In the future LTE Release 11 it is already envisioned to employ CA transmission schemes for another purpose as well: enhanced inter-cell interference coordination (eICIC) [12],[13]. 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 time-domain (TD) eICIC transmission modes standardized already in LTE-A. One typical application for the CA-based eICIC scheme is in large-scale small node deployments, such as Femto eNB or Home 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) [14]. Section VI-B describes the SAMURAI ACCS demonstrator platform 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 of the planned demonstrations in SAMURAI, one for MU-MIMO and one for CA.

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: OpenAirInterface is an experimental real-time, open-source hardware and software platform for experimentation in signal processing and wireless networks. OpenAirInterface features an open-source implementation of and LTE Rel. 8 software modem for UE and eNB [15], [16], [17]. 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 OpenAirInterface there are two different hardware modules available: CardBus MIMO 1 (CBMIMO1) and it Express
In order to demonstrate the potential gain and the feasibility of the ACCS algorithms, a specific C++ software platform has been developed within the SAMURAI project.

Figure 4. 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 RSRPs. Finally the OTAC control channel will be emulated through WiFi and a demo server that will properly route the received packets.

### 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 Proof-of-Concept (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 4 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 onboard FPGA. All the waveform-specific processing like modulation and demodulation are performed in software on the host computer.

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A third platform, Express MIMO 2, is under development. The CBMIMO1 board (see Fig. 3) comprises two time-division duplex (TDD) radio frequency (RF) chains operating at 1,901-1,920 GHz with 5 MHz channels and 21 dBm transmit power per antenna for an orthogonal frequency division modulated (OFDM) waveform (EURECOM has a frequency allocation for experimentation around its premises in Sophia Antipolis). Express MIMO (see Fig. 3) is a baseband processing board, which provides significantly more processing power and bandwidth than CBMIMO1. It has to be connected to an external RF frontend. Also shown in Fig. 3 are the UE antennas and the BS 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. For outdoor experiments 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 adoptions 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 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 precoding was performed according to the latest PMI report on PUSCH and thus allowing for a finer granularity of PMIs.

Both of these adjustments can be seen as an intermediate step towards LTE-Advanced. In LTE-A, a new transmission mode 9 has been defined that basically allows the two adjustments described above. However, LTE-A TM9 uses UE-specific demodulation reference symbols (DM-RS) and thus different to the original MU-MIMO scheme in LTE Rel. 8.

The finer granularity of PMIs (sub-band PMIs) now allow 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 opposite PMI in that sub-band (orthogonal PMIs). 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

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In order to demonstrate the potential gain and the feasibility of the ACCS algorithms, a specific C++ software platform has been developed within the SAMURAI project:
the Application-oriented Software on General-purpose processors for Advanced Radio Development (ASGARD) [18]. 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, RRM, 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 telecom 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 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 autonomy of the system within the selection of the BCC. The dynamic activation of the SCC 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 (HetNet) 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 [19].

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 Carrier Aggregation 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. [Anything more to add about T&M? I think we should.] 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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