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Analysis of Heterogeneous Networks with Dual Connectivity in a Realistic Urban Deployment

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Abstract— **Dual Connectivity (DC) has been studied and proved to be an effective solution to deal with the fragmented resources in deployment scenarios where the macro and small cells use different frequency carriers. The performance of DC has mainly been analyzed using generic network models such as those proposed by the 3GPP. However, the benefits of DC in real networks have not been proved. In this paper, we investigate the performance of DC in a realistic deployment from a big European city. Additionally, a novel opportunistic cell selection technique is also proposed. Results show that DC does improve the performance in this realistic layout. Due to the uneven load distribution observed in realistic deployments, DC is able to provide fast load balancing gains also at relatively high load - and not only at low load as typically observed in 3GPP scenarios. For the same reason, the proposed cell selection technique that aims at performing intra-layer load balancing shows promising benefits in this irregular deployment.**

I. Introduction

Heterogeneous Network (HetNet) consisting of macro and small cells is considered a very promising type of deployment for meeting future traffic demands [1]. One type of HetNet scenario is the dedicated deployment in which the macro and small cells are deployed at different Component Carriers (CC). Dual Connectivity (DC) between the macro and small cells allows User Equipments (UE) to simultaneously connect to both layers in order to fully access the available radio resources [2]. We investigate DC in the form of inter-site Carrier Aggregation (CA), meaning that the small cells are deployed as Radio Remote Heads (RRH) with centralized processing at the macros and a low-latency high-speed fiber fronthaul between macro and small cell. DC assuming traditional backhaul connections (e.g. X2 interface) has also been studied and is expected to be one of the enhancements introduced in LTE Release 12 [3].

Fig. 1 illustrates an example of a dedicated carrier deployment in a HetNet scenario. Macro cells are deployed at carrier frequency f_1 whereas small cells are deployed at carrier frequency f_2, thus no interference management technique is needed between the two layers. The drawbacks of the fragmented spectrum can be minimized by applying DC which gives to UEs the possibility of connecting to both the macro and the small cell layer, thus better utilizing the spectrum resources. UEs configured to operate with DC not only have access to larger transmission bandwidth, but also benefit from more robust mobility management [4], fast load balancing, and an increased frequency and spatial diversity.
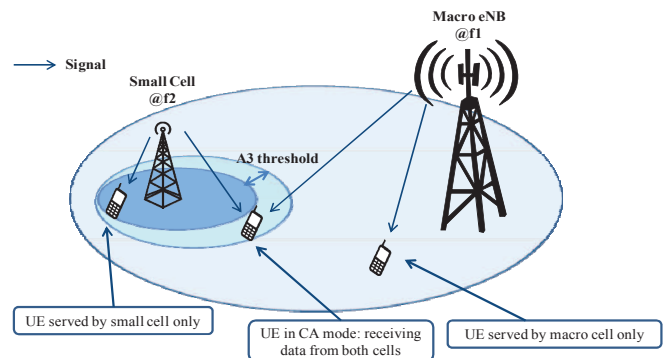

Fig 1. DC connection and A3-threshold concept.

The throughput and mobility performance of DC in HetNet scenarios have been studied in [2, 4, 5] under the assumption of commonly accepted stochastic models (e.g. 3GPP models). Cell association is an important design feature in HetNet and has been addressed in multiple studies [4, 5, 6]. The cell association is typically based on UE measurements of the received downlink signal strength, e.g. Reference Signal Received Power (RSRP) or Reference Signal Received Quality (RSRQ). Cell biasing is commonly used to balance the load between macro and small cells; however, these offsets are typically adjusted in a relatively low time-scale and therefore cannot cope with the rapid traffic variations in the network [6]. The first contribution of this study is a novel opportunistic cell association algorithm which can dynamically adapt to the load conditions. Compared to user association algorithms in [7, 8], our algorithm is performed at connection setup and operates on a fast basis, hence exploiting the time-varying nature of load conditions occurring in the network. The second contribution is the analysis of the downlink throughput performance with and without DC in a site-specific scenario corresponding to a large European metropolitan area. The network model includes macro-site locations, realistic traffic distribution and propagation maps from a ray-tracing tool. The corresponding user throughput performance is evaluated via advanced system-level simulations under realistic multi-cell and multi-user conditions with bursty traffic, and accurate representation of the many mechanisms that influence on the performance.

The rest of the paper is organized as follows: Section II describes the considered network model and performance metrics. Section III presents the cell association techniques and other Radio Resource Management (RRM) considerations. The

simulation assumptions are outlined in Section IV. Section V presents the performance results and corresponding analysis, followed by concluding remarks in Section VI.

II. NETWORK MODEL AND PERFORMANCE METRICS

There are basically two different modeling methodologies, namely (i) Generic models and (ii) Site-specific models. The generic models are commonly used as they allow the comparison of features and technologies across the industry and academia. Regular hexagonal network layout for macro sectors, uniform/hotspot traffic distribution in each macro sector, and stochastic and distance-dependant pathloss models are typical assumptions in these type of models [9].

However, real deployments are far from homogeneity. We have therefore decided to analyze the performance of DC in a site-specific network model. This particular model corresponds to a realistic deployment from a big European city. A three-dimensional (3D) topography map is used for the considered dense urban area. The map contains 3D building data as well as information on streets, open squares, parks, etc. The performance analysis is conducted in a 1.2 km² segment of the site-specific network which comprises several 3-sector macro sites plus 30 small cells deployed at different carriers (fig. 2). The macro sites (marked as red solid circles) correspond to a realistic deployment, whereas the small cells (marked as green triangles dots) were placed outdoor following the algorithm in [10] to improve the 5%-ile outage user throughput. The remaining macro sites (marked as blue circles) also correspond to realistic deployment but are only used for generating interference (transmitting at full power) in order to avoid border effects.

The radio propagation characteristics are estimated using state-of-the-art ray-tracing techniques based on the Dominant Path model (DPM) [11]. The scenario topography is taken into account and therefore the coverage area of the base stations varies significantly compared to the typical pathloss maps in generic models. Outdoor-to-indoor propagation is modeled according to [12].

A time-variant traffic model is assumed. As described in [9], the users are generated according to a Poisson process with arrival rate λ. Each user call has a fixed payload size of B Mb. Once the payload has been successfully received by the UE, the call is terminated and the UE is removed from the simulation. Thus, the average offered load in the network equals $\lambda \times B$. Whenever a new user is generated, the spatial location of the user in the horizontal plane is chosen randomly according to a two-dimensional probability mass function generated from a realistic traffic density map. For users that are placed at locations that coincide with multi-floor buildings, there is equal probability of placement per floor. The spatial traffic distribution is very irregular, in fact, 50% of the total traffic is generated in only 10% of the area. Moreover, 80% of the traffic is generated indoors even though only 40% of the area is covered by buildings.

The key performance indicators (KPIs) considered in this work are the 5%- and 50%-ile (median) downlink user throughput. The system utilization, defined as the percentage of Physical Resource Blocks (PRBs) transmitted in average,
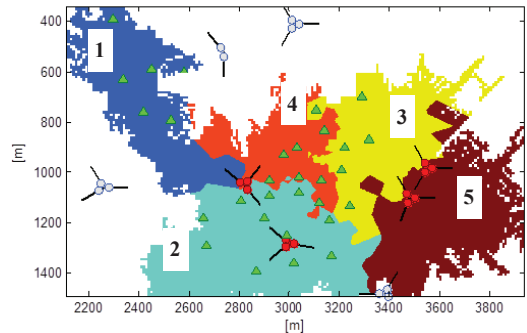

Fig 2. Sub-area division of the considered network area for localized performance analysis.

and the system capacity, defined as the maximum offered load that can be tolerated while still being able to serve 95% of the users with a certain target throughput, are also used. As the studied area is very irregular in terms of network layout and user distribution, the performance is analyzed not only globally, but also regionally according to the sub-area division shown in Fig. 2.

III. RADIO RESOURCE MANAGEMENT CONSIDERATIONS WITH DC

A. Cell Selection

As our system model does not include movement of users, and relatively short calls per user, the load balancing mechanism is performed at connection setup. In dedicated deployment, the cell selection is typically based on the downlink RSRQ measurement of the UE. RSRQ, defined as RSRP divided by the total received power, is preferred over RSRP as it partially captures the load and interference conditions in each layer.

1) UEs not supporting DC

For legacy UEs not supporting DC, the serving cell for the UE is typically the one with the highest RSRQ measurement. A range extension (RE) offset can be added to this measurement to offload more UEs from the macro cells to the small cells, thus balancing the load between the two layers. With this approach, the serving cell i^* is selected as follows:

$$i^* = \arg \max_{i \in M \cup S} \{RSRQ_i + RE_i\} \ , \ RE_i = \begin{cases} RE & \text{if } i \in S \\ 0 & \text{if } i \in M \end{cases}, \quad (1)$$

where M and S are the set of candidate macro and small cells respectively.

However, the cell selection in (1) has limitations. For example, since the RSRQ estimates the load conditions according to the total received power in each layer, the RSRQ might therefore not distinguish properly between cells serving only a few users and highly-loaded base stations. Moreover, using a single and common RE offset for the small cells solely determines the inter-layer load balancing while neglecting potential benefits of intra-layer load balancing.

To address this, we propose a dynamic cell selection technique that exploits the time-varying load conditions occurring in the network. We refer to this technique as *opportunistic* cell selection. This approach aims to optimize

the throughput of each user by choosing the cell which offers the best estimated throughput. Every time a UE arrives to the network, the serving cell $i*$ is selected as follows:

$$i^* = \arg\max_{i \in \mathbf{F}} \{R_i\} , \qquad (2)$$

where R_i is the estimated throughput of the UE if it is connected to base station i, and $\mathbf{F}$ is set of feasible candidate cells. In order to avoid the connection to cells with bad channel conditions, the set of candidate cells is limited to cells which fulfill the following condition:

$$\Gamma_{i_{dB}} \geq -5 \text{ dB} , \qquad (3)$$

where Γ_i is the conditional estimated wideband Signal-to-Interference-plus-Noise Ratio (SINR) of the user if served by cell i. In case none of the cells satisfy the condition specified in (3), the UE connects to the cell with highest RSRQ.

The estimated throughput R_i is calculated using Shannon's capacity formula, assuming that the resources are equally shared among the users in each cell, i.e.:

$$R_i = \frac{1}{N_i + 1} \cdot BW \cdot \log_2(1 + \Gamma_i) , \qquad (4)$$

where N_i is the number of users currently served by cell i and BW is the carrier bandwidth. The value of Γ_i is estimated as:

$$\Gamma_i = \frac{P_i}{\sum_{n \neq i} P_n \cdot W_n + N_o}$$
$$W_n = \begin{cases} 0 & \text{if } (i \in \mathbf{M} \text{ and } n \in \mathbf{S}) \text{ or } (i \in \mathbf{S} \text{ and } n \in \mathbf{M}) \\ 1 & \text{if } (i \in \mathbf{M} \text{ and } n \in \mathbf{M}) \text{ or } (i \in \mathbf{S} \text{ and } n \in \mathbf{S}) \end{cases} \qquad (5)$$

where P_i is the power received by the user from cell i, and N_o is the background noise. Please note that Γ_i only takes into account the intra-layer interference as the macro and small cells are deployed at different carriers.

Note that the throughput estimation in (4) is simplified and does not fully take into account all the elements influencing in the end-user throughput; however, for the purpose of cell association, basing on relative values rather than absolute values of throughput provides relatively reliable criterion for the cell selection decision. Compared to the cell selection mechanism based on (1), the opportunistic cell selection approach also provides intra-layer load balancing capabilities that are essential in the studied scenario.

2) UEs supporting DC

Certain conditions are applied to determine whether a DC-capable UE should be in DC mode or not. The principle of these conditions is to allow DC-capable UEs to connect to an additional cell only if they get a relevant benefit from this addition. In this paper, we adopt three different cell association algorithms to decide whether the UE should operate in DC mode or not. In the first approach, it is assumed that the UE have its Primary Cell [1] (PCell) according to (1). The DC decision is made following the A3 event [13], meaning that the connection to a Secondary Cell (SCell) is triggered if the RSRQ difference between the PCell and SCell is within a

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[1] More information on the PCell and SCell definition can be found in [17]

certain offset. We denote this offset as $A3_{Thresh}$. The condition can be written as follows:

$$|RSRQ_M - RSRQ_S| < A3_{Thresh} \qquad (6)$$
$$RSRQ_M = \max_{i \in \mathbf{M}} \{RSRQ_i\} , \ RSRQ_S = \max_{i \in \mathbf{S}} \{RSRQ_i\}$$

If (6) is fulfilled, the UE connects to both macro and small cell. Otherwise, the UE connects to the cell with the highest RSRQ plus RE offset (i.e. PCell) according to (1). This principle is shown in Fig. 1; the idea of this approach is to configure UEs experiencing similar channel conditions with DC, as these UEs are expected to benefit more from such technique.

The second approach consists on having the best macro cell for a certain user configured as its PCell, with the option of also having a small cell configured as its SCell when feasible, i.e.:

$$i_M^* = \arg\max_{i \in \mathbf{M}} \{RSRP_i\}$$
$$i_S^* = \begin{cases} \arg\max_{i \in \mathbf{S}} \{RSRQ_i\} & \text{if } \exists\ i \in \mathbf{S}: RSRQ_i > A4_{Thresh} \\ \emptyset & \text{otherwise} \end{cases} , \qquad (7)$$

where $A4_{Thresh}$ limits the minimum RSRQ level for the secondary cell. If the small cell has a RSRQ level above the RSRQ threshold (A4 event), the UE will be allowed to operate with DC, connecting to both layers; otherwise, the UE connects to the best macro cell. The idea of the second approach is to configure UEs with DC whenever the channel quality from the small cell is good enough.

Finally, we also propose the opportunistic cell selection algorithm for DC-capable UEs. For each UE, the algorithm first estimates the throughput of the base stations according to (4), and selects its PCell according to (2). The potential SCell for that UE is considered to be the base station in the opposite layer (to the PCell) that offers the highest throughput, and the connection is triggered only if the A3 condition between these two cells is fulfilled (see (6)).

B. Packet Scheduling

The well-known Proportional Fair (PF) packet scheduler is applied. For users connected to multiple cells, the PF metric is modified to take into account the past average throughput over all the configured carriers as suggested in [14], i.e.:

$$M_{i,j,k} = \frac{R_{i,j,k}}{\sum_{k=1}^{N} \overline{R_{i,k}}} , \qquad (8)$$

where $R_{i,j,k}$ is the estimated throughput of user i at sub-band j on CC k, $\overline{R_{i,k}}$ is the average throughput of user i on CC k, and N is the number of CCs assigned to schedule the UE. As shown in [14], this type of scheduling mechanism provides a more fair resource sharing among the users, especially in the cases where some users are served only by one cell, while other users are served by multiple cells using DC functionality.

IV. SIMULATION ASSUMPTIONS

All the elements of the site-specific scenario described in Section II were imported into a system-level simulator. This simulator follows the LTE specifications, including detailed

modeling of major RRM functionalities such as packet scheduling, hybrid ARQ (HARQ) and link adaptation explained in [15]. A closed loop 2x2 single-user MIMO with pre-coding and rank adaptation is assumed for each link and the UE receiver type is Interference Rejection Combining (IRC) [16]. Macro and small cells are deployed with two 10 MHz non-overlapping CCs at 2.6 GHz. The time-variant traffic model explained in Section II is applied, assuming payload size of B = 4 Mbit. Simulations are run for a time duration corresponding to at least 3000 completed calls; this assures a reasonable confidence level for the considered KPIs. Table I summarizes the simulation assumptions.

TABLE I: SUMMARY OF MAIN SIMULATION PARAMETERS

Network Layout	Site-specific Scenario
Antenna Gain	Macro: Real Network Data. Small cell: 5 dBi. UE: 0 dBi
Transmit Power	Macro eNB: 46 dBm. Small Cell eNB: 30 dBm
Bandwidth	2 x 10 MHz @2.6 GHz
Antenna configuration	2 x 2 MIMO with rank adaptation and interference rejection combining
Packet scheduling	Cross-carrier Proportional Fair
Available MCSs	QPSK (1/5 to 3/4), 16QAM (2/5 to 5/6), 64QAM (3/5 to 9/10)
HARQ modeling	Ideal chase combining with max 4 trans
Cell Association Metric	RSRQ or Opportunistic cell selection. $A3_{Thresh}$: 10 dB, $A4_{Thresh}$: -16 dB

V. SIMULATION RESULTS

A. Global Performance Statistics

Fig. 3 and Fig. 4 show the 5%- and 50%-ile UE throughput with different cell association techniques for both no-DC and DC configurations. It is observed that DC provides gain in the studied scenario. The gains of DC come from different factors: first, the UEs gain from a higher transmission bandwidth; this is especially beneficial at low load, i.e. when the probability of accessing all the available radio resources is higher. As observed in the median throughput, at low load, more than 25% gain is obtained from using DC. In the 5%-ile, the low-load gains are slightly lower than the obtained in the median as the worst 5% UEs are mostly macro-only UEs which do not have good channel conditions to small cells.

Second, DC also provides increased multi-user diversity and better inter-layer load balancing. The latter is especially important in this irregular deployment as it helps to balance the load among cells thus achieving a much higher utilization of the resources. In fact, at high offered load, more than 100% gain is obtained in the 5%-ile comparing the case of No-DC and DC with RSRQ-based cell selection. With DC, the carried load of highly-loaded cells is implicitly offloaded to less-loaded cells, which clearly improves the overall performance.

The benefits of the opportunistic cell selection technique become particularly relevant at high load, i.e. when several cells have multiple users to serve, thus the inter- and intra-layer load balancing capabilities of this technique allow UEs to select more appropriate cells. As observed in Fig. 3, the gain of opportunistic cell selection is more significant for non DC-capable UEs; in fact, the opportunistic approach without DC achieves even better performance than traditional DC configurations (based on RSRQ) at very high load. Moreover,
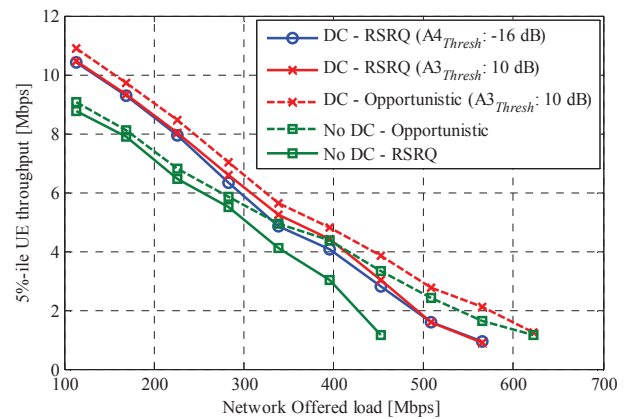

Fig 3. Summary of attained 5%-ile UE throughput performance for different cell selection configurations, for cases with and without DC.

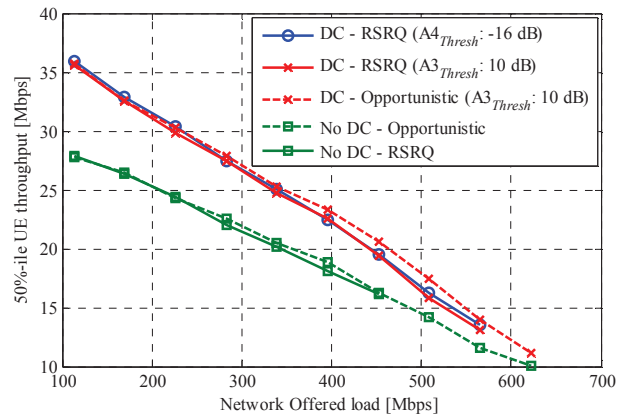Fig 4. Summary of attained 50%-ile UE throughput performance for different cell selection configurations, for cases with and without DC.

a 30% capacity gain at a 5%-ile UE throughput target of 1.5 Mbps is achieved by the opportunistic cell association technique compared to the no-DC with RSRQ-based cell selection case. These considerable gains highlight the importance of also having intra-layer load balancing capabilities in highly irregular networks.

It is worth mentioning that the assumed A3 and A4 values allow, respectively, around 60% and 70% of the total users to be in DC mode. Although the performance impact of having different A3 and A4 thresholds is not shown, we have observed that the performance generally increases with more relaxed thresholds (higher A3 and lower A4 threshold values) as more users are benefitted of DC.

B. Local Performance Statistics

We next analyze performance statistics separately for the areas depicted in Fig. 2. Fig. 5 shows the system capacity gain for a 5%-ile UE throughput target of 6 Mbps in areas 1 to 4. Statistics from area 5 are not shown since there are no small cells in that region. The capacity gain using DC based on the A4 event is also omitted as its performance is very similar to the obtained with RSRQ and A3-based cell association (as can be observed in the global analysis). The capacity gain is defined as the relative additional offered load that the system can tolerate with a certain minimum 5%-ile UE throughput, as compared to the case of no DC with RSRQ-based cell
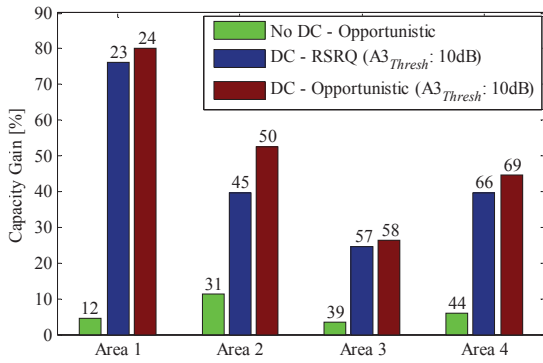
Fig 5. Capacity Gains at a 5%-ile UE throughput target of 6 Mbps for different cell selection configurations per area, as compared to no DC with RSRQ-based cell selection.

selection. The system utilization (in %) for the different configurations and areas is also depicted respectively on top of each bar. It is observed that a very different system utilization is required to achieve the same 5%-ile target throughput in each one of the areas. The latter fact emphasizes the diverseness and irregularity of the studied scenario.

The results in Fig. 5 show that DC provides significant capacity gains in all the considered areas. The main observations are: the highest capacity gains of DC are observed in area 1; in this area, the chosen throughput target is achieved with relatively low system utilization therefore, as concluded in related studies, the gains are more noticeable. For area 2, the observed trends are similar to the ones shown in the global analysis as many of the 5%-ile users are located in this area. The highest gain of opportunistic cell selection is achieved in this area due to the very uneven distribution of the UE traffic. It is worth mentioning that the benefit of the aforementioned technique becomes more significant at higher system utilization (i.e. higher offered load) as observed in the global performance. Area 4 does not get a significant improvement of performance by using the opportunistic cell selection algorithm (despite being at relatively high load). In this area, DC provides relatively high throughput gains at low load (45% and 35% in the 5%- and 50%-ile, respectively) as the small cells are well distributed and entirely covering the traffic hotspots, and there is generally good channel quality of the macro layer.

In general, the gains and benefits of the studied techniques vary severely from one area to another, depending on several factors such as the base stations position and traffic distribution. This fact emphasizes the importance of a local performance analysis in such an irregular network scenario.

VI.   CONCLUSIONS

In this paper we have analyzed the downlink user throughput performance of DC in a realistic network model based on information from a site-specific deployment. DC improves the studied KPIs (5%- and 50%-ile user throughput, and capacity gain) in this realistic deployment. The benefits and gains of DC were different in different areas of the network and mainly depended on the base stations placement and user distribution. New observations were found in this site-specific study not previously seen in related works: apart

from the usual trends at low load, DC was also essential at high load, mostly thanks to the implicit load balancing which allowed a higher utilization of the radio resources and therefore a much better 5%-ile UE throughput and capacity performance. Moreover, the benefits of an opportunistic cell selection technique were also studied. The inter- and intra-layer load balancing capabilities of this technique allowed to achieve considerable performance gains over traditional cell selection techniques and can be considered as a promising feature to further enhance the performance.

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