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Enhanced Uplink Carrier Aggregation for LTE-Advanced Femtocells

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Abstract— In this paper we investigate uplink carrier aggregation in the context of dense residential deployments of LTE-Advanced Femtocells. Previous work in the literature based on macro-cells suggested considering UE power limitations to infer which UEs should be allowed to employ multiple component carriers. However, due to the very small radius of femtocells, UEs are not expected to become power-limited at all. We propose a decentralized scheme with limited signalling requirements that incorporates power control information, not only to guide the UE-specific carrier selection procedure, but also to capitalize on the inherent power spectral density and path loss differences in order to minimize inter-cell interference. We present a series of system level simulation results which provide strong evidence that our scheme delivers substantial gains in terms of coverage compared to existing solutions without sacrificing the SINR.

Index Terms- Femtocells, LTE-Advanced, Uplink, Carrier Aggregation

I. INTRODUCTION

Femtocells and carrier aggregation (CA) are among the most active academic and industrial research topics currently. The so called femtocell, also known as Home eNB (HeNB) within 3GPP, is a low-power indoor base station operating in licensed spectrum using an IP-based wired backhaul. This ingenious concept is likely to be responsible for the new performance leap in terms of improved spectral efficiency per unit area. Nonetheless, the *ad-hoc* nature of femtocell deployments combined with the foreseen closed access mode - only a small set of restricted users can get access - is bound to result in chaotic inter-cell interference if left unchecked.

Carrier aggregation is one of the distinguishing features of upcoming 4G systems, such as LTE-Advanced, currently being standardized by 3GPP as part of LTE Release 10. With CA, it is possible to schedule a user equipment (UE) on multiple component carriers (CCs) simultaneously, each of which may exhibit different loads and radio channel characteristics such as interference levels. It then follows naturally, that CA could be employed as a new and promising instrument of inter-cell interference coordination. Hence, due to the potential synergy, femtocells and CA are often discussed together in the literature.

In [1] the authors identified the key benefits of femtocells, the technological, business challenges and research opportunities. The work in [2] provides an overview of CA in 3GPP LTE-Advanced and highlights that CA is being considered as a tool to mitigate interference by exploiting

cross-carrier scheduling. The authors of [3] evaluate the performance gains that can be achieved by using CA in the uplink (UL) of LTE-Advanced systems by taking the effect of UE power limitations into consideration. The rationale is that the limitation of UE transmission power might affect negatively the gains brought by multiple CCs transmission. The distinction between power-limited and non-power-limited UEs and the subsequent CC and power allocations are based on the path loss to the serving cell. Nonetheless, the evaluation therein is based on macro-cells; while in femtocells with all likelihood UEs will not become power-limited due to the very small cell radius. Consequently, in this context uplink CA decisions should be based on another metric, especially if inter-cell interference mitigation/coordination is taken into consideration.

Several self-organizing interference coordination candidate schemes for femtocells have been proposed in the literature [4]-[6]. One of them, known as Autonomous Component Carrier Selection (ACCS) [5] is a fully distributed interference management concept on a CC level. ACCS relies entirely on downlink (DL) measurements and avoids the unpractical frequency planning of each and every femtocell. In [6] ACCS is modified to employ additional DL and UL information at the expense of heavy inter-cell signaling. The work in [7] attests the efficacy of ACCS in the UL under realistic LTE power control settings. Nonetheless, to the best of our knowledge, the inevitable differences in terms of *power spectral density* (PSD) caused by UL fractional power control (UL FPC) – which leads to UE-specific interference ranges – are not actively exploited in the literature.

In this paper, power control information is incorporated into the carrier selection procedure in order to minimize the additional incurred signaling and to capitalize on PSD variations simultaneously. In its most general formulation, our approach facilitates UE-specific component carrier configurations in femtocells.

The rest of this paper is organized as follows: Section II briefly summarizes the basic ideas behind UL fractional power control, ACCS and describes the proposed method. Section III introduces the simulation methodology and assumptions. In Section IV we present and discuss the results obtained. Finally, Section V recapitulates the main findings and concludes the paper.

II. SYSTEM MODEL

A. Uplink Power Control

Power control is an important issue in UL as the UEs are limited by their maximum transmission power. It also helps to mitigate inter-cell interference and leads to longer battery life. The UL power control in LTE consists of open- and closed loop power control factors. Here, we focus on the former, whose goal is to compensate for path loss and shadowing. Excluding closed-loop and MCS power boosting correction factors, the total UE transmit power, expressed in dBm is given by [8]:

$$P_{tx}^{UE} = \min\{P_{\max}, P_0 + 10 \cdot \log_{10}(M) + \alpha \cdot L_{UE}^s\} \quad (1)$$

,where P_{\max} is the maximum UE transmit power, P_0 is a UE-specific parameter, M is the number of assigned Physical Resource Blocks (PRBs) to a certain user, α is the cell-specific path loss compensation factor and L_{UE}^s is the DL path loss measured by the UE towards its serving HeNB. We highlight the fact that the transmit PSD is independent of M and depends only on the path loss to the serving cells. Yet, the total mobile transmit power will vary as a function of the assigned number PRBs. As a consequence, for any UE pair (i, j) : $\text{PSD}_i \geq \text{PSD}_j \Leftrightarrow L_i^s \geq L_j^s \forall i, j$ provided that (i) P_0 and α are the same and (ii) the UE is not power limited due to the combination of large values of M and L_{UE}^s . For simplicity, we consider that UEs employ the same transmit PSD on all active CCs, according to (1). In other words, all CCs employ the same P_0 and experience equal path losses.

B. Problem Formulation

As discussed previously, the distinction between power- and non-power-limited UEs cannot be used to guide UL CA carrier aggregation decisions in a femtocell context. In principle, ACCS, a self-organizing and fully distributed interference management concept on a component carrier (CC) level [5], can be used to manage DL as well UL cell-centric carrier selection in femtocell deployments. However, despite its attested efficacy in the UL [7], the original ACCS mechanism does not fully explore the possibilities opened by UL FPC; e.g. ACCS does not facilitate UE-specific component carrier configurations. The interested reader can find a comprehensive description of BIMs and ACCS in [5]. Here we restrict ourselves to a brief description of the key elements, namely Background Interference Matrices (BIMs).

BIMs are built locally by each HeNB based exclusively on DL measurements. The *local* BIM information essentially predicts the *incoming* DL carrier to interference ratios (C/I) experienced locally whenever both cells (serving and interferer) use the same CC at the same time with equal transmit PSDs. The $a_{i,j}$ entry of an $M \times N$ matrix, where M is the number of served UEs and N is the number of neighbors that can be detected¹ by the served UEs is given by the ratio

$\{L_i^j / L_i^s, j \neq s\}$ where L_{UE}^s was defined in (1) and L_i^j is the path loss measured by UE_{*i*} towards neighboring HeNB *j*.

In order to curb the control signaling overhead, the assumption in [5] is that this local information is first “fused” and subsequently exchanged among HeNBs. The data fusion in [5] proposes a simple compression of the BIM into a 1 -by- N row vector $\mathbf{b} = [b_1, b_2, \dots, b_N]$ such that b_n is taken as the minimum value of each column of the BIM collected locally, i.e. $b_n = \min(a_{*n})$. Conceptually, this implies that in the context of femtocells, measurements from the UE experiencing the lowest C/I ratio dictate the values that are effectively exchanged. Once information has been exchanged, cells can also estimate their individual contributions as sources of (*outgoing*) interference. Finally, such exchanged values are compared against configurable thresholds whenever a HeNB wishes to deploy additional CCs.

Unfortunately, it is not straightforward to build BIMs based on UL measurements directly; hence in [5], [7] DL information is used to infer the uplink conditions. The difficulty lies in identifying the individual interference contributions of UEs from neighboring cells. A potential solution is presented in [6] where UL specific information is employed. The pitfall in [6] is the heavier inter-cell signaling, because for each neighbor at least two path loss values per UE must be signaled instead of a single C/I ratio per neighbor. That alone implies doubling the signaling requirements for the simplest single UE/cell case. Moreover, the scheme therein also fails to consider the UEs transmit power settings in its estimation of the UL SINR.

It would therefore be desirable to develop an UL-specific scheme that incorporates and extends the information available on BIMs with two goals in mind: (i) Make good use of the different UE interference confines induced by PC and (ii) keep extra signaling requirements as low as possible. Fig.1 helps us visualize the limitations of ordinary BIMs described previously. For simplicity, we consider just two HeNBs {1}-{2} and four UEs (A-D); understanding that the example can be extended to incorporate additional UEs and/or cells.

Taking HeNB{1} as the reference cell, the solid lines show the links (signal in blue and interference in red) used in the determination of the DL incoming BIM, hereafter denoted by $DL_{\{1\} \leftarrow \{2\}}$. The dashed lines show the links involved in the determination of the DL outgoing BIM of cell {1} – gathered, fused and signaled back by HeNB{2} – denoted as $DL_{\{1\} \rightarrow \{2\}}$. In our example, path loss measurements conducted by UEs [B] and [C] account for the exchanged incoming/outgoing information respectively as these are the users experiencing the lowest C/I values in Fig.1.

When it comes to UL carrier selection, the original ACCS makes the two following assumptions:

$$UL_{\{1\} \leftarrow \{2\}} \approx DL_{\{1\} \rightarrow \{2\}} \quad (2)$$

$$UL_{\{1\} \rightarrow \{2\}} \approx DL_{\{1\} \leftarrow \{2\}} \quad (3)$$

In other words, it explicitly assumes that the worst-case UL incoming ($UL_{\{1\} \leftarrow \{2\}}$) carrier to interference ratio is well

¹ Without loss of generality, if a UE cannot detect a certain neighbor, the ratio can be set to an arbitrary high value to

indicate lack of interference coupling between that UE and the respective neighbor.

approximated by the outgoing ratio ($DL_{\{1\} \rightarrow \{2\}}$). Similarly, the worst-case UL outgoing ($UL_{\{1\} \rightarrow \{2\}}$) is approximated by the DL incoming ($DL_{\{1\} \leftarrow \{2\}}$) ratio. This is because the interference paths (red arrows) are the same, just in the opposite direction (channel reciprocity).

Clearly, not all UL desired signals (blue arrows) are being considered; hence the worst-case approximation in e.g. (2) is only valid if the path loss of the “farthest” UE is similar to L_C^2 . As it can be seen, the latter is not verified in Fig.1, because $L_B^1 \gg L_C^2$. This inevitably leads to an optimistically biased UL C/I estimate as seen by [B]. Furthermore, since UEs typically use transmit power control, they will employ different power spectral densities, rendering the estimation even less accurate.

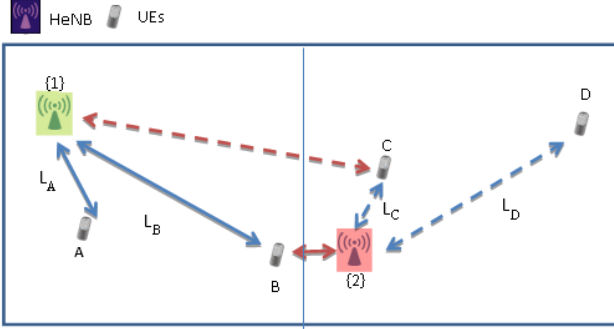


Figure 1: Simplified scenario illustrating how worst case DL and UL C/I values are estimated.

C. Enhanced Uplink Component Carrier Selection Scheme

The proposed scheme addresses the above biasing problem by realizing that downlink interference coupling can be adjusted according to differences in terms of transmit PSD and path loss differences of a small and upper bounded number of UEs to yield better worst-case approximations. Notice that the two values given by (4)-(5) still characterize all UEs and, as such, they provide cell-pair specific values, not UE specific estimations.

$$UL_{\{S\} \leftarrow \{n\}} \approx DL_{\{S\} \rightarrow \{n\}} - \Delta(L_i, L_j) + \Delta(PSD_i, PSD_j) \quad (4)$$

$$UL_{\{S\} \rightarrow \{n\}} \approx DL_{\{S\} \leftarrow \{n\}} + \Delta(L_k, L_l) - \Delta(PSD_k, PSD_l) \quad (5)$$

We resort to Fig.1 in order to exemplify our proposal, assuming that HeNB {1} is performing the evaluation. Therefore, we set $\{S=1\}$ (serving) and $\{n=2\}$ (neighbor) in the formulae above, where $\Delta(x, y) \equiv x - y$.

The first $\Delta(.,.)$ terms in (4) and (5) account for the path loss difference between UEs (i, j) and UEs (k, l) towards their respective serving cells. If the transmit PSDs were identical for all UEs, these terms would suffice to provide correct UL information based on DL inputs.

The PSD $\Delta(.,.)$ factors in (4) and (5) account for the transmit PSD differences between UEs (i, j) and UEs (k, l), respectively. If all UEs had equal path losses towards their serving cells, this factor would again suffice to correct eventual imbalances in terms of transmit power per CC. In general, both corrections are needed and the UEs involved in the estimation are:

- UE (i) is the UE, among the ones served by HeNB {1}, with the largest path loss towards it, in this example UE [B]. This UE is potentially the worst victim of incoming UL interference.
- UE (j) is the UE responsible for cell's {1} $DL_{\{1\} \rightarrow \{2\}}$, i.e. cell's {2} $DL_{\{2\} \leftarrow \{1\}}$. This is the UE served by HeNB {2} that potentially is the worst source of UL interference towards HeNB {1} – in this example UE [C].
- UE (k) in (5) is the one responsible for cell's {1} $DL_{\{1\} \leftarrow \{2\}}$, i.e. the worst source of outgoing uplink interference towards HeNB {2}. In this case, it is UE [B] as well ($k=i$), but this is **not** necessarily always true. Either way, this has no impact in terms of signaling since UEs (i, k) are served by the same evaluating cell.
- Finally, UE (l) is analogous to UE (i), in that, it is the UE with the largest path loss towards its serving cell {2} and hence the worst potential victim of outgoing interference, in our example: UE [D].

The PSD and path loss pieces of information pertaining to UEs (j, l) must be signalled by cell {2} as it can not be known otherwise by cell {1}. However, as explained in *Section II.A*, the PSD values can be easily calculated locally by cell {1} if P_0 and α – which are normally the same for all cells and set a priori by the operator – are known. This limits the burden of additional inter-cell signalling to at most two path loss values irrespective of the number of UEs served by the femtocells.

Once the UL interference coupling is estimated based on the proposed adjustments to the DL information, a more refined decision on whether to take a CC into use can be made.

D. User Specific Uplink Component Carrier Selection

In *Section I*, it was stated that the decision to take a CC into use in a cell may be made on a per-UE basis given the DL BIM corrections presented earlier. This can be done by extending the previous equations to allow for UE-specific CC usage evaluations. The concept enables HeNBs to identify, for each of its served UEs, the set of CCs that can be used given the current CC allocation of the neighboring cells. Subsequently, it would be up to the packet scheduler within the host HeNB to effectively distribute the radio resources of the CCs according to any internal metric.

The merit of this approach is that from the perspective of the HeNB the resulting CC allocation becomes the set union of the allocations of its served UEs as opposed to the set intersection when (4) and (5) are used. Once again let us examine Fig. 1 and realize that UEs [A] and [C] could potentially use the same UL component carriers. While UEs [B] and [D] cannot. We shall revisit this aspect in *Section IV*.

The proposed idea differs from UL channel aware scheduling in that, when HeNB {1} schedules e.g. UE [B], it can take into account the interference this allocation generates towards existing allocations in HeNB {2}. To do so, equations (4) and (5) are extended as follows:

$$UL_{\gamma \leftarrow \{n\}} \approx DL_{\{S\} \rightarrow \{n\}} - \Delta(L_\gamma, L_j) + \Delta(PSD_\gamma, PSD_j) \quad (6)$$

$$UL_{\gamma \rightarrow \{n\}} \approx DL_{\gamma \leftarrow \{n\}} + \Delta(L_\gamma, L_l) - \Delta(PSD_\gamma, PSD_l) \quad (7)$$

Using γ as an index to distinguish individual UEs, then $UL_{\gamma \leftarrow \{n\}}$ and $UL_{\gamma \rightarrow \{n\}}$ represent the conditional UL incoming/outgoing C/I ratios for UE (γ) if it reuses the same component carrier that is currently being used in neighbor cell $\{n\}$ (in this example, cell 2). One distinction between equations (6)-(7) and equations (4)-(5) is the fact that γ -th UE-specific PSD and path loss (towards the host cell) are considered in (6) and the use of $DL_{\gamma \leftarrow \{n\}}$ in equation (7). The latter is the ratio of path gains towards the serving and neighboring $\{n\}$ cells as measured by UE γ .

The UEs (j, l) in (6)-(7) are the same used in (4)-(5) because there is no simple way for one cell (e.g. the host HeNB $\{1\}$) to know whether UE [A] will be interfering with either UE [C] or UE [D] in the other cell, since that depends entirely on the scheduling that is carried out independently by the other cell HeNB $\{2\}$. All the host cell HeNB $\{1\}$ knows is that a certain component carrier is in use in the UL in other cell. Therefore, in order to ensure that most detrimental reuse of resources do not take place, the most severe interferer/interfered UEs are still used in the estimations, i.e. UEs [C] and [D].

III. SIMULATION METHODOLOGY

A. Simulation Tool

We derive our results from a Monte Carlo performance evaluation according to the methodology defined in [10] by 3GPP. The simulation tool is based on basic LTE specifications [9]. It relies on series of “snapshots”. During each snapshot, path loss, shadowing and the location of devices remain constant. Fast fading is not explicitly simulated. 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 (round-robin) packet scheduling algorithm is assumed. Error vector magnitude (EVM) modeling is included (5%), thus SINR is asymptotically limited. The UL received signal and interference at the HeNB are calculated per PRB and assume a maximum UE transmit power of 23dBm. Uplink Fractional Power Control is employed and its parameterization is aligned with the findings in [7], i.e. a high $P_0 = -40$ dBm. Finally, we apply Shannon fitting [11] to calculate the throughput.

B. Deployment Scenario

The simulation scenario and indoor path loss modeling follow that defined in [10]. The scenario consists of two buildings, each with two stripes of apartments, each stripe having 10 apartments per floor in a total of 3 floors, thus totaling 120 apartments. There is a 10m wide street between the two buildings. Both HeNBs and UEs are dropped uniformly at random positions indoors. All users operate under Closed Subscriber Group (CSG) access mode, i.e. UEs cannot connect to HeNB in other apartments. It is assumed that HeNBs are

deployed in 75% of the residences. In the absence of a HeNB, we assume that there are no active UEs in the apartment. Macro-cells are not considered in this study.

IV. RESULTS AND ANALYSIS

The numerical results were obtained as follows. In each snapshot, the deployed HeNBs were activated; one at a time in a random fashion, and a single base component carrier (BCC) had to be selected without any UE-side information. The selection was based on the previous decisions made by other HeNBs as in [5].

The subsequent phase of the simulation iterated over all active HeNBs in a random order and an attempt to select supplementary CCs (SCCs) is carried out. Initially, we assume a single UE/cell, in which case equations (4)-(5) and (6)-(7) are fully equivalent. The estimated SINRs had to be above 20 dB and 8 dB for BCCs and SCCs respectively.

Figure 2 compares the average UL SINR achieved by the original ACCS scheme and the proposed method. The 0% to 10% outage region is highlighted for clarity. The cell-specific path loss compensation factor α was the same in all cells and varied from [0.2, 0.8] in steps of 0.2. It can be seen that the correction is much more relevant for low values of α where the imbalance between DL and UL estimations increases. The behavior can be understood if one realizes that if P_0 is fixed and equal in all cells, then (6) - similarly for (7) - reduces to:

$$UL_{\gamma \leftarrow \{n\}} \approx DL_{\{S\} \rightarrow \{n\}} - \Delta(L_\gamma, L_j) \cdot (1 - \alpha) \quad (8)$$

And although $\alpha=0.2$ is not strictly supported in 3GPP specifications, the importance of corrections would be the same if the errors incurred were e.g. due to different values of P_0 , or radically different path loss distributions, such as those seen in heterogeneous networks.

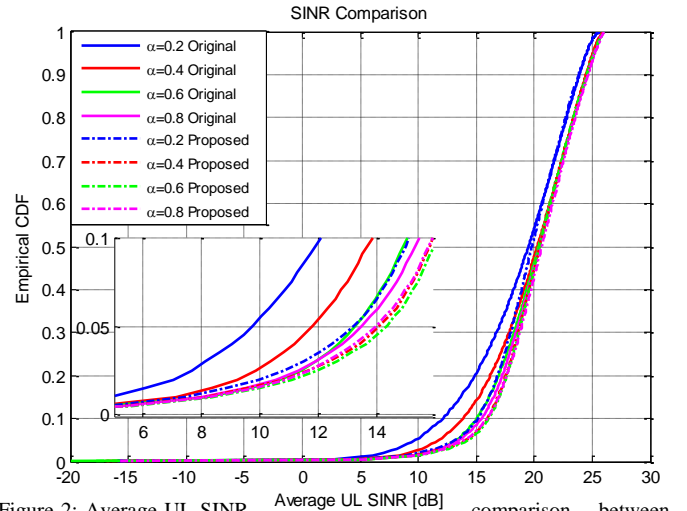


Figure 2: Average UL SINR comparison between the original ACCS and the proposed UL FPC aware method for various values of α .

Fig. 3 complements the SINR information from Fig.2. It can be seen that the share of UEs who have access to at least 2 CCs increases when compared to the original case. That

combined with the SINR improvement led to the significant relative gains in outage throughput seen in Fig.3.

The latter clearly demonstrates the potential of the proposed scheme, especially in terms of UL 5% outage throughput where relative gains of up to 52% are seen with respect to the original non-FPC-aware ACCS concept. Recall that in the latter the C/I estimations are taken from (2)-(3).

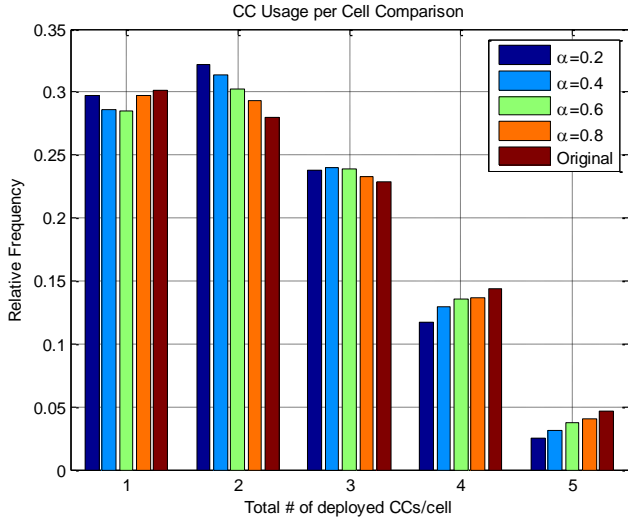


Figure 3: Histogram of the component carrier usage per cell for various values of α as well as the original ACCS concept.

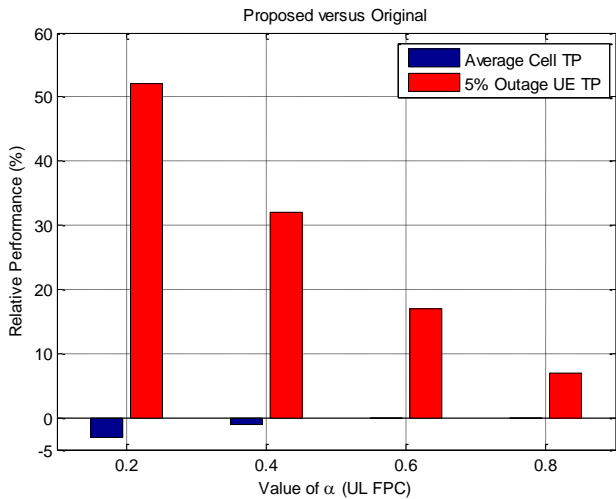


Figure 4: Relative performance comparison between the original ACCS and the proposed UL FPC aware method for various values of α .

Finally, Fig. 5 compares the CC usage when cells serve multiple UEs (3UEs/cell). Since now the effective CC usage *per cell* is the set union of the CC usage of its served UEs, one can see that cells reuse CCs more aggressively when compared to UEs. The differences are expected to be even larger, if the path loss distribution to the serving cell presents high variance. We limit the analysis to the CC distribution, because the effective achieved UE throughputs are heavily dependent on the scheduling decisions, which are beyond the scope of this contribution. For example, the internal packet scheduler could either try to increase fairness among its served UEs or boost the peak and average data rates.

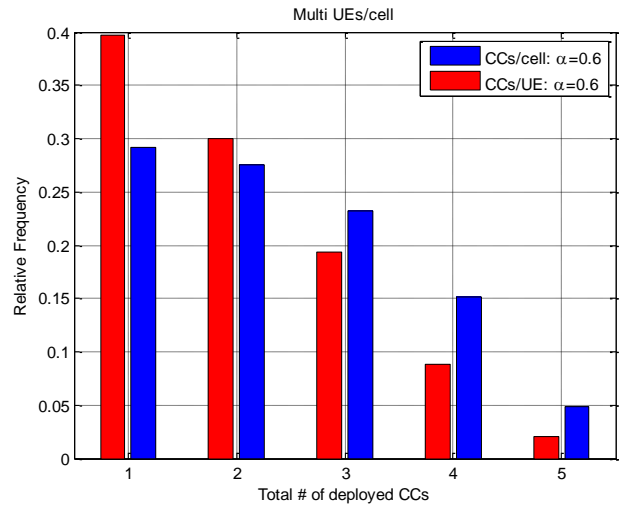


Figure 5: Histograms comparing the component carrier usage per cell and per UE for a fixed value of α .

V. CONCLUSIONS

In this paper we have shown that incorporating limited UL information to the baseline ACCS concept greatly improves the performance, especially in terms of UL coverage. Nonetheless, such improvement comes at the cost of additional signaling. We have proposed a scheme that accounts for inherent power spectral density differences due to fractional power control. On top of the performance improvement, it also facilitates UE-specific component carrier selection in the context of femtocells. Investigations in scenarios with radically different path loss distributions among cells, such as those seen in heterogeneous networks, as well as actively tweaking PC parameters using the proposed framework are suggested for future studies.

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