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*Research Article*

# Performance Study of Uplink and Downlink Splitting in Ultradense Highly Loaded Networks

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This paper provides new insights into the performance of Uplink and Downlink Splitting (UDS) in highly loaded wireless communication systems, in terms of both serving nodes and the number of users with high traffic activity. The study puts special focus on the gains that UDS could bring in terms of SINR and throughput when compared with systems with cell range expansion (CRE) in the classic downlink based cell association. CRE not only helps to offload users from macro- to pico-eNBs, but also improves UL service. Instead of an aggregated throughput analysis, a detailed classification of users is performed to figure out the causes of users' gain or loss after applying each strategy at the system level. Results show marginal gains of a pure path loss based UDS when compared with the intrinsic UL gains of CRE. Given the extra flexibility in radio resource management that splitting both links could bring, using an individual UL adjustable cell offset appears to be an interesting strategy to allow for a finer control of UL interference. The dependency of UDS performance with small cell density has also been a matter of study. Results show that the gains of UDS do decrease after a certain density of pico-cells is surpassed.

## 1. Introduction

In order to keep up with the increasing network traffic, cellular networks are evolving from a single-tier homogeneous network to multi-tier heterogeneous and small cell networks (HetSNets) in which low power nodes offload macrocells and increase the system capacity with an aggressive frequency reuse distance. However, this radio planning paradigm cannot avoid problems, load imbalance and suboptimal uplink (UL) performance being two of the most important ones [1].

Traditional cell selection is based on downlink (DL) Reference Signal Received Power (RSRP). In scenarios where small cells are deployed in a cochannel manner, the service area is prominently reduced by the presence of macrocells since their power is higher than the power of small cells as shown in Figure 1. This means that offloading is poor.

Power imbalance also implies that the best DL serving cell might not be the optimal option for the UL. Users that are closer to the pico-enhanced node-B (eNB) would enjoy a better link budget with this eNB. However, the RSRP DL based criteria implies choosing a macro-eNB anywhere outside the DL small cell serving area.

In order to increase the coverage and load of pico-eNBs, Cell Range Expansion (CRE) is introduced. The idea is to add a cell selection offset to the RSRP of pico-eNBs, thus making them more attractive to UEs. This is a straight forward technique with low impact on the system architecture.

CRE yields a negative downlink Signal to Interference plus Noise Ratio (SINR) in the new expanded areas and so poor peak data rates. In order to palliate this, Long Term Evolution (LTE) Release 10 introduced enhanced mechanisms for Intercell Interference Coordination (eICIC) that allow for SINR enhancement, though at the cost of reducing macrocell capacity. These techniques are mostly variations of the same idea: frame muting and coordinated scheduling [2].

In the context of evolved LTE-Advanced (LTE-A) systems and 5G networks, new architectural designs should go one step further and address the difference in uplink (UL) and

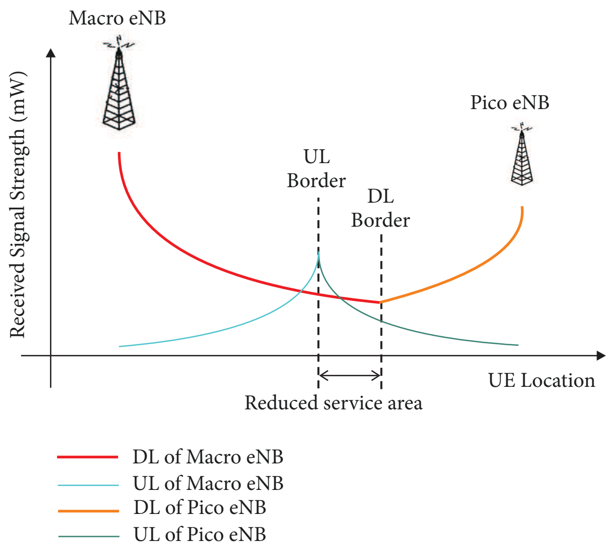


Figure 1: UL/DL imbalance issue in HetSNets deployments.

downlink (DL) cell ranges. One of the enablers for this purpose is dual connectivity. As the name indicates, it allows for a UE establishing 2 connections with 2 different eNBs. This opens the path to break the unity of the classic cell. Thus control and user planes can be managed by different nodes data flows that can be split between LTE and 5G New Radio [3] and also UL and DL can be split [4].

In this context, UL and DL splitting (UDS) has been proposed as an alternative to provide a fully optimized UL performance [5–7]. The idea is to decouple UL and DL and allow for the user to be served by a different access point at each link. Thus, in its simplest form, the UE chooses the eNB with best RSRP for the DL and the eNB having the lowest path loss for the UL. More sophisticated associations can be defined to account for load conditions too [8]. However, application of UDS requires a centralized, cloud-based solution or low latency X2 interfaces. Otherwise, it needs changes in the current system architecture [9, 10] and handover events [11]. The literature on UDS or the use of CRE with eICIC is intensive but still there are some questions unanswered and that are targeted in the current work. Thus, the novelties of this paper are as follows:

(1) Some works claim that the gains of UDS could reach up to 200%-300% in the 5th percentile of UL throughput when compared to a baseline case without CRE [12]. UDS could lead to significant gains in network throughput, outage and power consumption at a much lower cost compared with CRE. However, the combination of CRE and eICIC is more realistic in real deployments, since it allows for the utilization of larger CRE. Therefore, the first novelty in our work is that we compare UDS with CRE combined with eICIC.

(2) In all previous works, results are provided in an aggregated manner. Meaning that CDFs of performance metrics for all UEs are analyzed at a time. This paper provides and individualizes analysis so that hidden effects can also be observed. Thus, the work identifies UEs having throughput losses or gains and it shows that, under high loaded conditions, both UDS and CRE+eICIC net gains come at the cost of reducing the quality of experience of certain UEs. Causes and effects are investigated in depth

(3) The work in [10] summarizes the potential benefits of UDS and compares aggregated throughput values with different CRE cases. However, considering that the gains of UDS are focused on UL performance and exist in the low medium load case, some authors argue that these gains do not justify the added complexity and the technique was not prioritized by standardization bodies [11, 13]. The degree of gains due to UDS in ultradense deployments is unclear. Hence, we investigate the gain of UDS in highly loaded networks.

(4) This work also studies the dependency of UDS performance with respect to small cell density. In previous works, macrocells cover just a few small cells in the typical HetNet scenario, which somehow forces the asymmetrical coverage in UL or DL. This situation promotes the gains in the UDS case. But, in dense urban environments, ultradense networks (UDNs) composed of a dense layer of small cells are seen as a key planning solution to obtain a capacity boost. In such case, it is not evident that coverage asymmetries will be so present and, for this reason, we investigate the sensitivity of the performance gains with respect to the network density

The rest of the paper is organized as follows: in Section 2, the principles about CRE, eICIC, and UDS are illustrated within our system model. In Section 3, the methodology and simulation setup including a description of the synthetic and realistic scenarios are presented. In Section 4, the simulation results are analyzed and finally, in Sections 5 and 6, the discussions and conclusions are presented.

## 2. System Model

*2.1. Cell Range Expansion and eICIC.* CRE allows for a better load balancing among cells through a more effective offloading of macrocells towards pico-cells. This expansion can be achieved by changing the cell (re)selection and handover conditions. In particular, it can be achieved by introducing an offset that artificially modifies the RSRP measured over pico-cells. A secondary gain of this strategy is a better UL performance, as previously indicated. LTE/LTE-A offers mechanisms to introduce this extra margin:

(i) For users in idle mode, the system has the possibility of broadcasting an offset $Q_{\text{OffsetCell}}$ for each co-channel neighbour cell listed in the system information block (SIB) number 4 [14]. This number modifies the measured RSRP ($RSRP_n$). Besides, the RSRP at the serving cell ($RSRP_s$) may be modified by the offset

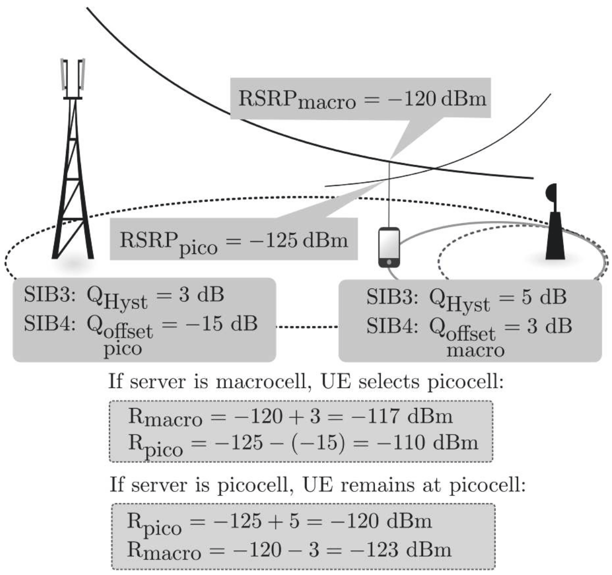


Figure 2: Illustration of the CRE for a UE in idle mode.

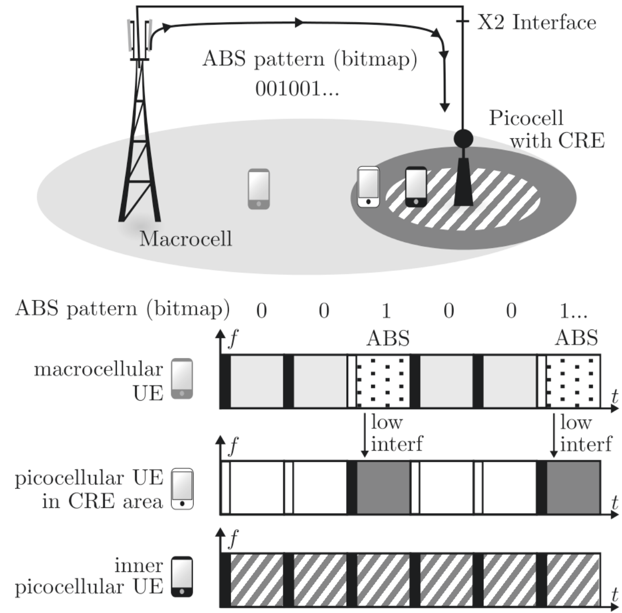


Figure 3: Illustration of how an LTE frame can consist of ABS subframes. Users in CRE area are only scheduled when the (time synchronized) macrocell transmits an ABS.

$Q_{\mathrm{Hyst}}$. This way, the values considered for reselection at the serving cell ($R_s$) and the neighbours ($R_n$) are

$$R_s = \mathrm{RSRP}_s + Q_{\mathrm{Hyst}}, \qquad R_n = \mathrm{RSRP}_n + Q_{\mathrm{OffsetCell}}. \tag{1}$$

Note that the offsets must be correctly adjusted at all cells to avoid ping-pong or multiple reselections. Figure 2 shows an example of correct adjustment in which selection decisions are kept invariant.

(ii) For users in connected mode, a cell individual offset (CIO) can also be configured to modify the handover measurement events A3, A4, A5, and A6 [14]. For example, the entering condition for event A3 is

$$M_n - \mathrm{A3}_{\mathrm{offset}} + \mathrm{CIO}_n > M_s + \mathrm{A3}_{\mathrm{Hyst}} + \mathrm{CIO}_s, \tag{2}$$

where $M_n$ and $M_s$ are the measurement results (RSRP and/or RSRQ) of the neighbouring and serving cells, respectively. $\mathrm{A3}_{\mathrm{offset}}$ and $\mathrm{A3}_{\mathrm{Hyst}}$ are event specific offset and hysteresis margins, respectively. Finally, $\mathrm{CIO}_n$ and $\mathrm{CIO}_s$ are the actual CIOs of neighbouring and serving cells, respectively.

We assume that every pico-eNB is deployed with a cell selection offset and corresponding CIO so that the extension is the same in idle and connected mode UEs. It should be noted that the users in the CRE area have very low (likely negative for medium and high loads) SINR in the new expanded pico-cell coverage area. This is due to the high DL interference from macro eNBs. Furthermore, the CRE will also reduce the control channel reliability if no eICIC is enabled. Decreasing such severe DL interference is the reason why eICIC and further eICIC have been developed [15].

The principle of eICIC is to avoid the macro eNBs and the pico-eNBs transmitting at the same subframes at certain periods of time. This keeps the UEs in the CRE area away from high DL interference caused by the macro eNBs. During periodic subframes termed Almost Blank Subframes (ABS), the macro eNBs still transmit broadcast signals. Since these signals occupy just a fraction of the OFDMA subcarriers, the overall interference is much lower. At those specific frames, the pico-eNBs will schedule the UEs in the CRE area. Thus their SINR values are better at ABS and higher data rates can be achieved. On the other hand, the existence of ABS reduces the macrocell capacity. ABS principle is depicted in Figure 3.

*2.2. UL and DL Splitting.* In order to decouple the UL and the DL, different cell selection criteria are required for each one. The user evaluates the normal RSRP/RSRQ reselection/handover criteria for the DL and a secondary new condition for the UL. The best approach from a link budget perspective is associating the UL with the cell having the minimum path loss. This is the approach that has been considered in the present system model. Other alternatives are based on DL RSRP/RSRQ measurements and limit the UL range by introducing a specific cell range expansion for the UL (CRE-UL) [11]. Thus, when a second UL margin is introduced, UL and DL will be split in the non-overlapping area defined by CRE-UL and "normal" CRE. Other approaches also take the cell load into consideration for association purposes [8].

It is important to understand that CRE already favors the UL of users in the expanded area, since they transmit to a closer eNB after the range expansion. So, one question to answer is whether UDS provides noticeable gains in terms of SINR and throughput with respect to CRE, in particular in high dense deployments and high traffic density. On the other hand, the serving cell is the same for UL and DL in CRE. Thus UDS allows for independent radio resource management

Table 1: Comparison between different cases.

| Case | DL selection | UL selection | Interference coordination |
|---|---|---|---|
| Normal | **Max RSRP** | **Max RSRP** | No |
| CRE | **Max RSRP+offset** | Max RSRP+offset | No |
| CRE + eICIC | **Max RSRP+offset** | **Max RSRP+offset** | Yes |
| UDS | Max RSRP | **Min path loss** | No |
| UDS + CRE | Max RSRP+offset | Min path loss | No |

in uplink and downlink which adds extra flexibility to the system and so constitutes an interesting feature by itself.

When UDS is implemented, UEs connected to different eNBs in the UL and DL need a strategy to send and receive acknowledgments, channel state information, power control commands, and the rest of feedback information. Note that current X2 interfaces show a latency of around 15 ms. This is not enough for a correct functioning of feedback procedures when UL and DL operate at different eNBs. Different architecture options have been proposed to make UDS feasible, with different levels of complexity and with important restrictions on the backhaul maximum delay. In this sense, architectures offering high capacity low latency backhaul connections are more suitable environments to deploy UDS. Nevertheless, along this work, we assume that delay restrictions are fulfilled. It can be due to such centralized deployment or the existence of low latency backhaul. The system model assumes that the feedback procedures are correctly executed without additional delays. For more information on possible architectures for UDS implementation, the reader can refer to the 3GPP documents [13, 16].

Considering that CRE benefits the UL in heterogeneous networks, this should be included as a benchmark to evaluate UDS gains. Table 1 shows the cases that have been considered in this work. Please note that redundant information has been omitted for the sake of clarity. For example, the Normal case (cell selection based on RSRP for both UL and DL) and the UDS case have the same DL selection criterion. As a result, the DL performance is identical for both cases. Hence, for conciseness, three cases are considered in the DL (bold in the table): the Normal case, the CRE case, and the CRE + eICIC case. Similarly, just three situations are considered in the UL (bold cases): Normal, CRE + eICIC, and the UDS case. The results of UDS + CRE case can be obtained by the combination of DL results from the CRE case and UL results from the UDS case.

## 3. Simulation Setup

The methodology that has been followed is dynamic system level simulations. For this purpose two scenarios were considered. A realistic scenario in the city of Vienna and a synthetic scenario. This allows for establishing a comparison between the results under synthetic conditions and the output that an operator might get in its deployment.

*3.1. Realistic Scenario.* The realistic scenario consists of 51 macro eNBs and 221 pico-eNBs. The macro layer locations are inherited from previous standards. Pico-cells are used as a densification layer. They are deployed at street corners and strategic hot spots. The path loss data, represented in Figure 4, has been obtained by means of 3D ray tracing, which guarantees accurate and confident results.

*3.2. Synthetic Scenario.* For comparison purposes, this scenario was designed to be analogous to the realistic one in its dimensions and number of macro/pico-eNBs. It accounts for 54 macros and 221 picos. Macrocells are deployed following a classic hexagonal tessellation pattern and pico-cells are uniform randomly distributed under constraints of minimum intersite distances. The path loss has been calculated based on the 3GPP LTE urban model [17]. This is a stochastic propagation model having a breaking distance for LoS (Line of Sight) conditions. The results of this prediction model are shown in Figure 5. Under synthetic conditions, it was observed that the user cell association was depending on the distance from which the LoS is lost for pico-eNBs ($D_{\mathrm{LoS}}$) and the Intersite Smallest Distance among small cells ($D_{\mathrm{ISD}}$). Therefore, simulations with different $D_{\mathrm{LoS}}$ and $D_{\mathrm{ISD}}$ were performed to find out the closest scenario to the realistic one. Recall that the realistic scenario is not using a stochastic propagation model, but 3D ray tracing. The obtained values are $D_{\mathrm{LoS}} = 100$ m and $D_{\mathrm{ISD}} = 30$ m. Under these conditions, the user cell associations are very similar in the synthetic and realistic scenario. Indeed, Figure 6 shows the percentage of users that are associated with macro or pico-cells in a Normal association case, association with CRE of 10 dB and UDS with UL association based on minimum path loss. As previously indicated, one of the objectives of this work is to investigate the performance of different association options under urban dense conditions. From the deployment viewpoint, this means a second and dense layer of small cells. From the load perspective, this means a high density of active UEs. In particular, 7000 outdoor pedestrian users are uniformly distributed. This number implies that all eNBs are likely to have at least 1 UE in connected mode. UEs are also characterized by download like traffic during the observation time, meaning they have full buffers during the simulation time. Note that results are obtained from several snapshots with a duration of 1000 TTIs. UEs are placed at different positions at each snapshot; thus this is statistically equivalent to deactivate UEs after such observation time (i.e., finite buffers) and placing them in new positions, which introduces the required diversity to obtain statistically reliable results.

Another contribution in this research work is analyzing the dependency of UDS performance with an increasing network densification that evolves towards ultradense deployments. For this purpose, the number of pico-eNBs will be

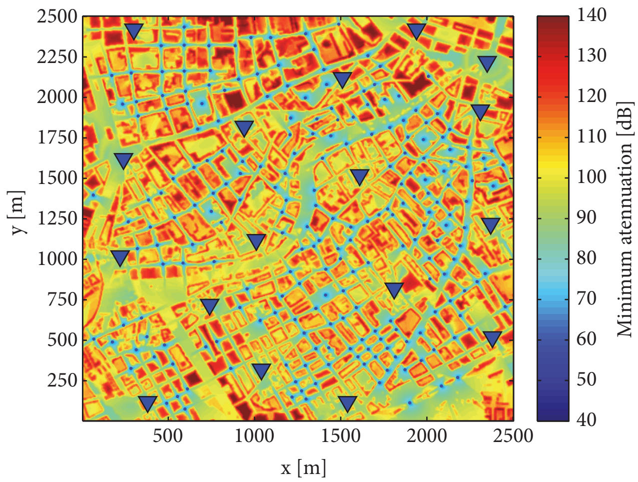


FIGURE 4: Minimum attenuation of the realistic scenario (Minimum attenuation for the complete (and not part of the) system area is represented. The path loss values correspond to both macro (triangles) and pico-cells (dots); hence this is the minimum net pathloss a UE would experience. 51 macros and 221 small cells are deployed in realistic case.).

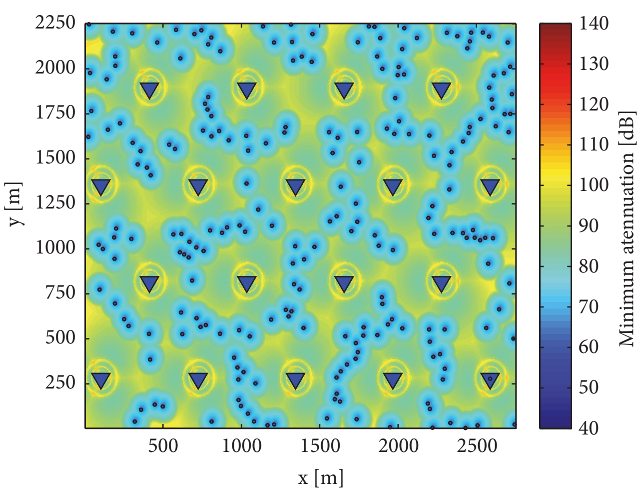


FIGURE 5: Minimum attenuation of the synthetic scenario (54 macros and 221 small cells are deployed in synthetic case.).

varied so that the ratio of number of picos to the number of macrocells varies from 1~8 as indicated in a subsequent section.

Open loop power control is considered in the UL. The algorithm follows the 3GPP specification [18]. Thus, the transmitted power of UEs is given by

$$P_{\mathrm{UE}} = \min\{P_{\mathrm{MAX}}, 10\log_{10}(M) + P_0 + \alpha L\} \quad (3)$$

where $P_{\mathrm{MAX}}$ is the maximum allowable transmitted power of UEs. $M$ is the number of Physical Resource Blocks (PRBs) assigned to the UEs. $P_0$ is a parameter used to control the SINR target. $\alpha$ is the path loss compensation factor, and $L$ is an estimation of the UL path loss, which is indeed the DL path loss measured from RSRP. In the simulation, $(\alpha, P_0)$ were set to (0.8, −80 dBm).

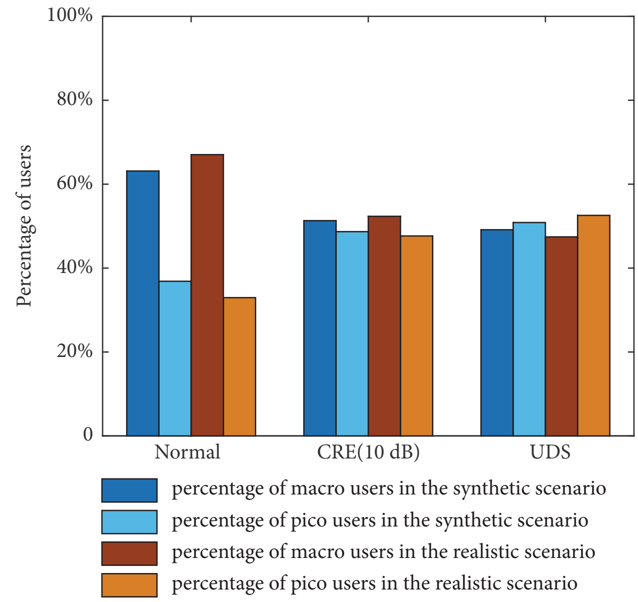


FIGURE 6: User cell association in both synthetic and realistic scenarios.

When CRE is applied, the offset is set to 10 dB. The ABS muting ratio is 1/10, i.e., one muted frame out of 10. Note that the use of eICIC allows for increasing the CRE value. ABS allows for removing interference from both the data and control channels and UEs are also assumed to implement reference signals interference cancellation (further eICIC). This allows for rising the classic CRE of 6 dB to higher values. We have finally used 10 dB since it has been identified as the optimum CRE for scenarios with hotspots [19]. Also the work [20] analyzes the optimal values for CRE for different ABS patterns and concludes that the optimal CRE moves in the range from 8 dB to 12 dB. Finally, the rest of simulation parameters are shown in Table 2.

## 4. Simulation Results

Previous works provide results in an aggregated manner; however, during this research, it was observed that UDS is not beneficial for all situations. An aggregated gain may be obtained while reducing the quality of experience of a subset of UEs. In order to provide a clear insight into this issue, different types of users have been identified and analyzed separately:

(1) Macro users: they are connected to macro eNBs in DL and UL in all cases, that is to say, before and after changing the *normal* cell selection and handover conditions (association rules) with CRE or UDS.

(2) Pico users: they are connected to pico-eNBs in DL and UL in all cases.

(3) Edge users: they change their UL connection from macro eNBs to pico-eNBs after using CRE or UDS.

For each case, there might be users in such a situation that gain or loss throughput after changing the classic association

Table 2: Simulation parameters.

| | Synthetic scenario | Realistic scenario |
|---|---|---|
| Operation frequency | 1.8 GHz | 1.8 GHz |
| Bandwidth | 20 MHz (100 PRBs) | 20 MHz (100 PRBs) |
| Deployment | 54 macros, 221 picos | 51 macros, 221 picos |
| User distribution | 7000 (uniformly distributed) | 7000 (outdoors) |
| Scheduler | Round Robin | Round Robin |
| Simulation time | 1000 ms | 1000 ms |
| Path loss calculation | 3GPP LTE Urban model | 3D ray tracing |
| Maximum TX power | Macro = 46 dBm<br>Pico = 30 dBm<br>UE = 20 dBm | Macro = 46 dBm<br>Pico = 30 dBm<br>UE = 20 dBm |
| Antenna system | Macro: 2 × 2<br>Pico: 2 × 2 | Macro: 2 × 2<br>Pico: 2 × 2 |
| Antenna gain | Macro: 18 dBi<br>Pico: 2 dBi | Macro: 18 dBi<br>Pico: 2 dBi |
| UEs mobility | Pedestrian (3 km/h) | Pedestrian (3 km/h) |
| Supported UL modulation schemes | QPSK<br>16 QAM<br>64 QAM | QPSK<br>16 QAM<br>64 QAM |

rule. The reason for this is twofold: first, the modification in SINR values and, second, the different availability of radio resources (cell load). For example, a UE having lower SINR might have associated with a cell with more available resources and thereby getting an increase in average throughput. Note, however, that lower SINR values require more conservative modulation and coding schemes and hence the attainable peak throughput is lower.

For this reason results are presented in the following order:

(i) Firstly, we identify the users that have obtained a throughput gain or loss after splitting UL and DL and analyze the changes in SINR and resource availability with respect to the normal cell association. For comparison purposes, this action is also performed with our second benchmark, CRE with eICIC.

(ii) Having analyzed the variables that impact throughput, throughputs themselves are compared for the different types with special focus in the comparison of UDS versus CRE+eICIC.

(iii) The last subsection analyzes the impact that different levels of pico-cell density have on the UDS gains/losses obtained in the previous two sets of results.

*4.1. Variation of UL SINR and Radio Resource Availability.* The UL SINRs of users in the realistic scenario are shown in Figures 8, 9, and 10 for macro, pico, and edge users, respectively. Similarly, Figure 7 shows the synthetic case. The following nomenclature has been used in the legends:

(i) The *before* cases, i.e., with normal association:

  (1) Loss, normal (for UDS or CREe): UL SINR of UEs that would experience a throughput loss after applying the offloading technique (UDS or CREe). Since the SINR is almost identical for both offloading cases, one single curve is plotted.

  (2) Gain, normal (for UDS or CREe): The same but for UEs having a throughput gain.

(ii) The *afterwards* cases, i.e., after applying UDS or CRE with eICIC:

  (1) Loss (or gain), UDS: UL SINR of UEs having an UL throughput loss (or gain) when UDS is being applied.

  (2) Loss (or gain), CREe: UL SINR of UEs having an UL throughput loss (or gain) when CRE + eICIC is being applied.

Both UDS and CREe imply an offload from macrocells, which means more radio resources available for remaining macro users. However, offloaded users remain geographically near and now they have turned into active interferers affecting the macro users. They also enjoy more scheduling grants since pico-cells have less users. This means that, in environments of highly active UEs, offloading will bring an increase in the number of interference sources. Consequently, the SINR of macrocell users is expected to be lower and, hence, the modulation and coding schemes will be more conservative.

Given this, the throughput of macro users can increase or decrease depending on the balance between more radio resources but lower SINR. If results were provided in an

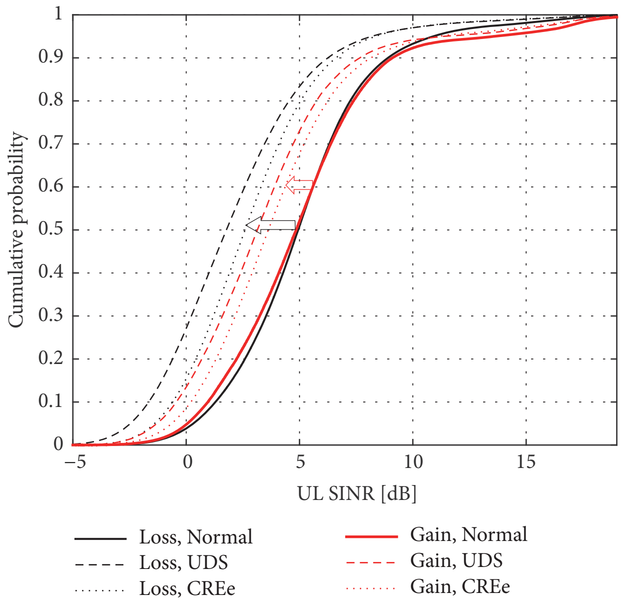


Figure 7: CDF of the macro users' UL SINR in the synthetic scenario.

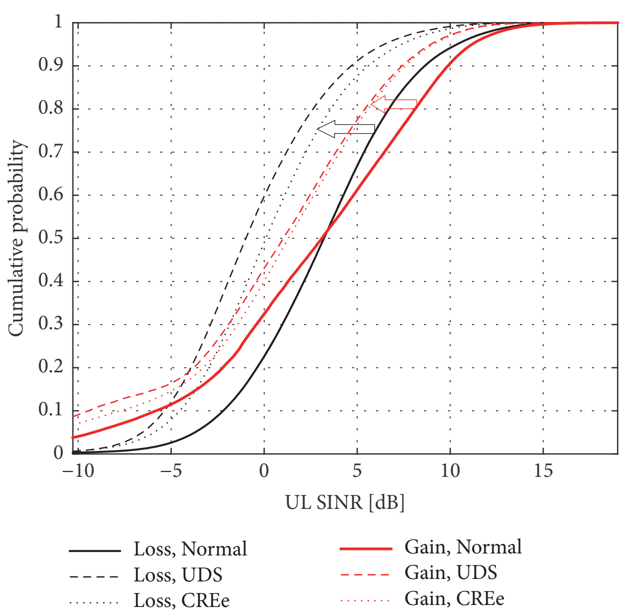


Figure 8: CDF of the macro users' UL SINR in the realistic scenario.

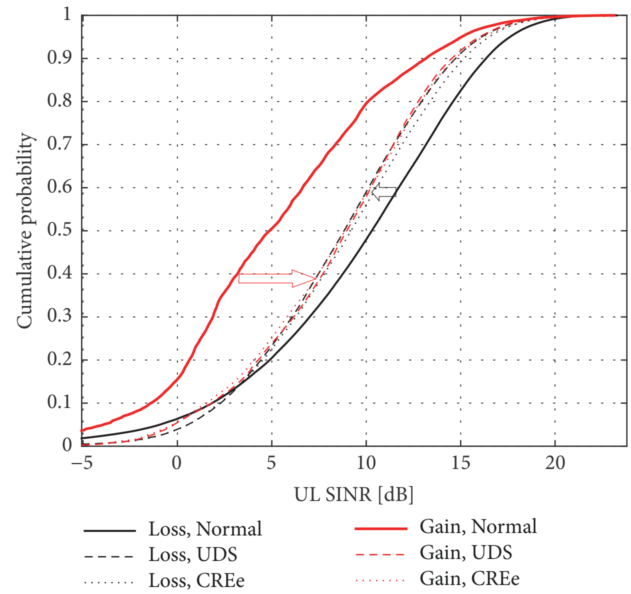


Figure 9: CDF of the pico users' UL SINR in the realistic scenario.

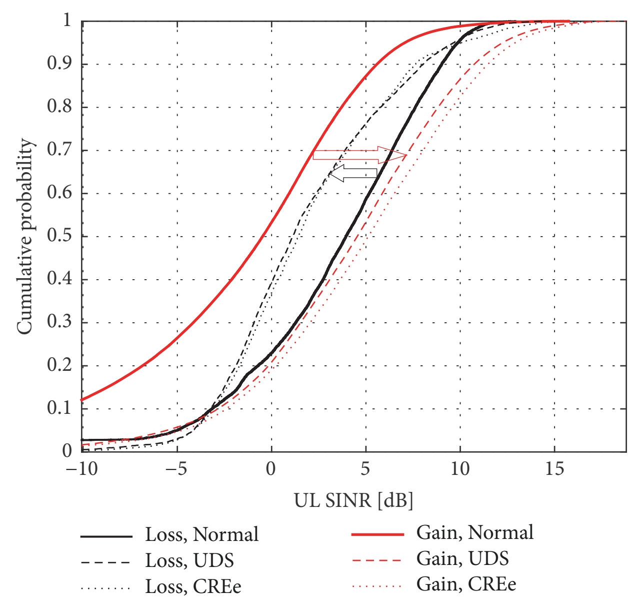


Figure 10: CDF of the edge users' UL SINR in the realistic scenario.

aggregated manner for all UEs in the system, a net gain can be obtained while masking the fact that some UEs have been degraded. This work provides an individualized analysis and identifies UEs having throughput losses or gains.

This effect is shown in Figures 7 and 8, which represent the UL SINR of macrocell users before and after applying the offloading techniques for the synthetic and realistic case, respectively. Note that the arrows indicate how the SINR CDF is shifted after applying the offloading techniques. Then, black lines indicate the final SINR for UEs experiencing a throughput loss (for both UDS and CREe). This corresponds to UEs in which the SINR is highly reduced and, then, it cannot be compensated by the lower occupancy of radio resources in the macrocell. On the other hand, some UEs perceive a SINR reduction but still get a throughput gain with UDS or CREe (red lines). It can be noticed that, even though a CRE of 10 dB is in the limit of what could be supported by LTE with (f)eICIC, UDS is able to perform an even more aggressive uplink offloading, which implies slightly lower SINRs. The impact on the global network throughput will be analyzed in the next section, but at this point it can be stated that gains in some UEs are at the cost of losses in other ones. All conclusions hold in both the realistic and synthetic case.

Regarding the SINR for the users that associate with pico-cells, interference patterns also change before and after applying UDS or CREe. For a given pico-cell, UL interference sources from high power macro users (at the cell edge) are now turned into low power interferers connected to other pico-cells or, even more, they do not generate interference at all if associated with that particular pico-cell. Therefore, it is expected that several pico users improve their SINR. Of course, the price to pay is having to share the radio resources with the new incoming UEs. Hence, there is a balance between SINR and available radio resources, which may be positive or negative in terms of throughput.

Figure 9 shows that, in effect, some of the pico-cell UEs experience SINR increases that can reach 5 dB and that translates into a throughput improvement (red lines). There is a gain despite the fact that pico-cells are more loaded and transmission opportunities are reduced. On the other hand, there are also some UEs having a slight SINR degradation (black lines). Depending on the UE positions, a subset perceives interference from offloaded UEs that are more active and that generate interference more frequently. Since conclusions hold again in the synthetic case, only the realistic CDFs are shown.

Finally, the SINR variation of offloaded users themselves is analyzed. In this case, UEs will associate with a pico-cell being much less loaded than the previous server, the macrocell. So, it is expected that in average offloaded users have a throughput gain. When looking specifically at the UEs, it is noticeable that the users having a throughput gain (red lines in Figure 10) have also experienced an important improvement in UL SINR. On the other hand, it is indicative that some UEs associate to a new cell in which they experience a throughput loss (black lines). This is not uncommon and affects 6% of the offloaded (cell edge) users. In such cases, the UEs have a high UL interference and they decrease their performance even after associating to a less loaded cell. Indeed, the utilization ratio of the transmission time intervals in which the offloaded users are served has a dramatic improvement. More specifically, it is increased from 11.62% to 57.35% after using CRE+eICIC and UDS, respectively.

*4.2. Throughput Comparison with Special Emphasis in UDS versus CRE + eICIC.* Figures 11 and 12 show the results of UL throughput in the synthetic and realistic scenarios, respectively. As expected from the previous analysis, a subset of both macro and pico users experience a loss. In the first case, this is due to a worse SINR, in the second due to a pico-cell load increase caused by offloading from macrocells. Note that the CDFs do not cross in any of the cases. Hence, the general UL performance is worse. Note that the low throughput in macrocells is due to the high load in the system and a high absolute number of users per macrocell (around 63 users). On the other hand, even though a small percentage of edge UEs experienced a loss, the notable increase in average UL throughput is clear. The gain can reach up to 588% and 553% in the CRE + eICIC case and the UDS case, respectively. The reasons (effective offloading and better UL SINR) have been already analyzed.

All these observations apply for both a complete UDS policy and a non-split deployment with CRE + eICIC. It can

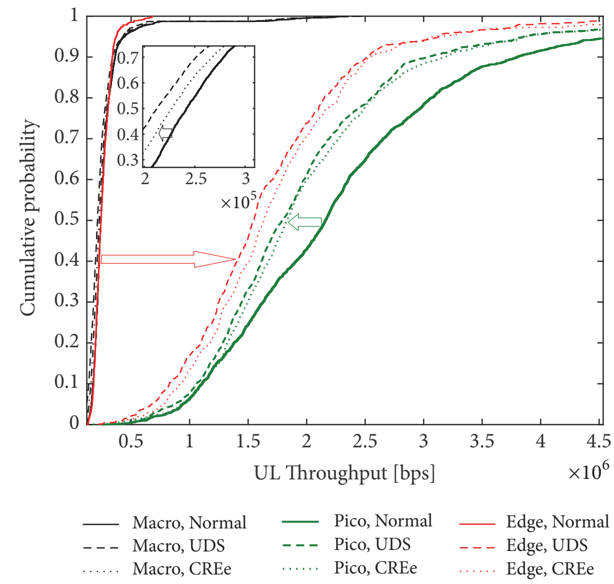


FIGURE 11: CDF of UL throughput in the synthetic scenario.

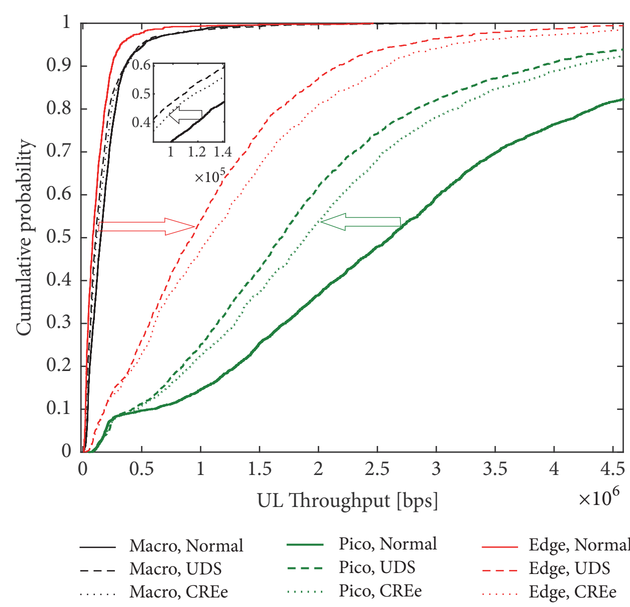


FIGURE 12: CDF of UL throughput in the realistic scenario.

be argued that the noticeable throughput gain for the majority of edge UEs could compensate the slight losses for macro and pico users and yield an actual system throughput gain. For example, the average loss of the macro users reaches up to 11%, well below the edge UEs gains.

The total system throughput is only increased in the synthetic scenario, whereas for the realistic case it is decreased. Note that offloaded users can transmit more frequently in pico-cells due to the lower load. This implies that those UEs generate interference more frequently to the macrocell (and other pico-cells) than they do to the current pico-cell server. However, those UEs are transmitting much lower power than before and, hence, the interference from them might be very low. Particularly, if there is not LoS between the user and the macro, which leads to the increase of total system throughput in the synthetic scenario. However, for the realistic case, coverage areas are more overlapped and the interference distribution becomes worse.

Several works dealing with UDS typically provide results with respect to a heterogeneous network with no CRE. However, what is indicative here is that UDS shows a worse performance than CRE in the current high load and pico-cell density. This loss is even larger in the realistic case. For the synthetic scenario, the total system uplink throughput in CRE + eICIC was 0.44% better than UDS, whereas, for the realistic case, CRE + eICIC was 6.59% better.

For a better comparison between CRE + eICIC and UDS, the percentage of edge users and percentage of their data traffic are shown as below.

(i) When CRE (10 dB) + eICIC is applied in synthetic scenario, 10.9% edge users exist in the network and the corresponding UL and DL throughput percentages are 17.5% and 13.9%.

(ii) When UDS is applied in synthetic scenario, 13.3% edge users exist in the network and the corresponding UL and DL throughput percentages are 20.3% and 3.0%.

(iii) When CRE (10 dB) + eICIC is applied in realistic scenario, 15.0% edge users exist in the network and the corresponding UL and DL throughput percentages are 18.3% and 4.0%.

(iv) When UDS is applied in realistic scenario, 20.1% edge users exist in the network and the corresponding UL and DL throughput percentages are 22.2% and 1.6%.

Along the previous subsections, it could be observed that the UL SINR differences between UDS and a high CRE of 10 dB are minimal. Thus, if CRE + eICIC is already implemented in the DL, decoupling provides a marginal additional gain in terms of UL SINR. In light of the previous results, if UDS is implemented, the introduction of a second adjustable offset to control the UL offloading appears to be a wise option, instead of the pure path loss based approach. This would allow for a finer control of UL load balancing, macro and pico-cell potential losses, and the subset of UEs that would experience a loss if handed over to the pico-cell.

Regarding the DL performance, note that UDS does not force any sort of offloading. Users associate to the best cell following the classic best RSRP criteria in LTE.

*4.3. Dependency of UDS Performance with Small Cell Density.* Along the previous sections, it was outlined that UDS may report marginal gains in terms of UL SINR if a CRE strategy is already applied in a dense network, in both number of serving nodes and number of users generating high traffic load. This section studies the impact of further ultradensification. The context here is a scenario in which pico-cells constitute the main means of coverage.

Without loss of generality, results are provided for the synthetic case. This is due to space constraints and also to the feasibility to generate scenarios with different pico-cell

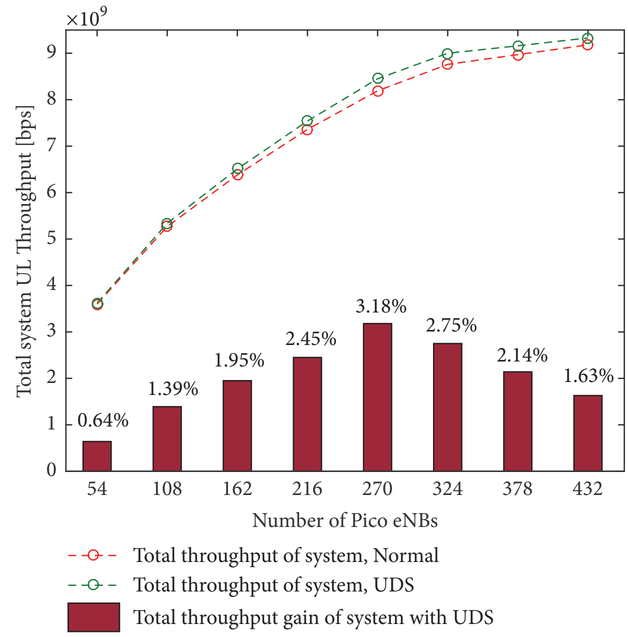


Figure 13: CDF of the total system UL throughput in the synthetic scenario.

densities. Previous results have shown how conclusions hold in the realistic context and just absolute values are shifted due to a more complex propagation environment.

Figure 13 shows the variation of total system UL throughput as the increase of pico-eNBs. It is reasonable that the total system UL throughput improves with the number of pico-eNBs, given the increase of bandwidth per $km^2$. However, it is noteworthy that the total system gain of UDS has an optimal value. The increase of small cells has marginal effect on throughput after a certain point. In particular, the gain from offloading is not notable as before. Meanwhile, the increasing number of pico-eNBs incurs more active interference sources with LoS to the interfered receivers, which leads to worse UL SINR. Hence, the total system gain of UDS decreases when the scenario is crowded with pico-eNBs.

The level of heterogeneity in the network can be measured from the ratio between the number of macro and pico-cells. With ultradensification, pico-cells might generate a secondary coverage layer, fully lying below the macrocellular coverage and so the percentage of area in which UL and DL associations are different also tends to diminish.

Figures 14 and 15 show the percentage of users with gain after using UDS and the average UL throughput of users, respectively.

It is obviously observed that the percentage of pico users with gain increases with the increase of pico-eNBs. As shown in Figure 16, more pico-eNBs not only bring effective offloading, which largely decreases the load of macro cells, but also largely increase available radio resources. Besides, the blue dashed line in Figure 15 also indicates that more pico-eNBs can improve the UL throughput performance of pico users on average level.

The enhancement of pico-eNBs has a little influence in the percentage of UDS users who gain after UDS. This is because,

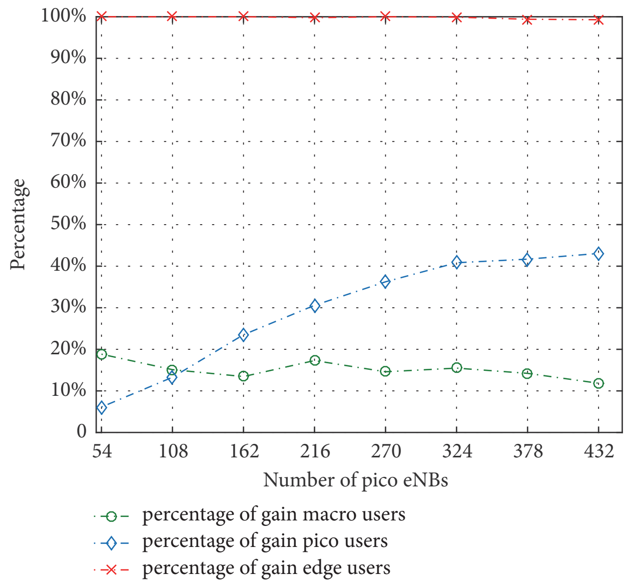


FIGURE 14: Percentage of users with gain after using UDS.

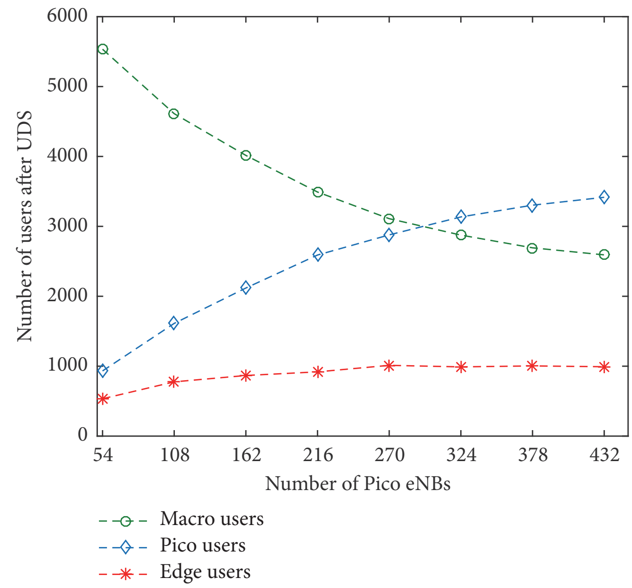


FIGURE 16: Users cell association in the synthetic scenario.

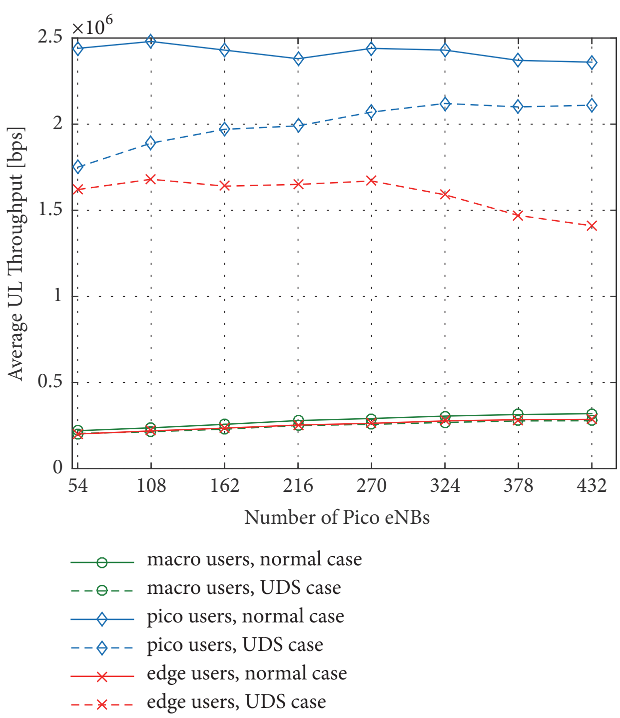


FIGURE 15: Average UL throughput of users in the synthetic scenario.

for a UDS user, changing its connection from macro-eNB to pico-eNB dramatically, improves the UL throughput performance due to less load and higher activated frequency. Hence, the increase of pico-eNBs can hardly change the situation where almost all the UDS users have better UL performance after using UDS. However, as shown in Figure 15, the average UL throughput of UDS users has slight peaks and valleys when the number of pico-eNBs is less than 270. This is due to the interaction between gain from less small cell load and loss brought by more interference sources. Beyond this point, the offloading effect approximates to saturation as shown in Figure 16. The gain from offloading cannot compensate the loss from more interference sources, which leads to the decrease of average UL throughput of UDS users.

In Figure 14, it is noticeable that the percentage of macro users has slight rise and fall. Generally, the increase of pico-eNBs largely reduces the high load of macro eNBs, which should have resulted in more macro cells improving their performance. However, the increasing number of interference sources, particularly the offloaded UEs, which are frequently scheduled by the low loaded pico-cell, generates high interference. When the number of pico-eNBs is large enough, the offloading effect is no longer obvious, which is shown in Figure 16. Hence, the loss from higher interference overpasses the gain from offloading and the UL throughput improvement of macro users is less and less.

## 5. Discussion

This paper provides new insights into the performance of UDS in highly loaded systems, in terms of both serving nodes and the number of UEs with high traffic activity. The study has put special focus about the gains that UDS could bring in terms of SINR and throughput when compared with systems with range expansion offsets in their association rules. Instead of an aggregated throughput analysis, in this paper, a detailed classification of users is performed to figure out the causes of users' gain or loss after applying each strategy. Users have been isolated depending on their throughput variation and analyzed independently. The dependency of UDS performance with small cell density has also been a matter of study.

CRE + eICIC slightly outperforms pure path loss based UDS in improvement of UL SINR and user throughput under high traffic load. Using an individual UL adjustable cell offset allows for a finer control of UL interference. This appears to be a more interesting strategy than an association fully based on UL path loss.

Referring to DL, it does not seem that UDS is a radio planning strategy to be applied by its own. Small cell deployments require DL offloading to improve the utilization of pico-cells and provide an important quality increase in macrocell edge users. Given this, both strategies complement each other well. eICIC is a mandatory option to increase the DL throughput, especially for edge users. In environments with a large number of users that cannot be directly offloaded to pico-cells (e.g., vehicular users that would have very short time-of-stays and too large handover failure rates), eICIC should be carefully planned to minimize macrocell capacity reduction.

Increasing the number of pico-eNBs largely improves the performance of pico and macro users initially but the gains are marginal after a certain density of small cells. From an economic and energy efficiency viewpoint, and considering the optimal total system gain with UDS, the best UDS performance is achieved when each macro-eNB is accompanied with 4~6 pico-eNBs.

## 6. Conclusions

CRE + eICIC slightly outperforms UDS in the improvements of UL SINR and user throughput in highly loaded networks. Under such conditions, the average quality of experience gain coming from offloading techniques happens at the cost of degrading some UEs. A finer control of UL interference can be achieved by using an individual UL adjustable cell offset. However, it seems that UDS is not a radio planning strategy to be applied by its own. Hence, CRE + eICIC and UDS complement each other well. In the perspective of economic and energy efficiency, the best UDS performance is achieved when each macro-eNB is accompanied with 4~6 pico-eNBs.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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