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On the Impact of Explicit Uplink Information on Autonomous Component Carrier Selection for LTE-A Femtocells

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Abstract— **The increasing popularity of the femtocell concept has revamped the interest in dynamic interference coordination techniques for dense and uncoordinated deployments of low-power home base stations. One of the proposed schemes for 4G OFDMA femtocells is known as Autonomous Component Carrier Selection (ACCS). ACCS capitalizes on the carrier aggregation framework of LTE-Advanced to curb inter-cell interference levels. Albeit being exclusively based on downlink information, previous contributions attested the effectiveness of the scheme in the uplink as well. This paper extends the initial argumentation by including uplink information into the component carrier selection process. We assess and discuss the uplink performance of two proposed variants of ACCS via extensive system level simulations. The striking conclusion based on the results is that the mere addition of uplink information, which is difficult to estimate in the real world, does not provide substantial performance improvements.**

Index Terms-**Autonomous Component Carrier Selection, Uplink, Femtocells, LTE-Advanced**

I. INTRODUCTION

The enticing idea of cost-effective user-deployed low-power base stations operating in licensed spectrum is currently drawing a lot of interest due to the potential benefits that it offers to operators and end-users [1], [2]. For the user equipment (UE), these low-power base stations using an IP-based wireline backhaul, known as "femtocells" or home eNBs in LTE-Advanced terminology, will appear as normal eNBs.

LTE-Advanced, an evolved version of UTRAN Long Term Evolution (LTE), is being standardized by 3GPP seeking to fulfill the targets defined in [3] and [4]. One of its distinguishing features is carrier aggregation (CA). Carrier aggregation opens the possibility for a dynamical configuration of the system bandwidth and facilitates simple yet effective frequency domain interference coordination schemes. Moreover, several contributions in the literature [5] have highlighted the fact that unlike traditionally planned macro and micro cell deployments; the uncoordinated and potentially chaotic deployment scenario of femtocells calls for some form of interference management.

Several interference coordination schemes for such cases have been proposed [6]. One of the candidate schemes for LTE-Advanced is called Autonomous Component Carrier Selection (ACCS) [7]. Previous contributions presented in-depth ACCS performance results corroborating its usefulness.

Nonetheless, in order to limit the inter-cell signaling overhead the original ACCS algorithm does not employ actual uplink (UL) measurements; instead it infers the UL conditions based on the exchanged downlink (DL) measurements. In this paper, the statistical validity of such approximation is addressed. A second contribution is the evaluation of the potential uplink performance improvement resulting from the utilization of actual UL information. Two enhancements to the original ACCS algorithm are proposed and compared to the original solution.

The rest of this paper is organized as follows: Section II briefly summarizes the basic ideas behind ACCS and describes the proposed variants. Section III introduces the simulation methodology and states our simulation scenario and parameters. In Section IV we present and discuss the obtained results. Finally, Section V recapitulates the main findings and points to future work.

II. SYSTEM MODEL

A. *Original ACCS*

In this section we shortly summarize the basic idea of the ACCS mechanism and henceforth denoted *original ACCS*. The interested reader can find a more comprehensive description in [7], [9]. ACCS is a self-organizing and fully distributed interference management concept on a component carrier (CC) level that avoids the unpractical frequency planning of each and every femtocell.

It is proposed that each home eNB automatically selects one of the CCs as its base or primary carrier (PCC) when the home eNB is powered on [7]. As the offered traffic increases, home eNBs may take more component carriers into use. We call these supplementary component carriers (SCC). However, a cell is only allowed to put SCCs into use as long as this will not cause excessive interference to surrounding cells.

This evaluation relies on so-called background interference matrices (BIMs), which are built by each eNB based on downlink UE Reference Signal Received Power (RSRP) measurements [8]. The BIM information essentially "teaches" each cell about its interference coupling with neighboring cells in terms of carrier to interference ratios (C/I). The BIMs allow cells to estimate the impact of new allocations on surrounding cells, both as victims (*incoming*) and sources (*outgoing*) of interference.

ACCS uses the four following differences [9] to make reuse decisions for each component carrier *c*. In (1)-(4) $(C/I)_{SCC}$ stands for the imposed SCC threshold and $(C/I)_{TGT}$ is equal to $(C/I)_{PCC}$ or $(C/I)_{SCC}$ depending on the use given to this component carrier, either base or supplementary, by the corresponding neighbor cell. If only one of these differences is negative for any neighbor cell, the reuse of component carrier *c* is not allowed.

$$Diff_1(c) = (C/I)_{\text{DL incoming}} - (C/I)_{\text{SCC}} \quad (1)$$

$$Diff_2(c) = (C/I)_{\text{DL outgoing}} - (C/I)_{\text{TGT}} \quad (2)$$

$$Diff_3(c) = (C/I)_{\text{DL outgoing}} - (C/I)_{\text{SCC}} \quad (3)$$

$$Diff_4(c) = (C/I)_{\text{DL incoming}} - (C/I)_{\text{TGT}} \quad (4)$$

Equations (1) and (2) handle the DL allocation while (3) and (4) deal with the UL part. It is important to notice that both UL estimations are approximations relying on DL information due to channel reciprocity. In other words, UL C/I estimates use inaccurate but correlated information from the DL because incoming/outgoing DL interference propagates through the same path as the outgoing/incoming UL interference.

This is illustrated in Fig.1, where CELL 1 is used as the reference cell: signal power (C) and interference power (I) contributions for worst case C/I values are shown, taking into account each possible direction (DL incoming, DL outgoing, UL incoming and UL outgoing). Focusing on DL outgoing interference, it can be seen that UE #1 of CELL 2 is potentially the most interfered one. It turns out that the same UE is (potentially) creating the strongest interference towards the home eNB in CELL 1. Simply put, strongly interfered UEs in the DL are likely sources of severe UL interference.

Notwithstanding, relying on channel reciprocity can in principle lead to errors as discussed next, because the desired signal factor (C) is obviously independent since the interfering UEs are in different cells.

B. ACCS with actual UL

A potential problem in the original ACCS concept discussed above is the fact that UL C/I condition of e.g. UE #1 of CELL 1 and UE #3 of CELL 2 in Fig.1 are disregarded during the decision process as the downlink-based BIM entries do not contain information related to them. Referring to our example in Fig. 1 again, it can be seen that by construction the DL incoming worst case BIM entry is determined by only one UE (UE #3 of CELL 1) while the DL outgoing entry is given by (UE #1 of CELL 2).

Unfortunately, it is not straightforward to build BIMs based on UL measurements directly. The home eNBs can only measure the *total aggregate* interference power; thus identifying interference contributions of UEs from neighboring cells one-by-one – required for outgoing interference estimation – may be neither feasible nor desirable.

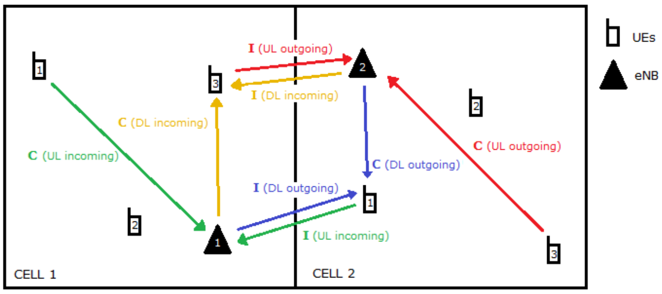


Figure 1. Simplified scenario illustrating how worst case DL and UL C/I values are estimated.

Nonetheless, some techniques to improve the concept can be devised. In principle, it is possible to avoid the need for actual interference measurements in the UL at the expense of additional inter-cell signaling but with no additional burden put on the UE side when compared to the original scheme. Cells could exchange interference DL path loss information as in [13]. The problem is that instead of a single C/I ratio, now two path loss values per UE must be signaled, which implies a signaling overhead of at least 100% for the simplest single UE per HeNB case. Yet, under the idealistic assumption of equal power spectral density (PSD), if these two pieces of information are combined, the cell can produce more accurate estimation of the UL C/I ratios. In our example, CELL 2 would report to CELL 1 the path loss (blue I arrow) measured by UE #1. In turn, CELL 1 would combine this information with the knowledge of its path loss towards its served UE #1 (green C arrow). In a similar fashion UL outgoing C/I values can be calculated. This leads to a variant of ACCS that takes advantage of actual UL information. We shall refer to it as *ACCS with actual UL* throughout the rest of this paper.

C. Decoupled ACCS

Another feature of original ACCS is that the CC allocations in the DL/UL are coupled i.e. the same CCs are always used for DL and UL in TDD (paired if FDD is used). This precludes asymmetric allocations and hinders reuse in one direction, e.g. DL, where C/I conditions might be favorable, due to unfavorable conditions in the other direction, e.g. UL. In possession of actual and independent information for both directions, a natural extension is to try and circumvent the symmetry restriction, by decoupling DL/UL decisions, so that component carriers used in the DL can differ from those used in the UL. This variant will be called *decoupled ACCS.*

III. SIMULATION METHODOLOGY

A. Simulation Tool

The performance was evaluated through semi-static system level simulations. The simulator is based on basic LTE specifications [10]. It relies on series of "snapshots". During each snapshot, path loss, shadowing and the location of devices remain constant. Several snapshots are simulated to ensure statistical reliability.

We consider a full buffer traffic model and a 2x2 antenna configuration for all links allowing up to two code words. A simple equal resource sharing packet scheduling algorithm is assumed.

Path loss and log-normal shadowing are considered, but fast fading is not explicitly simulated. Therefore, the results can be viewed as the performance averaged over a sufficiently long time period. For any given UE, the signal to interference and noise ratio (SINR) is calculated in accordance to the UE's specific conditions. Error vector magnitude (EVM) modeling was introduced in order to account for various imperfections, such as IQ imbalance, in the implementation of Radio Frequency (RF) components.

Look-up tables map the SINR to corresponding throughput values according to a modified Shannon's formula from [11]. Implicitly this entails ideal link as well as single-/multi-stream adaptation along with hybrid automatic repeat-request (HARQ). The raw spectrum efficiency is limited to 10.8 bps/Hz. We summarize the most important parameters in Table I.

TABLE I. SIMULATION PARAMETERS

System Model		
Spectrum Allocation	5 CCs of 20 MHz each	
UE parameters	Max. TX power	23 dBm
	Antenna system	Omni (0dBi)
		UL: SC-FDMA
Duplexing scheme	TDD	DL: 50%
		UL: 50%
Propagation Model		
Minimum coupling loss	45 dB	
Shadowing std. deviation	LOS	3 dB
	NLOS	Light Wall: 6 dB
		Heavy Wall: 8 dB
Scenario Model [3]		
Home	Room size	5m x 5m
	Internal walls	5 dB attenuation
	External walls	10 dB attenuation
	eNB position	Randomized
Traffic Model		
User location	Random: 2 users/cell	
Data generation	Full buffer	

B. Deployment Scenario

Our simulations assume an indoor residential scenario, known as regular home scenario [12], consisting of 4 apartments with dimensions 10x10 m., with 4 rooms of 5x5 m. per apartment. It is assumed a single floor with one home eNB per apartment. Both home eNBs and UEs are dropped uniformly at random positions. All users are located indoors with 2 UEs per flat under Closed Subscriber Group (CSG) access mode, i.e. UEs always connected to eNB in the same apartment. A simplified UL power control is considered, which coupled with the round-robin scheduler and a fixed and equal number of users per cell ensure that the aforementioned same PSD assumption remains valid. This assumption has little impact on the general conclusions, because the objective of this paper is to quantify the advantage of having actual uplink information, without attempting to exploit any additional gains stemming from power control.

IV. RESULTS AND ANALYSIS

As stated above, the goal of this section is to assess the impact of actual UL C/I values when included in the algorithm as well as the benefits induced from decoupling DL and UL reuse decisions. To evaluate the former, we start showing the statistical accuracy of the UL estimations based on DL measurements versus the actual UL C/I values. This is represented for the regular home scenario, by means of the scatter plot of Fig. 2.

It is worth mentioning such values were obtained without EVM modeling, in order to better appreciate the accuracy of the estimations without any truncated C/I values. It can be observed that there is indeed a liner correlation between the DL-based C/I estimation and the actual UL C/I. Nonetheless, the observed correlation is only moderate and for a fixed actual UL value estimations can vary over a wide range of C/I values. This result alone could challenge the applicability of the *original ACCS* purely based on DL measurements to the UL. Yet, the next set of results indicate that this concern is not justified.

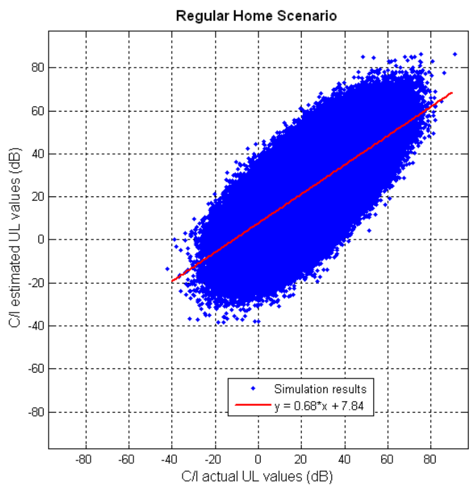
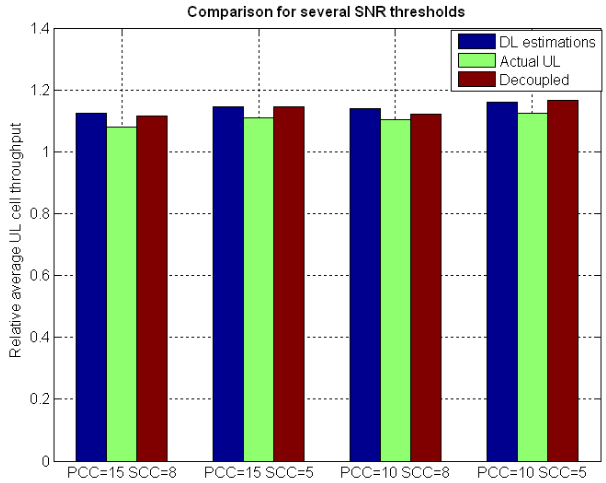
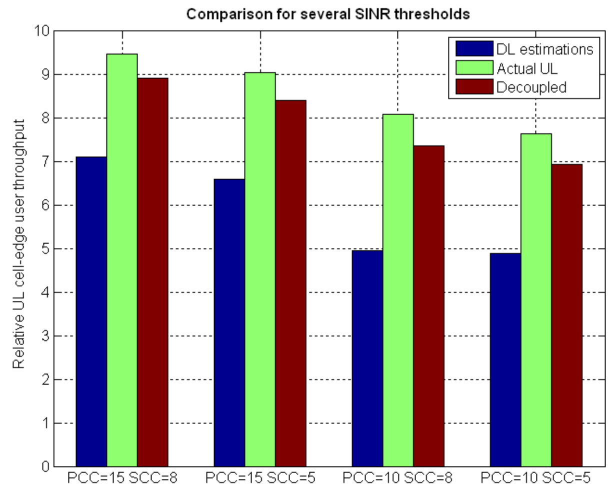


Figure 2. Scatter plot showing the deviation between actual UL C/I values and their corresponding estimations based on DL measurements.



(a)



(b)

Figure 3. Normalized performance (with respect to reuse one) of the three variants of ACCS when several SINR thresholds are used for primary and secondary component carriers. (a) Relative average UL cell throughput. (b) Relative UL cell-edge user throughput.

To compare the three variants of ACCS, two metrics are considered: (i) *average UL cell throughput* and (ii) *UL cell-edge user throughput;* corresponding to the 5% percentile taken from the user throughput Cumulative Distribution Function (CDF).

The results obtained are shown in Fig. 3. Several SINR thresholds for Primary Component Carrier (PCC) and Supplementary Component Carrier (SCC) have been chosen to test the algorithms with different conditions of allowed interference, with higher thresholds leading to a sparser reuse of component carriers. The results are normalized with respect to those obtained for reuse one.

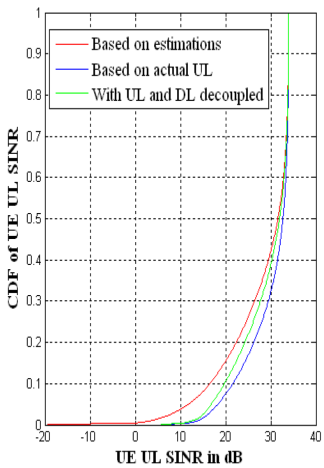
As expected, there is always a balance between average cell throughput and cell-edge user throughput, increasing the former and decreasing the latter as we move toward less restrictive SINR thresholds. Comparing the three algorithms, it is observed that the same trend holds for every pair of thresholds.

The *original ACCS* based on DL estimations suffers a notorious degradation on cell-edge user throughput if very permissive thresholds are used, whereas the average cell throughput is not correspondingly improved. *ACCS with actual UL* has the lowest average cell throughput and the highest cell-edge user throughput, whereas *decoupled ACCS* presents a good balance of both metrics. This behavior is better understood in connection with Fig. 4.

It is shown that UEs experience the highest SINRs with *ACCS with actual UL* whereas the *original ACCS* has the lowest average SINR with a 6 dB gap at the 5^{-th} percentile. On the other hand, in the original version a higher average number of CCs is available for transmission, therefore yielding higher average cell and lower cell-edge user throughputs when compared to the variant based on actual UL information.

In addition, considering the tighter reuse pattern achieved in the DL when compared to the UL in the *ACCS decoupled* variant (see Fig. 4(b)), it can be concluded that the UL is clearly more restrictive than the DL. This can be further verified in Fig. 5, where it is observed that worst case C/I values, i.e. the C/I value experienced by the user with the lowest C/I ratio in the cell, which effectively determines the reuse decisions in ACCS, are usually lower in the UL. It is relevant to stress that the values represented are not actual SINR ratios obtained at the end of the simulations, i.e. considering total interference; rather they are the BIM entries. Nonetheless, we have observed that the mean aggregate interference is not much higher than that caused by the dominant interferer.

The reason for the UL being more restrictive lies in the way worst case C/I values may occur. Referring to Fig. 1 once more and focusing on incoming values, it can be seen that two UEs are always involved (instead of only one in the DL): the strongest potential interferer toward the reference home eNB that is UE #1 of CELL 2, and the served UE with the lowest received signal power, that is UE #1 of CELL 1. This means an additional degree of freedom when estimating UL worst case values, namely the worst C along with the highest I.



(a)

Variant of ACCS	Average number of CCs used	
	DL	UL
Original	2.5	2.5
With actual UL	2.3	2.3
Decoupled	2.7	2.4

(b)

Figure 4. SINR and frequency reuse for the three variants of ACCS. (a) SINR comparison by means of the CDF of UL SINR experienced by users. (b) Comparison of the average number of CCs used by each cell.

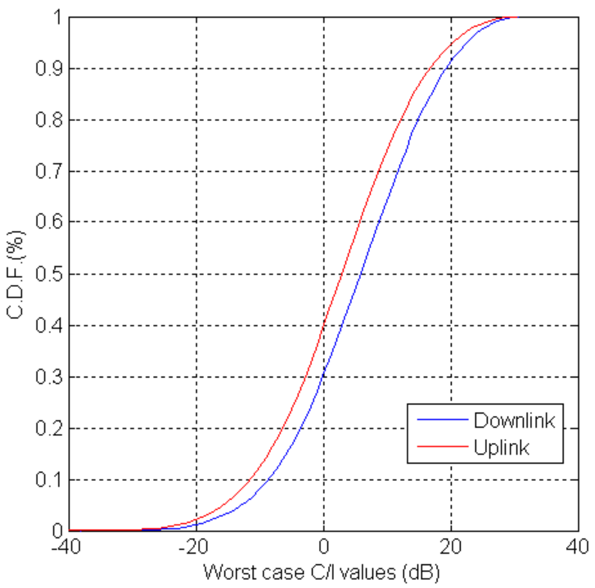


Figure 5. Cumulative distribution function (CDF) of worst case C/I values for DL and UL.

As stated earlier, worst case UL C/I values are usually lower than worst case DL ones leading to a higher probability of having negative differences in (3) and (4), now modified to employ actual UL information in the two proposed variants. This explains why *ACCS with actual UL* is more restrictive than the *original ACCS*[1] as well as the unbalanced CC usage of the *decoupled ACCS*.

Finally, we try to find optimal thresholds for each variant, in the sense that they provide a good balance between average cell throughput and cell-edge user throughput. After an extensive search, the thresholds found for each variant are different, depending on the different restrictiveness of ACCS versions, having obtained the results in Fig. 6.

It can be seen that the three algorithms provide substantial gains in terms of cell-edge user throughput (above 600%) when compared to an unplanned femtocell deployment, i.e. reuse one, while maintaining a slightly superior average cell throughput (10% - 15%). The improvement in average cell throughput is almost the same for the three variants: 1.1, 1.12 and 1.15, respectively. It is also observed that *decoupled ACCS* performs modestly better than the other two variants. This is reasonable if we consider that this version contains two add-ons compared to *original ACCS*: actual UL information and decoupling between DL and UL. Nonetheless, it is observed that the gain introduced at the cost of using UL information is small.

V. Conclusions

Even though DL based C/I estimations are not perfectly accurate representatives of actual UL C/I values, our results demonstrate that the mere addition of UL information does not have a considerable impact on the performance of ACCS. The performance of the unmodified ACCS purely based on correlated DL information is shown to be roughly equal. This leads to the conclusion that eventual performance discrepancies can be roughly compensated by properly setting the SINR thresholds for PCC and SCC. On the other hand, if UL information is incorporated in a clever manner to minimize the associated heavy inter-cell signaling, the decoupling between DL and UL could become much more attractive. For example, UL fractional power control inevitably leads to differences in power spectral densities and hence different UE interference zone radiuses. This fact can be exploited e.g. to facilitate UE specific component carrier configurations. This is suggested as an interesting topic for future work.

[1] Recall that, in its original form, (3) and (4) include DL estimations instead of actual UL values, yielding a lower probability of having negative results.

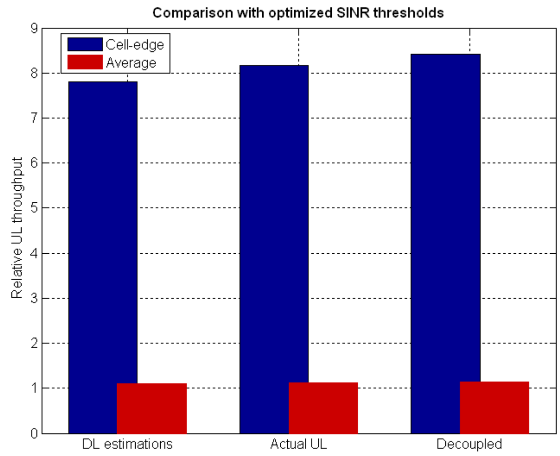


Figure 6. Relative gains in terms of UL cell-edge user throughput and UL average cell throughput (with respect to reuse one) of the three variants of ACCS when optimal SINR thresholds for each variant have been chosen.

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