Spectrum Aggregation: initial outcomes from SAMURAI project

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Abstract: Multi-user MIMO and Spectrum Aggregation (also referred to Carrier Aggregation) are two key enablers of next generation wireless systems. Although those techniques were already quite well investigated at theoretical level, their practical implementation is not immediate and raises numerous challenges. The SAMURAI project aims at investigating such challenges as well as at providing realistic performance results. This paper presents first outcomes of the project, with a specific focus of Carrier Aggregation (CA). Two aspects are discussed: CA at PHY/RF level with implementation challenges. Then, the system aspect of CA, providing new flexibility in terms of radio resource management is investigated. System simulations show capacity improvement when CA is enabled. SAMURAI outcomes in the MU-MIMO aspects are reported in a companion paper [9].

Keywords: 4G, Carrier Aggregation, LTE-Advanced, system simulation.

1. Introduction

The last decade has witnessed a huge growth in the number of mobile subscribers all over the world. Since its early introduction in the 90's, users of GSM (Global System for Mobile communications) and its evolutions represent today more than 4.3 billion subscribers according to [2]. In parallel, driven by Internet success, data communication shows a tremendous growth. Convergence between those two trends leads to the emergence of new systems and devices to enable broadband wireless communications. The recent market success of devices at the border of communication and multimedia such as smart phones or tablets 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.

Nowadays, after several evolutions of mobile systems standards and general adoption of data services, the requirements expressed for the next generation broadband wireless services are even more challenging. For instance, the International Telecommunication Union (ITU), in the framework of IMT-Advanced (International Mobile Telecommunications – Advanced) systems has defined a downlink target of 1Gbit/s for low mobility and 100Mbit/s for high mobility for mobile wireless communication scenarios [3]. Similar requirements have been expressed by the Next Generation Mobile Network (NGMN) association, regrouping leading operators [4].

One way to reach these requirements of higher data rates and system efficiency is by increasing the bandwidth used for the transmission. However, the spectrum is a scarce resource and large chunks of frequencies are unavailable to one single operator. Therefore, spectrum aggregation represents an opportunity to overcome this limitation. It consists in putting together several (non-contiguous) frequency channels to benefit from a larger bandwidth for a single communication. While conceptually simple, this idea brings significant system and user equipment technical challenges.

Data rates can also be increased by improving the spectral efficiency. This can be achieved using multiple antennas at the transmitter and/or the receiver. Single-user multiple-input multiple-output (SU-MIMO) systems have proved their potential and are included in several standards, such as WiFi, WiMAX and 3GPP LTE. Multi-user MIMO (MU-MIMO) has been proposed to bring these gains also on a system level. Although much research has been done, practical implementations are still unavailable.

The goal of EU FP7 SAMURAI project is to investigate those two key enablers of 4G systems: spectrum or carrier aggregation (CA) as well as MU-MIMO. However, a specific attention is given in the project to practical realizations, to assess the impact of those techniques in realistic context[1].

This paper presents the first outcomes of the project with a specific focus on carrier aggregation. Project outcomes relative to MU-MIMO are reported in [9]. The paper is organized as follows: Section II presents the challenges of CA at low layer (PHY/RF) while system level performance assessments of CA are presented in Section 3.

2. Carrier aggregation in next generation wireless systems

As introduced in the previous section, one way to increase data rate is to use higher bandwidth. Because of the regulatory aspect of spectrum allocation all over the world, it is not obvious to increase the overall available spectrum and to identify a single (large) band that could be available everywhere across the globe. Another approach, promoted by ITU-R, IEEE and 3GPP is to do spectrum (or carrier) aggregation. Carrier aggregation consists in aggregating several (and possibly) fragmented bands to yield to a (virtual) single larger band. Two scenarios are possible: aggregation of contiguous bands and aggregation of non-contiguous bands. The non-contiguous approach may provide larger flexibility as well as diversity but on the other hand is more difficult to achieve in integrated devices.

The carrier aggregation feature definitely requires changes in the transceiver parts of the equipment (to enable the simultaneous usage of multiple bands) but requires in addition modifications at the upper layers. Indeed, the possibility to benefit from CA increases the freedom and the complexity in the radio resource management strategy. In a context where the eNodeB has the capability to autonomously manage radio resource allocation, novel approaches to benefit from CA feature must be defined. As a result, CA could be investigated at least from these two perspectives: at the lower layer to solve implementation issues and at the upper layers to derive advanced resource management schemes to fully benefit from the additional degree of freedom provided.

In the following, we refer to the 3GPP standardization bodies, although both 3GPP and IEEE 802.16 (WiMAX) has defined CA schemes. The first release of LTE (Release 8) does not include CA support. CA comes with Release 10, for which the first specification will be available at the end of 2010. In theory, CA could yield to a maximum bandwidth of 100 MHz, thanks to aggregating up to 5 Component Carriers (CC) (in LTE Rel. 8, the

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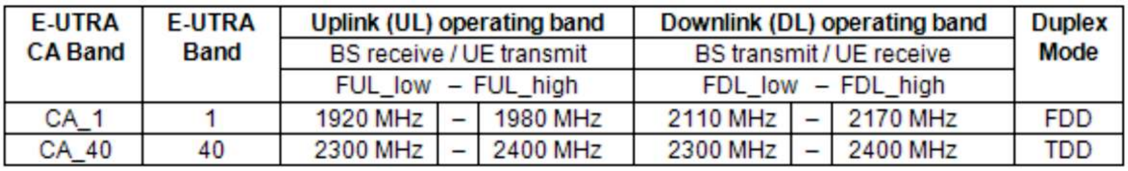
[1] SAMURAI stands for: Spectrum Aggregation and Multi-User MIMO: Real-World Impact

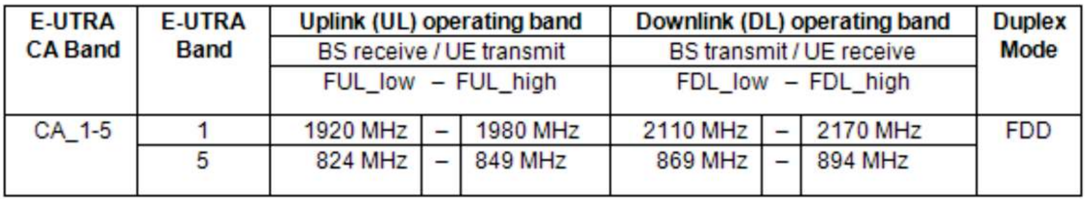
maximum bandwidth is 20 MHz). However, in the current state of the Rel.10 standard, only two CC are contemplated, yielding to a maximum bandwidth of 40 MHz. Moreover, when looking to available bands for CA, it is expected that lower bandwidth will be considered in practice due to the spectrum availability in the operators. At last, CA schemes must ensure backward compatibility with equipments (terminal) which would be only Rel. 8 compliant. In other words, the system enables CA only for terminals which can support CA. For that purpose, new terminal categories are being defined.

The Figure 1 and Figure 2 extracted from [7] show respectively the band which are seen in the standardization as the most likely bands where CA could happen.



E-UTRA CA Band	E-UTRA Band	Uplink (UL) operating band			Downlink (DL) operating band			Duplex Mode
		BS receive / UE transmit			BS transmit / UE receive			
		FUL_low	–	FUL_high	FDL_low	–	FDL_high	
CA_1	1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
CA_40	40	2300 MHz	–	2400 MHz	2300 MHz	–	2400 MHz	TDD

Figure 1: Intra-band candidate carriers for carrier aggregation



E-UTRA CA Band	E-UTRA Band	Uplink (UL) operating band			Downlink (DL) operating band			Duplex Mode
		BS receive / UE transmit			BS transmit / UE receive			
		FUL_low	–	FUL_high	FDL_low	–	FDL_high	
CA_1-5	1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
	5	824 MHz	–	849 MHz	869 MHz	–	894 MHz	

Figure 2: Inter-band candidate carriers for carrier aggregation

To enable in practice CA, various specifications are being updated, from the PHY layer up to the RRC (from [7])

3. Challenge at RF/PHY layer

Depending on the CA scenario (intra or inter band, contiguous or non-contiguous), multiple transceiver architectures could be imagined.

3.1 RF front-end design

In theory, it should be possible to use a single IFFT/FFT 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, as depicted in Figure 3, 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.

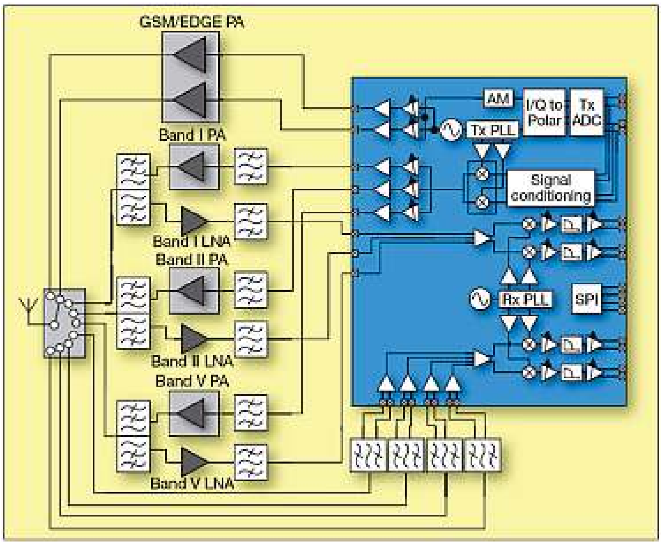


Figure 3: A typical multi-band multimode RF front end [www.rfdesign.com].

3.2 Base-band processing.

As just discussed, the base-band processing should include multiple FFT/IFFT for processing the multiple CC. The additional load due to this processing will have a direct impact on the power consumption of the chipset, but almost negligible compared to the power consumption originated by getting various RF front-ends.

Moreover, additional signal processing should be defined to mitigate the specific aspect due to CA. Let us imagine for instance a contiguous CA case as illustrated by Figure 4, where two carriers are aggregated (with possibly nulling the guard bands in between the two CC to benefit from additional data carriers). It can be imagined that the two carriers are not perfectly synchronized (in time or in frequency), which breaks the orthogonality of an OFDM signal. As such, a single FFT to process the two CC should be adapted to take into consideration the possible time-frequency misalignments. In the following, we focus on intra-band contiguous CA case.

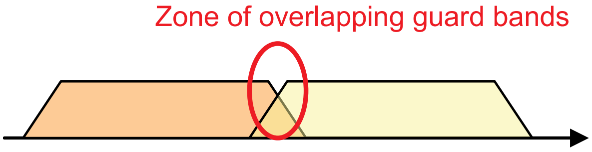


Figure 4: Contiguous carrier aggregation case

Moreover, in-between the two CC, some spurious noise may appear, for instance originated from interferer already present in the spectrum, or from transmitter or receiver imperfection. Such interfering noise impacts definitely the performance as illustrated in the Figure 5 and mitigation methods in the base-band processing must be defined.

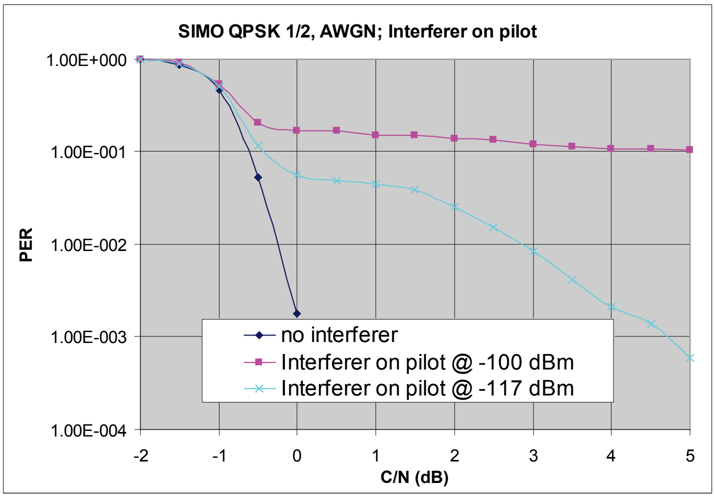


Figure 5: Effect of spurious interferer in an intra-band contiguous case

In Figure 5, a 2x 5 MHz CC is considered, with a spurious interferer affecting the pilots. Even with low power (relatively speaking to the considered signal), the impact of such interferer could be dramatic. Definitely, with interfered pilots, the channel estimation goes wrong and affects all the nearby data.

4. Challenge at MAC layer

As mentioned before, CA beings an additional degree of freedom in the radio resource management functionalities. Indeed, the eNodeB has the flexibility to schedule users in time/frequency manner but as well on various CC. This flexibility eases load balancing strategies or gives the possibility to better manage quality of service requirements. To illustrate the gain provided by CA, system level simulations were conducted. The reference results of CA of 1x2 SIMO system with full buffer load, full inter-cell interference were presented in [5]. It has been shown that the average throughput of the UEs in the system with 100% LTE-Advanced UEs population is only slightly better than that of the system with 100% LTE-Release 8 population. The marginal improvement results from the assumption of full buffer load and fixed number of UEs in the systems as well as the limitation in utilizing the spatial diversity and spatial multiplexing gain of the SIMO system.

We analyse the performance of rank-adaptive 2x2 MIMO transmission mode in full buffer and bursty traffic load. The scenarios and major assumptions used in the simulations are described in Table 1. There are 10 UEs per cell and the assignment of CC to LTE-Release 8 UEs was done in a round robin manner. It should be noted that it is quite important for system performance evaluation in MIMO cases to have good modelling of the CQI/PMI/RI reporting, which drives the selection of MIMO modes and influence the performance. In the case of CA, CQI/PMI/RI must be reported for the various CC, which increases the overhead. SAMURAI project has also investigated feedback compression schemes to improve the feedback efficiency in context of CA (see [8]).

Table 1: Summary of main system parameters for simulation

Parameters	Setting/Value
Test Scenario	3GPP Macro cell case 1 [6], Full buffer traffic load: 19 sites, full inter-cell interference and fixed number of UE per cell Bursty traffic load: 7 sites, 21 cells with wrap around and only interferences from active cells are considered
Carrier frequency	2 GHz
Carrier aggregation configuration	2x20 MHz, 4x10 MHz, contiguous CCs
CQI group size	1 CQI per 6 PRBs (system bandwidth dependent setting will be considered)
CQI Estimation error	Log normal with 1 dB std
CQI reporting resolution	4 bits
CQI, PMI reporting delay	5 TTIs
CQI, PMI reporting period	2 TTIs
PMI/RI group size	As set for CQI group size
PMI/RI feedback error model	None
Time domain packet scheduling	Round Robin (of all active UEs in the cell)
Frequency packet scheduling	Proportional fair across all CCs for LTE-Advanced UEs
1st transmission BLER target	20% (baseline 3GPP LTE evaluation)
Traffic type	Full load and Bursty traffic
Link-to-system interface (link layer abstraction)	Based on EESM; wideband SISO links in TU20 fading channel; includes CRS-based channel estimation errors; minimum of 25 MCS levels

Figure 6 shows the average cell throughput of CA system with different CC settings and UEs populations. LTE-Advanced system (100% LTE-Advanced UEs) performs better than LTE-Release 8 system (100% LTE-Release 8 UEs) by 8% and 23% with the 2x20 MHz and 4x10 MHz CC settings respectively. The Proportional Fair Time-Frequency Scheduler (FDPS) gain mechanism is the main reason for the performance enhancement of the LTE-Advanced system over LTE-Release 8 system. In average the number of UEs in LTE-Advanced system is *N* times (*N* is the number of CC) higher than that in LTE-Release 8 system. Therefore, higher FDPS gain can be obtained in LTE-Advanced system than in LTE-Release 8 system as a result. It should be noted here that the gain we observed here holds only for low number of UEs in the system. Once the number of LTE-Release 8 UE per CC is larger than a certain threshold, this gain becomes diminished. The higher gain in average throughput of 23% in 4x10 MHz CC is due to the fact that the LTE-Advanced UEs are assigned to 4 times larger bandwidth that LTE-Release 8 UEs meanwhile this number is only 2 for 2x20 MHz setting. As expected, there is not much difference in the average cell throughput between LTE-Release 8 system and LTE-Advanced system.

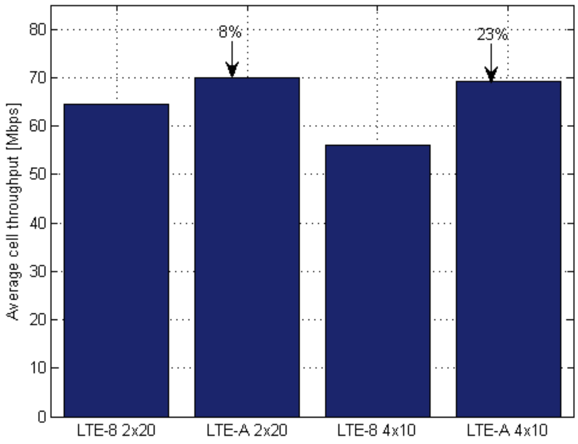


Figure 6: Average cell throughput of SA system with various CC configuration and UE populations under full buffer traffic load conditions.

Figure 7 shows the distribution of the user goodput for different CC settings and UEs types. Both the 2x20 MHz and the 4x10 MHz setting give the same user goodput performance as we expected from the average cell throughput results. It is observed for a full buffer traffic there is almost no difference in the 95%-ile (peak) user goodput between LTE-Advanced and LTE-Release 8 UEs. However, being able to operate on all CCs it is possible to obtaine a very high gain in the median and the 5%-ile (cell-edge) user goodput. The gain is dependent on the CC settings. The highest gains are observed in 4x10 Mhz settings with 40% and 27% in the median and cell-edge user goodput respectively. These numbers for 2x20 MHz setting are 17% and 15%.

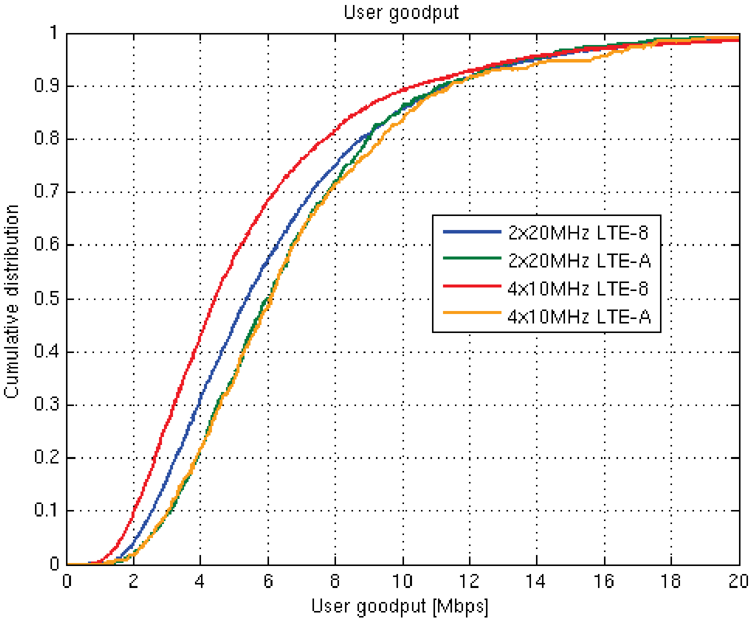


Figure 7: Distributions of the user goodput for different SA setting and UEs types under full buffer traffic load conditions.

It is expected that the performance of the SA LTE-Advanced system in a bursty traffic will be significantly better than that of the LTE-Release 8 system especially at very low load traffic. Here, we only show the results for 2x20 MHz setting as the system with 4x10 MHz setting show the same behaviours and trends in the results.

In Figure 8 we show the goodput experienced from the UEs vs the traffic load. The 5%-tile (cell-edge), average and 95%-tile (peak) user goodputs are shown on the same figure. Almost two fold improvement in the user throughput between LTE-Advanced and LTE-Release 8 UE can be obtained at low offered load. The gain in the experienced goodput of LTE-Advanced UEs over that of LTE-Release 8 UE gradually reduces as the offered load increases. This behaviour can be explained as follows. At low load, the bandwidth available for LTE-Advanced UEs is *N* times higher that of LTE-Release 8 UEs. Having more bandwidth to transmit the data, LTE-Advanced UEs outperform LTE-Release 8 UEs in the experienced data rate. This can also happen at higher traffic load although the chance for an UE being simultaneously scheduled on *N* CCs gradually becomes lower. On top of that as the number of UEs increases with the offered load, more UEs are multiplexed over a fixed amount of bandwidth. At a highly loaded cell, the performance difference between a system with all UEs activate in all *N* CCs and a system with UE restricted to a single CC becomes negligible.

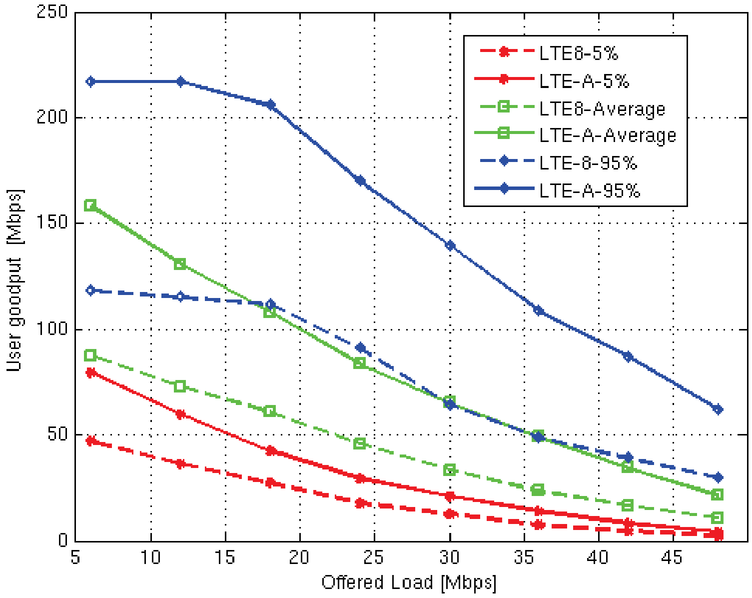


Figure 8: Data rate experienced at the LTE-Release 8 and LTE-Advanced UEs in different traffic load conditions.

5. Conclusion

In this paper, the main challenges of carrier aggregation for next generation mobile systems were presented. They could be sorted into 2 main categories: challenges at low layer, mainly RF and PHY layer, with respect to practical implementation; challenges at upper layers, in terms of additional complexity in the radio resource management to handle the possibility to allocate multiple component carriers.

As an initial case, contiguous carrier aggregation was first envisaged for the PHY/RF investigation and we have shown that beyond the design challenges, signal processing must be adapted to cope with CA, for instance to mitigate spurious noise that could be inherited by the use of CA.

At system level, the downlink performance of intra-band CA transmission with rank-adaptive 2x2 MIMO has been studied. The 2x20 MHz and 4x10 MHz CC settings in combination with full buffer and bursty traffic load assumptions have been used. To illustrate the advantage of CA we have simulated the systems with 100% LTE-Release 8 UEs and 100% LTE-Advanced UEs.

The results showed that for the full buffer traffic load, LTE-Advanced UE can provide up to 23% average cell throughput increase compared to the performance with LTE Release 8 UE only. The gain in user the UE throughput is dependent on the CC settings and the highest gains are observed in the 4x10 MHz setting with 40% and 27% in the median and cell-edge UE goodput respectively. For a more realistic traffic condition with finite buffer load, it has been shown that the performance gains of CA system over a single component carrier vary according to the load condition. At low load, the average goodput of the UEs in a CA system can be *N* times (*N* is the number of aggregated CCs) higher that of the UEs in a traditional single component carrier. The gain of the CA system gradually degrades from low to medium cell load conditions. At very high loaded cell the gain of the CA system becomes negligible.

Acknowledgement

The authors would like to acknowledge the support of the European Commission through the FP7 project SAMURAI [1]

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