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Configuration of Dual Connectivity with Flow Control in a Realistic Urban Scenario

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Abstract— **Dual connectivity (DC) is a promising technique to boost the user throughput performance by allowing user equipments (UEs) to receive data simultaneously from a macro cell and a small cell. In order to ensure high degree of realism and practical relevance of the results, we investigate the performance of DC in a realistic deployment based on three-dimensional data from a dense urban European capital area, assuming realistic flow control on the backhaul connections between the macro and small cell eNBs. It is found that the configuration of UEs with DC plays a critical role in the performance of DC under realistic conditions. A modified opportunistic cell association algorithm is proposed. Simulation results show that with proper configuration of UEs with DC, the performance of DC exhibits similar gains as observed in generic 3GPP scenarios.**

I. INTRODUCTION

In order to maximize the benefits of small cell deployments, different multicell cooperation techniques with the target of tight integration with the macro layer have been introduced [1]. In scenarios where the macro eNB and small cell eNB are deployed at different carrier frequencies, dual connectivity (DC) which allows user equipment (UE) to simultaneously receive data from both a macro and a small cell is a promising technique. The benefit of DC depends on the configuration of DC, the type of small cells, as well as the inter-eNB connections. Generally, highest gain is achieved when the small cells are implemented as remote radio heads (RRH) assuming centralized base band processing at the macro and virtually zero latency fiber-based fronthaul connections between the macro and RRHs. This type of DC is also referred as inter-site carrier aggregation (CA) in the open literature. The user throughput performance of inter-site CA has been studied in [2] for commonly accepted stochastic models (e.g. 3GPP models). In [3], the performance of inter-site CA is evaluated in a realistic site-specific scenario and an opportunistic cell association algorithm is proposed.

The scope of inter-site CA is further extended to DC in 3GPP Release 12 to account for the cases where the macro and small cell eNBs are inter-connected via traditional backhaul connections (i.e., X2 in 3GPP terminology) characterized by certain latency and separate radio resource management (RRM) functionalities residing in each cell [4]. In such a scenario, data have to be forwarded from the macro cell eNB to the small cell eNB over the X2 before UEs configured with DC can benefit from simultaneous data reception from the two cells. A flow control algorithm between the involved eNBs is proposed in [5] and the corresponding performance is evaluated under 3GPP scenarios. It is found out that flow control is important in DC with realistic backhaul connections.

In this paper, we analyze the downlink user throughput performance of DC under realistic conditions. In order to ensure high degree of realism, a site-specific scenario corresponding to a dense urban European capital area, realistic traffic distribution and propagation maps from a ray-tracing tool, and realistic flow control over the non-ideal backhaul connections are included. The analysis is performed via extensive system-level simulations. New observations are found when applying the cell association algorithm for DC proposed in [3] under realistic flow control in a site-specific scenario. A modified opportunistic cell association algorithm is proposed for configuring UEs with DC with the target of harvesting the full potential gain of DC. The presented results shed additional light on the performance of DC under realistic conditions as compared to the findings based on generic 3GPP scenarios.

The rest of the paper is organized as follows: Section II describes the the concept of DC, the flow control, and the proposed DC configuration algorithm. The considered network model and simulation assumptions are presented in Section III. Performance results are analyzed in Section IV. Finally, conclusions are drawn in Section V.

II. RADIO RESOURCE MANAGEMENT WITH DC

A. Dual Connectivity Concept

Let us consider a scenario composed of a set of macro cells and a set of small cells deployed at two non-overlapping carrier frequencies. UEs configured with DC can receive data simultaneously from the two connected cells, i.e. a macro cell and a small cell. The assumption is that the UE has its Primary Cell (PCell) configured on the best macro cell, with the option of also having a small cell configured as Secondary Cell (SCell) when feasible. Figure 1 illustrates further details on the downlink data flow for UEs in DC mode between a macro and a small cell. Data from the Core Network (CN) are first transferred to the macro eNB (operating as the master eNB (MeNB)). In the macro eNB the data flow is split, so some data are transmitted to the UE via the macro cell (PCell), while other data are transferred over the X2 interface to the small cell eNB (operating as the secondary eNB (SeNB)), and transmitted to the UE via the corresponding cell (SCell). The X2 interface is a traditional backhaul connection, meaning that

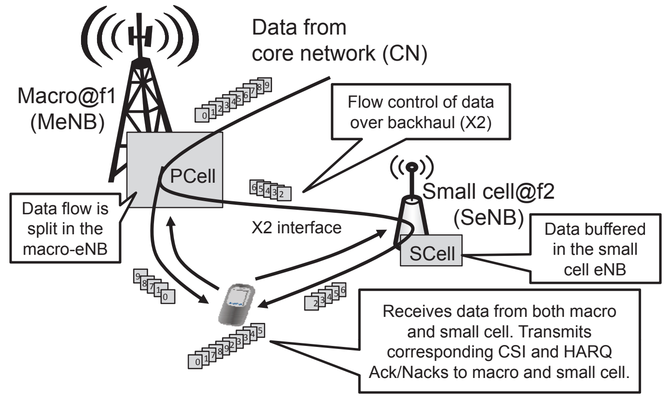

Fig. 1. High-level sketch of assumptions for a user in DC between a macro cell and a small cell operating at different carrier frequencies

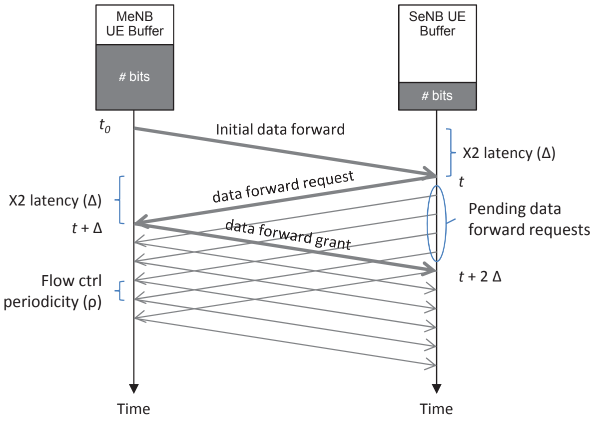

Fig. 2. Schematic illustration of the X2 flow control mechanism

it imposes latencies from few milli-seconds to several tens of milli-seconds depending on the backhaul implementation.

B. Flow Control between MeNB and SeNB

As highlighted in [5], the design of flow control between the MeNB and SeNB over the X2 interface is of importance. If the MeNB doesn't forward enough data to the SeNB, the SeNB buffer may often run out of data, thus limiting the user throughput gain of DC. On the other hand, if too much data is pushed to the SeNB, buffering delay at SeNB is increased and the MeNB buffer may run empty. In this study we adopt the flow control algorithm proposed in [5], which is schematically illustrated in Figure 2. It is a request-and-forward scheme, where the SeNB periodically sends data requests to the MeNB on a per-user basis. The requested amount of data is based on the average past scheduled throughput of the corresponding user at the SeNB, the current SeNB buffer status, and the pending data forward requests. It is worth mentioning that due to the time varying channel conditions and dynamic resource allocation, the estimation of how much data the SeNB should request from MeNB can never be perfect. The accuracy of flow control depends on the backhaul latency, the flow control periodicity, as well as the load conditions [5].

C. Proposed User Cell Association

In most DC studies, the serving cell for the UE is determined based on UE measurements of the received downlink signal strength plus a range extension (RE) value. The use of RE enables a simple form of inter-layer load balancing between the macro and small cell layers. It is observed in [3] that with very inhomogeneous load distributions, intra-layer load balancing becomes even more important than inter-layer load balancing provided by RE (in case of single connectivity) or DC, especially at high load conditions. Thus an opportunistic cell association algorithm was proposed in [3] by not only taking the channel quality, but also the cell load into considerations. The gains provided by opportunistic cell association over traditional RE based cell association can be found in [3]. It is worth mentioning that ideal fiber-based fronthaul connections are assumed in [3], which means that there is no flow control between the MeNB and SeNB.

In scenarios where the small cells are connected to the macro cells with realistic backhaul connections, flow control is needed. Because of the imperfect user throughput estimation at SeNB as well as the X2 latency, flow control between MeNB and SeNB will add additional operation cost on DC. Previous studies show that the gain with DC decreases as the load increases [3][5]. At high load, UEs configured with DC can not benefit from increased transmission bandwidth. Furthermore, unnecessary configuration of DC may worsen the congestion in some of the highly loaded cells due to the fact that those cells might be configured as the secondary cell for DC users. Therefore, the configuration of DC should be carefully designed. Configuration of DC is necessary only if the expected gain from DC is larger than the cost. Otherwise, configuration of DC may result in a performance loss as compared to the case with single connectivity.

Based on those observations, we propose a modified opportunistic cell association algorithm in this paper. For UEs not supporting DC, the serving cell is selected as:

$$n^*_{\mathrm{noDC}} = \arg \max_{n \in \mathcal{M} \bigcup \mathcal{S}} \left\{ \hat{R}_n \mid (\mathrm{RSRQ}_n \geq \mathrm{RSRQ}_{\mathrm{TH}}) \right\} \quad (1)$$

where $\mathcal{M}$ and $\mathcal{S}$ denote the set of macro cells and small cells respectively, RSRQ_n is the Reference Signal Received Quality (RSRQ) from cell n (in dB), $\mathrm{RSRQ}_{\mathrm{TH}}$ is the minimum received RSRQ threshold for candidate cells, and $\hat{R}_n$ is the estimate user throughput in cell n using Shannon's capacity formula and assuming equal resource sharing among the users per cell, i.e.,

$$\hat{R}_n = \frac{1}{U_n + 1} \cdot W_n \cdot \log_2 \left(1 + \hat{\Gamma}_n\right) \quad (2)$$

where W_n is the carrier bandwidth in cell n, U_n is the number of active users in cell n, and $\hat{\Gamma}_n$ is the estimated wideband Signal-to-Interference-plus-Noise Ratio (SINR) for the UE if served by cell n.

For UEs supporting DC, the configuration of DC is based on the estimated gain of allowing the user to connect to a secondary cell as compared to the case with single connectivity. If the estimated user throughput gain is larger than a certain threshold, DC is configured. Otherwise the user is not configured with DC.

$$
\begin{aligned}
n_M &= \arg\max_{n\in\mathcal{M}} \left\{\hat{R}_n \mid (\mathrm{RSRQ}_n \geq \mathrm{RSRQ}_{\mathrm{TH}})\right\} \\
n_K &= \arg\max_{n\in\mathcal{S}} \left\{\hat{R}_n \mid (\mathrm{RSRQ}_n \geq \mathrm{RSRQ}_{\mathrm{TH}})\right\} \\
n^*_{\mathrm{DC},P} &= n_M \\
n^*_{\mathrm{DC},S} &= \begin{cases} n_K & \text{if } \frac{\hat{R}_{n_K}}{\hat{R}_{n_M}} \geq \mathrm{DC}_{\mathrm{TH}} \\ \phi & \text{otherwise} \end{cases}
\end{aligned}
\tag{3}
$$

where n_M and n_K are the best candidate cell in the macro layer and small cell layer respectively, $n^*_{\mathrm{DC},P}$ and $n^*_{\mathrm{DC},S}$ are the serving PCell and SCell respectively, if the user is configured with DC. For UEs not configured with DC, the serving cell is selected according to (1).

The proposed cell association algorithm in (3) prevents configuring a user with DC if that user can not benefit from connecting to a secondary cell, either due to the reason that the channel quality to the secondary cell is too low or the load in the secondary cell is too high.

III. SIMULATION METHODOLOGY

A. Site Specific Network Model

We consider the same site-specific network model studied in [3], which 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 concentrated in a 1.2 km^2 segment of the area which comprises several 3-sector macro sites plus 30 small cells deployed at different carrier frequencies as depicted in Figure 3. Macro base stations (marked as red solid circles) are placed according to realistic operator deployment in the considered area to provide wide coverage, whereas the small cells (marked as green triangle dots) were placed outdoor according to the algorithm in [6] to improve the 5%-ile outage user throughput. The remaining macro base stations (marked as blue empty circles) are only used for generating interference in order to avoid border effects. The radio propagation characteristics are obtained by using state-of-the-art ray-tracing techniques based on the Dominant Path Model (DPM) [7]. Outdoor-to-indoor propagation is modeled by adding an additional 20 dB wall penetration loss as well as 0.6 dB per meter that the users are placed inside the building [8]. As the considered dense urban area is highly irregular in terms of network layout and user distribution, the statistics are not only analyzed globally based on the samples from users in the entire considered area, but also regionally based on samples from users positioned in each sub-area defined in Figure 3.

A dynamic birth-death traffic model is applied for generating user calls, where call arrival is according to a Poisson point process with arrival rate λ and fixed payload size of $B = 4$ Mbits. Once the payload has been successfully received by the UE, the UE is removed from the simulation. Thus, the offered load equals $L = \lambda \cdot B$. 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 the realistic traffic density map. For users that are placed at locations coinciding with multi-floor buildings, there is equal probability of placement per floor. The spatial distribution of user traffic is very irregular (50% of the total traffic is generated from 10% of the area). Moreover, 80% of the traffic is generated from indoors buildings which cover only 40% of the simulated area.

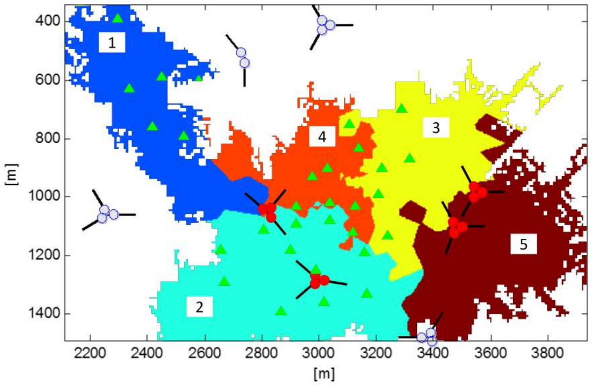

Fig. 3. Spatial location of macro and small cells in a site-specific scenario and sub-division of the considered network area. The macro cells are marked as circles with sectionized antennas while the small cells are marked as green triangle dots.

B. Simulation Assumptions

The simulator follows the LTE specifications, including detailed modeling of major RRM functionalities such as packet scheduling, HARQ and link adaptation [9]. Macros and small cells are both deployed at 2.6 GHz, assuming 10 MHz carrier bandwidth on each component carrier. 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) [10]. Channel-aware cross-carrier proportional fair (PF) scheduler is used in order to achieve better performance in terms of user fairness and coverage [11]. X2-type backhaul connections are explicitly modeled by an X2 latency ranging from 5 ms to 20 ms. The specific flow control parameters are set according to [5]. Simulations are run for a time duration corresponding to at least 3000 completed calls in order to obtain statistical reliable results. Table I summarizes the main parameters used in the system-level simulations.

IV. PERFORMANCE RESULTS

A. Global Performance Statistics

We first present performance results based on statistics collected from the entire network, i.e. global performance. Figure 4 and Figure 5 show the 5%-ile and 50%-ile user throughput with and without DC under different cell association algorithms and backhaul configurations in the whole

TABLE I

SUMMARY OF MAIN SIMULATION PARAMETERS

Parameters	Settings
Transmit power	Macro eNB: 46 dBm; small cell: 30 dBm
Bandwidth	2×10 MHz @ 2.6GHz
Antenna configuration	2×2 MIMO with rank adaptation and interference rejection combining
Antenna gain	Macro: 17 dBi; small cell: 5 dBi
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)
BLER target	10% for the first transmission
HARQ modeling	Ideal chase combining with max 4 trans.
X2 latency	5 ms, 10 ms, 20 ms
Flow ctrl periodicity	Every 5 ms
Cell Association Metric	$\mathrm{RSRQ_{TH}} = -16$ dB $\mathrm{DC_{TH}} = 0.2$

network. The performance with inter-site CA assuming ideal fiber-based fronthaul connection without flow control is also plotted in order to have an upper bound performance of DC. The selected range of offered load corresponds to a system in equilibrium, where the carried load equals the offered load. By applying the opportunistic cell association algorithm from [3] in site-specific scenario with realistic flow control, it is observed that the 5%-ile user throughput with DC gets worse as compared to the case without DC (i.e. single connectivity) at high load conditions. This behaviour is not observed in [3] due to the assumption of ideal fronthaul connections without flow control. Detailed statistic analysis with DC at high load reveals that almost half of the worst 5%-ile users are DC users, among which 77% of them receives $\geq$ 90% of the traffic from only one connected eNB. It indicates that quite many UEs are configured with DC but do not actually benefit from receiving data from the two connected eNBs. Furthermore, statistics show that in those highly loaded macro or small cells around 45% of the users are DC users, which indicates that the configuration of DC has to be careful otherwise it may worsen the congestion in those highly loaded cells.

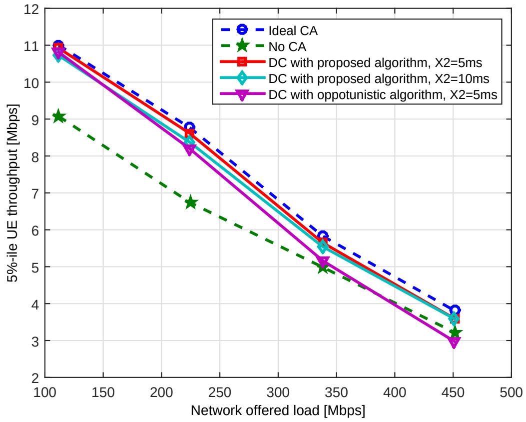

Fig. 4. 5%-ile user throughput from global statistics with/without DC under different cell association algorithms and backhaul configurations.

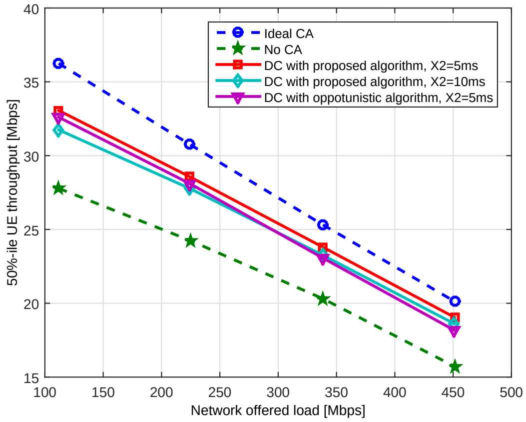

Fig. 5. 50%-ile user throughput from global statistics with/without DC under different cell association algorithms and backhaul configurations.

By proper configuration of DC with the proposed cell association algorithm, the performance of DC in site-specific scenario exhibits similar trends as observed in 3GPP scenarios [5]. Both the 5%-ile and 50%-ile user throughput with DC are significantly higher than the case without DC. The user throughput performance decreases as the X2 latency increases, but in any case it is significantly better than the performance without DC. The gain with DC is mainly from higher transmission bandwidth, increased multi-user diversity order, and faster inter-layer load balancing, thus achieving a better utilization of the radio resources across macro and small cell layers. It is observed that the ratio of UEs configured with DC in site-specific scenario ($\sim$ 45%) is much less as compared to generic 3GPP scenarios ($\sim$ 90%), due to the highly irregular nature of the considered network in terms of radio propagations and the non-uniform spatial traffic distributions. Statistics also show that most of the worst 5%-ile users are the macro-only users of which are not in the coverage area of small cells, thus can not benefit from DC. That is why the gain of DC at 50%-ile user throughput is slightly higher than the 5%-ile user throughput.

B. Local Performance Statistics

We next analyze the local performance statistics collected for each of the defined network areas as illustrated in Figure 3. Figure 6 shows 5%-ile user throughput with and without DC under different backhaul configurations in different areas. Statistics from area 5 are excluded as there are no small cells deployed in area 5. DC gain is quite obvious for areas 1-4 where both macro and small cells are deployed, but the specific performance in each area is quite different. In general, there is relative large variability of the performance from one area to another due to the different characteristics of each area, such as base station locations and traffic distributions. This fact emphasizes the importance to analyze the local performance statistics in such an irregular network scenario.

Figure 7 shows the system capacity gain with DC in different areas. The capacity gain is defined as the relative additional offered load that the system can accommodate with

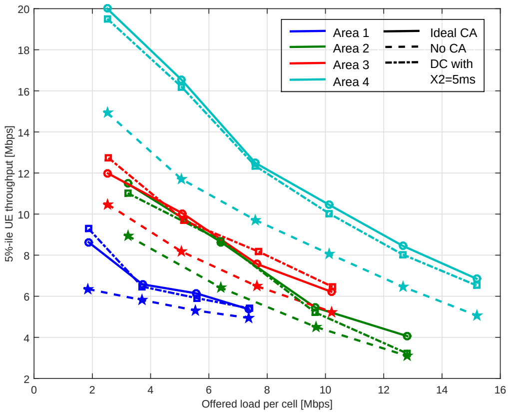

Fig. 6. 5%-ile user throughput per area with/without DC under different backhaul configurations. Offered load per cell is defined as the offered load per area divided by the number of cells in each area.

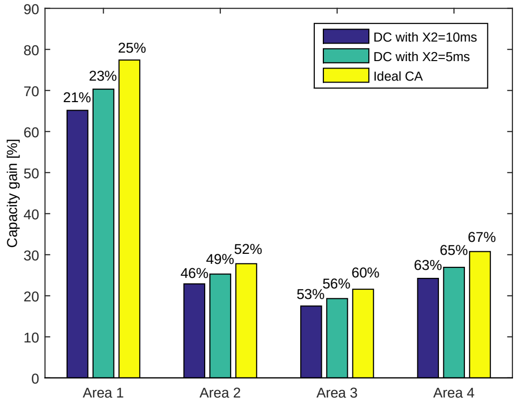

Fig. 7. Capacity gain of DC for a target 5%-ile UE throughput of 6 Mbps per area under different backhaul configurations as compared to no DC with opportunistic cell association, and the average resource utilization in each area

DC for a certain minimum 5%-ile UE throughput (6 Mbps in our study), as compared to the case without DC. The average system resource utilization (in percentage) in each area is depicted on top of each bar. It is shown that a very different resource utilization is required to achieve the same 5%-ile target user throughput in different areas, which reflects the diversity and irregularity of the considered area. Area 1 achieves the highest capacity gain of DC because of the relative low system utilization. This is in accordance with the observations from previous CA/DC studies which indicate that the gain is more noticeable at low load [3]. It is worth highlighting that although each area exhibits quite different characteristics such as network layout and user distribution, promising DC gains are observed in each area (ranging from 20% to 70%). The specific gain number in each area is different from [3] due to the change of cell association in the reference scenario. It can be concluded that the proposed UE cell association algorithm together with the flow control algorithm proposed in [5] are able to adapt to the local time-variant conditions in a realistic network deployment, thus having high potential to be applied in practice.

V. CONCLUSIONS

In this paper, we have analyzed the downlink user throughput performance of DC in a realistic network based on data from a segment of a irregular dense urban European capital area, assuming realistic flow control and non-ideal backhaul connections between the macro and small cell eNBs. It is observed that the configuration of UEs with DC has a big impact on the performance of DC under realistic conditions, especially at high load conditions. Unnecessary configuration of DC may cause a performance loss not only due to imperfect flow control between the involved eNBs, but also may cause further congestion to some of the highly loaded cells by configuring DC UEs to those cells as secondary cell. A modified opportunistic cell association algorithm is proposed to configure a UE with DC only if the estimated gain by connecting to a secondary cell is larger than a certain threshold. Simulation results show that with proper configuration of DC, promising throughput gains are observed both for the entire considered area as well as for sub-region areas with different characteristics. The findings shed additional light on how to harvest the full potential of DC in a practical setting. We conclude that the proposed scheme for DC (i.e., modified opportunistic cell association and flow control) is generally applicable for real-life dense urban environments.

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