Data-Driven Performance Evaluation of Carrier Aggregation in LTE-Advanced

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***Abstract*—Carrier aggregation increases the throughput of LTE mobile networks by aggregating bandwidth at different frequencies. The theoretical effectiveness of carrier aggregation has been widely studied in the literature and operators claim it substantially increases the network data rate. However, to the best of our knowledge no practical evaluation of the performance of carrier aggregation has been performed using real traffic data. We perform a thorough measurement-based study to assess how carrier aggregation improves the service offered in selected locations in Madrid, Spain. Although the best results for data rate boost are in line with the operator claims, we find that resource usage in aggregated bands is frequently suboptimal, and higher data rates could be achieved by simply overloading a single band. On the other hand, the quality of service achieved by users effectively exploiting carrier aggregation could not be achieved without it.**

***Keywords*-LTE-Advanced; Carrier Aggregation; measurements; traffic profiling;**

I. Introduction

Mobile broadband communications have been recently experiencing a huge growth in terms of user number and quality demands [1]. Moreover, high definition multimedia applications are becoming the first source of mobile traffic. As a consequence, the network is requested to provide an even higher aggregate throughput and higher data rates to individual users.

To face these new requirements Carrier Aggregation (CA) has been introduced in Long Term Evolution (LTE) networks starting from release 10 in 2011. CA allows operators to combine the services offered at different frequencies in order to increase the peak data rate [2]. This technology is offered in urban areas by the main operators, which claim to be able to double the offered data rate. For instance, in Spain, data rates of up to 300 Mbps are advertised [3].

To the best of our knowledge there are no works in the literature that evaluate the performance of CA with practical experiments. In fact, academic papers mainly focus on its optimization: for instance, [4] studies smart and fair resource allocation methods; application-aware resource allocation methods aiming to improve user experience and resource optimization are discussed in [5], while [6] proposes algorithms to minimize CA (Multi-stream) energy consumption in heterogeneous networks. Finally, [7], [8] evaluate the energy efficiency of CA by means of practical measurements. However no work so far grounds its results on real traffic data. Since traffic information is almost exclusive to operators, the academic community is mostly limited to theoretical conclusions. Hence, there is no indicator of how efficient is this technology in real deployment or whether theoretical results are feasible. In this paper, we evaluate CA on real traffic measurements to understand whether the operators' claims are correct and whether users should expect different performance from what advertised.

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In order to study CA on real data, we investigate the LTE traffic in three different locations in Madrid. To this extent we log scheduling information of operators adopting CA in the measurement locations. We perform our measurement campaign using the Online Watcher of LTE (OWL) [9], which reliably decodes the LTE Control Channel. For our measurements we use a laptop with three BladeRF boards [10], a Software Defined Radio (SDR) platform with LTE sampling capability.

We compare the network performance of users with and without CA in a measurement campaign that lasted 21 days. Our data shows that CA is not consistently used everywhere and, for certain scenarios, up to 60% of the users could have obtained higher data rates without CA, but at a high network resource cost. However, in the best cases the operators' claims are confirmed. In addition, we find that the CA traffic served in the three locations could have been served by using a single carrier with minimal performance degradation. In most of the cases the experienced communication delay would not exceed 10 milliseconds and in no case would it be larger than 100 milliseconds.

The rest of the paper is organized as follows: Section II describes the basis of CA theory. Section III describes the parameters and metrics we use to evaluate CA performance. Section IV gives the details of our measurement campaign. Section V presents the experimental results. Finally, Section VI concludes the paper.

II. Carrier Aggregation in LTE-Advanced

Carrier Aggregation expands the effective bandwidth assigned to a user device through the utilization of radio resources in different LTE bands simultaneously. We refer to each of the bands used in LTE that can be aggregated for transmission as Component Carriers (CC). CA does not increase the spectral efficiency, but enhances data rates by assigning more bandwidth to the individual users.

In LTE, Radio Resource Control (RRC) protocol is used to configure the connection between user equipments (UEs) and base stations (eNodeB). When a UE connects to the network or when it changes eNodeB, it is assigned to a CC, which is referred to as Primary Cell (PCell). Subsequently, if CA is supported by the UE and the operator can exploit different CCs in the area, the RRC can be used to add one or more additional CCs [11]. The additional CCs are referred to as Secondary Cells (SCells). RRC performs CC addition and removal based on channel quality measurements to ensure the best link quality for each band and, in turn, the best efficiency.

The CCs combined can belong to the same band (i.e., using the same frequencies) or to separate portion of the spectrum. We refer to the two options as intra and inter band CA, respectively. In addition, inter band CA study is more interesting, because the radio characteristics of the different CCs, such as coverage or channel quality, are almost completely decoupled [12], while in intra band CA, it is more likely that the performance of PCell and SCell is quite similar.

The LTE control channel is a dedicated group of resources in the downlink channel and is used to provide users with scheduling information and power control commands. In the control channel UEs are identified by Cell Radio Network Temporary Identifiers (C-RNTIs). This identifiers are 16-bit addresses unique only within the eNodeB scope. Thus, C-RNTIs cannot be used to obtain the users unique identities (i.e., International Mobile Subscriber Identity (IMSI)). They are discarded if a UE is inactive for longer than 10 seconds and on handover. While each CC has its own control channel, each user has a single RRC active session, thus the UE shares the same C-RNTI identifier for PCell and any SCells regardless of the number of CCs used [13].

Figure 1 illustrates the C-RNTI usage in one of our test locations for an operator performing CA using 2 CCs. We observe that the C-RNTIs belonging to the two CCs monitored in the location only occupy a portion of the possible address space. For instance, C-RNTI values for users in band 1 (light red in the figure) range from 3000 to 4200, while band 2 values (light blue) range from 5000 to 6000. A set of C-RNTIs are common for the two CCs. These overlapping addresses belong to users for which CA is configured, using the same identifier in both CC. We highlighted the CA RNTIs (i.e., RNTIs that are observed in one cell, but belong to the RNTI range of a different cell) using dark blue and dark red, for band 1 and 2, respectively. Finally, RNTIs on both ends of the address space are reserved for control operation: random access procedure uses RNTI in the range 1 to 10, while paging and system information communications use RNTI 65534 and 65355, respectively.

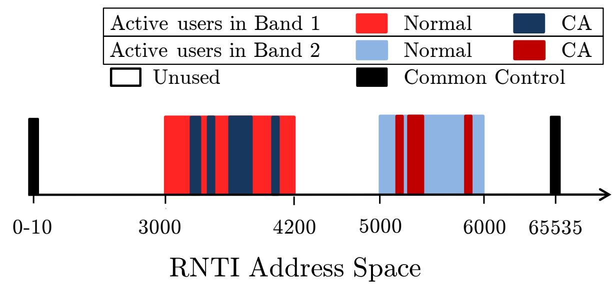


Fig. 1: RNTI utilization for two LTE bands performing carrier aggregation.

Resource scheduling methods have been also modified for CA. For communications without CA, a dedicated control channel is used for each CC. However, when CA is enabled, SCells can be either scheduled using their own control channel or they can be scheduled using PCell control channel. The two methods go under the names of Same Carrier Scheduling (SCS) and Cross Carrier Scheduling (CCS), respectively. The latter needs the inclusion of a Carrier Field Indicator (CIF) that specifies which CC the scheduling message refers to. Although we have included CCS support in OWL for the measurements, we find no evidence of intra band CA or CCS usage in the selected locations.

III. Evaluating Carrier Aggregation Performance

This section focuses on the performance of inter band CA with SCS. This configuration consists of different CCs in different frequency bands (inter band CA) that can be aggregated to provide UEs with higher data rate. The scheduling information for each CC is provided in its own control channel (SCS). We analyze the performance of a UE with CA, and compare this to the performance the UE would have obtained, had it only been associated with the PCell and had the combined traffic been served exclusively by the PCell.

The control channel of each CC specifies the following set of parameters for each transmission:

▷ **Modulation and Coding Scheme (MCS)**, $m_{i,j} \in \{0, 1, \ldots, 28\}, i \in \mathcal{T}, j \in \mathcal{N}$, specifies which modulation and coding scheme is used for user j at time i for data transmission. $\mathcal{T} = \{0, 1, \ldots, T\}$ is the set of the T time slots considered in our test and $\mathcal{N}$ is the set of the N active users in the test. The MCS indicates how much information can be packed in a single resource unit. This parameter depends on the channel quality so that better channel conditions correspond to higher MCS values.

▷ **Resource blocks (RB)**, $c_{i,j} \in [1, c_M]$, is the amount of network resources scheduled for a user, where a resource block is the smallest amount of frequency resources assignable to a user in a transmission time interval (TTI) and c_M is the number of resource blocks available in the CC bandwidth. c_M is 6, 15, 25, 50, 75 or 100 for 1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz and 20MHz respectively.

▷ **Transport block size (TBS)**, $b_{i,j} \in [0, b_M]$, is the amount of bits transferred by the communication and b_M is the maximum transport block size and depends on the CC bandwidth. Note that this parameter translates to the instantaneous data rate in Kbps assigned to a given user since it represents the bits transferred in a millisecond.

In what follows, we use a compact notation for the sum over users and time slots: $\sum_{i\in\mathcal{T}} x_i = \sum_{\mathcal{T}} x$ and $\sum_{j\in\mathcal{N}} x_j = \sum_{\mathcal{N}} x$, where x is a dummy variable. Next, we define the metrics we use to evaluate CA performance:

▷ **Load**, $L \in [0, 1]$, is the average fraction of network resources allocated in a CC and is computed as $L = \sum_{\mathcal{T}\mathcal{N}} c/Tc_M$.

▷ **Data rate**, $R_j \in [0, R_M]$, is the average quantity of bits transmitted in a period of time for user j, R_M being the maximum data rate, and is computed as $R_j = \sum_{\mathcal{T}} b_j/T$.

▷ **CA usage**, $C \in [0, 1]$, represents the ratio between the CA traffic size and the total traffic of the CC and it is defined as $C = \sum_{\mathcal{T}\mathcal{N}_s} b / \sum_{\mathcal{T}\mathcal{N}} b$, where $\mathcal{N}_s$ is the set of users that use the CC as SCell.

▷ **Efficiency**, $\eta \in [0, 28]$, is the ratio between the MCS used to communicate in the SCell and the MCS that the PCell has at the same time or, in other words, it is a comparison of the channel quality obtained using CA and what that would have been achieved if CA had not been used. We compute carrier aggregation efficiency for user j at time i as $\eta_{i,j} = m_{i,j}/\widehat{m}_{i,j}$, where $m_{i,j}$ and $\widehat{m}_{i,j}$ are the MCS of the SCell and the PCell of user j at time i, respectively. In this way, $\eta > 1$ implies CA strategies are more efficient, while the opposite is true for $\eta < 1$.

▷ **Data rate boost**, $G \in [0, \infty)$, is the average fraction of data rate increase due to CA transmission. In fact, using additional CCs enables higher data rates. The data rate boost is computed as $G = R_s/R_p$, where R_p and R_s, are the average data rate of the PCell and SCell, respectively.

▷ **Effective boost**, $\phi \in \mathbb{R}$, measures how effective is the scheduling in the SCell. We compute this as $\phi = (R_s - \widehat{R}_p)/\widehat{R}_p$, where $\widehat{R}_p$ is the average data rate obtained by CA communications if they were performed in the PCell. Note that, for $\phi < 0$ higher data rate would be achieved if resources were allocated only in PCell.

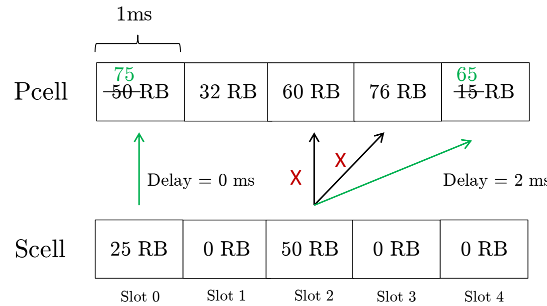


Fig. 2: Delay example for 20MHz band in PCell

▷ **Load saving**, $\mu \in [0, 1]$ is the fraction of the PCell load that is saved by means of CA communications. It is computed as $\mu = \widehat{L}_p/(\widehat{L}_p + L_p)$, where L_p is the average load of the PCell and $\widehat{L}_p$ is the average load the SCell communication would have had in the PCell if CA had not been used.

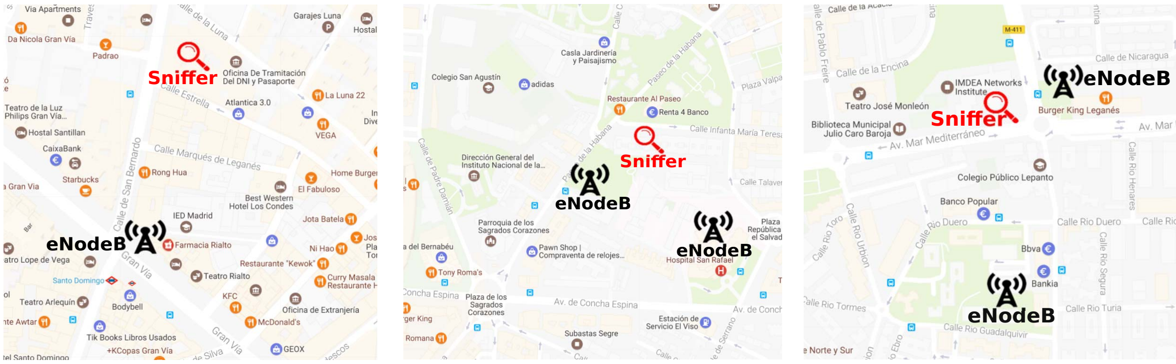
▷ **Feasibility**, $F \in [0, 1]$ is the fraction of CA transmission that could have been scheduled in the PCell within D_M ms from their transmission time, where D_M is the maximum allowed delay for a given communication. For each CA transmission we compute the amount of resources that it would have used in the PCell and we check whether it could have been scheduled there or not.

▷ **Delay**, $D \in [0, D_M]$, describes the average delay incurred if CA transmissions have to be scheduled in the PCell only. In Figure 2 we exemplify feasibility and delay by illustrating the scheduling of 5 time slots (i.e., subframes) in PCell (top) and SCell (bottom) for a 20 MHz LTE channel (i.e., 100 RBs per CC). In each slot we write the number of used RBs in PCell and SCell. In the example there are two CA transmissions to be moved in the PCell. The first, in slot 0, can be scheduled in PCell with no delay, since the sum of the RBs used by both CCs is smaller than the size of either of the two. Instead, the second CA transmission at slot 2 cannot be scheduled in the PCell in the same slot, but has to wait 2 ms to find enough free resources to be served. In this example we do not adjust the required resources to move CA transmissions in the PCell, because we assume the two CCs to have the same MCS. However, this does not hold in general.

IV. Experiment Description

The objective of our measurement campaign is to evaluate the usage of carrier aggregation by different operators and in different locations in Madrid. To this end we use the latest version of OWL [9], an open-source decoder of the LTE control channel[1]. Thanks to this tool, which we modified to support the LTE features related to CA, we can decode the control channels of up to three LTE bands using three SDRs and a laptop.

[1] Link: https:\\git.networks.imdea.org\nicola_bui\imdeaowl



(a) Gran Via (b) Bernabeu (c) IMDEA

Fig. 3: Measurement locations

In Spain, the three most relevant operators, Vodafone, Movistar and Orange, offer carrier aggregation in urban areas since 2015, and the supported frequencies are in bands 3 (1800 MHz), 7 (2600 MHz) and 20 (800 MHz). However, none of the operators provide further information about where and how CA is implemented.

Fig 3 provides the maps of the three monitored locations: two are in Madrid (Gran Vía and Bernabeu) and one at IMDEA Networks Institute, in Leganés (Madrid suburbs).

a) Gran Vía: This location is in one of the most crowded areas of the city, which is characterized by high network load [14]. From this location, the only operator that we could log in multiple bands is Vodafone that uses bands 3 and 20.

b) Bernabeu: This location is a residential area close to the stadium Santiago Bernabeu and, here, the network load is much lower than in the city center. Due to the stadium location the traffic level increases during match days. In this location we log Vodafone channel in bands 3 and 20.

c) IMDEA: From our laboratories we monitor a low traffic residential area, which is mainly served by Yoigo and Vodafone, but only the latter operates on more than one band, specifically bands 3 and 20. The antennas of the different CCs are not co-located (see Fig. 3c).

The final output of the measurement campaign is a data set of 21 days, more than 500 hours of LTE Control Channel measurements with 1ms data granularity divided in three locations and for 2 bands per location.

V. Experimental results

While carrier aggregation is mainly known for its peak rate increasing capability, it is also used to distribute the load among CCs. In fact, in the three locations of our data set, we find that CA is more frequently used to boost the data rate at IMDEA. Moreover, in all the three locations not more than 5% of the users (RNTIs) are active in both CCs.

Moreover, we observe that the CA configuration in Gran Vía and Bernabeu consists of a wider (75 and 100 RBs) PCell in the 1800 MHz band and a narrower (50 RBs) SCell in the 800 MHz. Due to the weaker pathloss at lower frequencies, this setup allows to provide more consistent service to cell-edge users. In these locations not only is the data rate boost of CA rarely used, but also, when it is, it does not last longer than 100 ms. Note that the low penetration of CA may also be due to mobile phones not supporting it (i.e. pre category 6 devices).

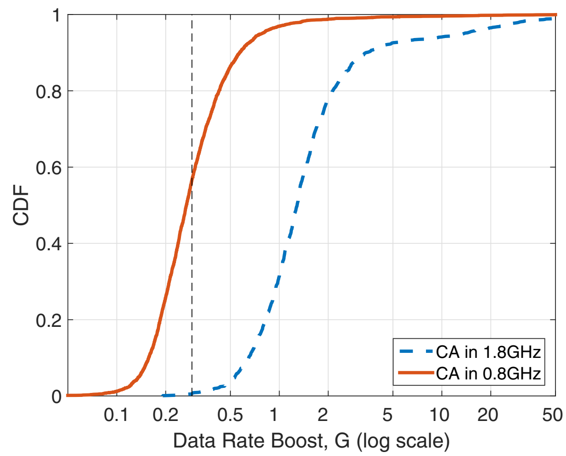


Fig. 4: Data rate increase due to carrier aggregation. The vertical dashed line marks the start of the energetically efficient operations.

Instead, at IMDEA, CA is used to increase the users' data rate in 96% of the 10000+ communications. In addition, we observe that the percentage of CA traffic is 16% at 800 MHz and slightly higher than 4% at 1800 MHz. In both cases, CA is used more consistently than in the other locations and usually for longer than 2000 ms.

In what follows, we focus on the data rate boosting capability of CA, which is the feature most advertised by operators. In particular, we consider all the users active simultaneously in two CCs in all the three locations to evaluate whether the quality of service delivered is inline with what the users can expect and whether CA is

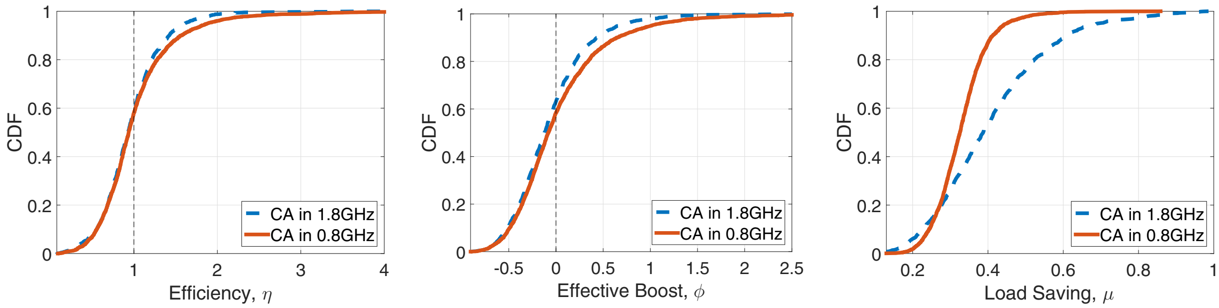


Fig. 5: Comparison of the CA efficiency for 800 MHz and 1800 MHz SCells.

efficient in terms of network load compared to standard (i.e., release 9) LTE performance.

Figure 4 illustrates the Cumulative Distribution Function (CDF) of the data rate boost achieved using CA. The graph is obtained by considering each user individually, averaging on his/her boost, and computing the CDF over the users. In this and the next three figures, we separate the results achieved by performing CA from a CC at 800 MHz to one at 1800 MHz (red solid line) from the opposite case (blue dashed line). Since in Europe the spectrum leases at 1800 MHz and 2600 MHz are wider than those at 800 MHz, performing CA to 1800 MHz offers higher performance gain. In fact, in our data set more than 70% of the cases of CA to 1800 MHz can effectively double the data rates, while performing CA to a 800 MHz CC only provides between 20% and 60% boost. However, absolute values for data rate improvement show that CA to 800 MHz band achieves aggregated data rates of 88 Mbps, while for the opposite configuration 34.7 Mbps are achieved. Also, on average, SCell in 800 MHz offers data rates of 1.2 Mbps, whereas the other configurations show only 741 Kbps.

In terms of energy efficiency, the authors of [7] estimate that a data rate boost of at least 29% makes CA more energy efficient than single carrier alternatives. Thus, from our measurements, half of the communications using a 800 MHz SCell and almost all those at 1800 MHz are energetically efficient. However, for 800 MHz SCell, also half of the users are experiencing an increase in power consumption without a significant boost in data rates.

The three graphs in Fig 5 provide our results in term of CA efficiency. The graph on the left shows the CDF of the users average efficiency η, the one in the center shows the CDF of the effective boost ϕ, and the graph on the right shows the CDF of the load saving μ. All the three plots report CA at 800 MHz as red solid lines and at 1800 MHz blue dashed lines.

In Figure 5 (left), values $\eta < 1$ correspond to users for whom using CA (i.e. receiving from the SCell) is less efficient than using a single carrier. In fact, for $\eta < 1$ the average MCS used in the SCell is smaller than that used in the PCell, which makes CA transmission less efficient than using more resources in the PCell. The channel quality of SCell communication is better than that on PCell for circa 41% and 40% of the users, when the SCell is at 800 MHz and 1800 MHz, respectively.

This behavior can be due to users connecting to the network by configuring the PCell as the best CC, and additional CCs have usually worse channel quality. This is emphasized when the different CCs are placed at different locations as at IMDEA. These results suggest that, network load permitting, it is usually more efficient to allocate resources on the PCell.

This is further justified by the central graphs of Figure 5 which represent the data rate variation had the SCell transmissions been scheduled on the PCell. Here, negative values, $\phi < 0$, mean that the PCell would have achieved higher data rate had it been used instead of the SCell. As per the previous graph, almost 64% of the users would experience an increased data rate using the PCell only. Moreover, we find that CA with SCell at 800 MHz achieves slightly higher data rates.

Although, on the one hand, communications on the PCell are usually more efficient, on the other hand, scheduling some of the transmissions on the SCell decreases the load on the former. Figure 5 (right) shows the CDF of the average load saving due to CA. Since CCs at 1800 MHz have usually twice the bandwidth of those at 800 MHz, performing CA in the former achieves higher network load savings. In fact, the average saving with CA from 800 MHz to 1800 MHz is about 40% of the CC resources, while the opposite achieves about 30%.

So far, our results assumed it is possible to schedule all the CA traffic on the PCell. In the next two graphs of Figure 6 we consider the feasibility of this assumption. In particular, the plot on the left shows the CDF of the fraction of traffic that can be scheduled in the PCell without delaying the transmission for longer than $D_M \in \{8, 20, 100, \infty\}$ ms[2], while the plot on the right accounts for the average delay of those transmissions.

From the feasibility analysis, we observe that in our data set even the most stringent requirement successfully deliver more than 99% of the transmission. However,

[2]These values correspond to the LTE HARQ period (8 ms), standard VoIP period (20 ms), and 10 LTE frames.

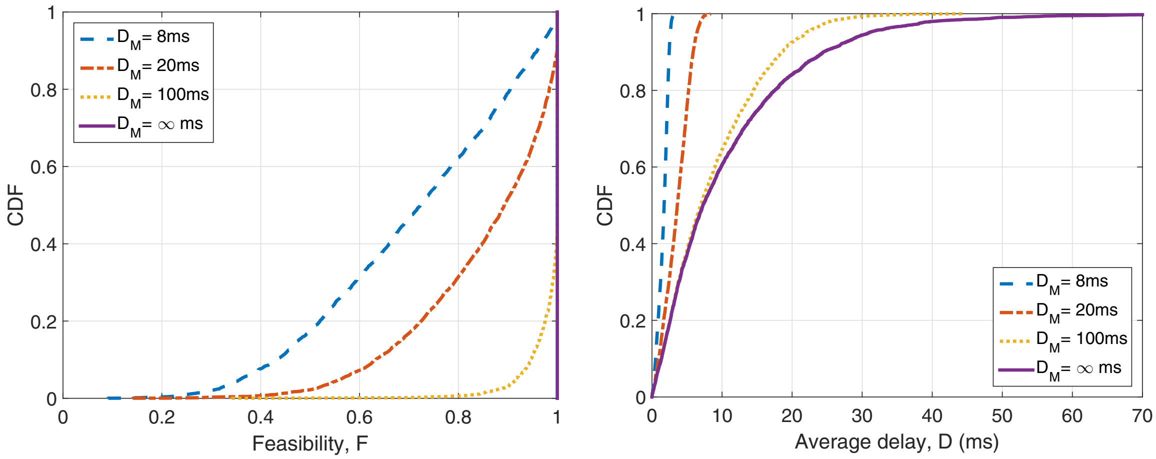


Fig. 6: Feasibility analysis of reallocating CA transmissions to the PCell.

this might not be true for locations with a higher average load. In addition, even a small drop rate may substantially hamper the HARQ process. Instead, more delay tolerant applications would suffer almost no impact at all from using a single carrier rather than CA. Finally, considering the average delays due to the usage of a single carrier, we observe that, even allowing an infinite maximum delay, the worst case average delay is not longer than 70ms.

VI. Conclusion

In this paper we presented the first evaluation of the performance of carrier aggregation solutions in LTE-advanced networks based on real measurements independent of any network provider. Our data shows that, although in the best case scenarios CA achieves the performance claimed by the operators, the larger part of the users could have been served with a single carrier obtaining the same or even better performance. In addition, we found that CA is often used to balance the load between the different carrier components.

However, for the users effectively exploiting CA we found that it would not be possible to guarantee them the same quality of service with the primary cell alone. Thus, even though users are not fully exploiting the potential of CA strategies, the increased spectrum agility and the higher achievable rates make CA a very promising addition for 5G networks.

Further analysis is needed to evaluate the effectiveness of CA strategies when the network load is higher than what we could measure in the chosen locations. In addition, an experimental study on the energy efficiency will help better understanding whether and when to activate multiple CCs.

Acknowledgment

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