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***Abstract*—Carrier Aggregation (CA) is introduced in LTE release 10 to improve data rates by allowing the User Equipment (UE) to receive data on more than one LTE carrier. The related increased complexity is expected to affect the UE current consumption, but yet no empirical evaluation has been published on this topic. Currently there are only theoretical expansions of LTE release 8 power models available, but this article presents the first publicly available current consumption measurements on a commercial CA-capable UE.**

In this work it is examined how the activation and use of CA (10 + 10 MHz) affects the UE current consumption with different traffic profiles such as FTP or web browsing. For a large FTP download the average CA current consumption is reduced 13 % compared to single-carrier 10 MHz due to increased data rate and extended idle time, which allows the UE to enter a low-current sleep mode. For small data bursts, such as keep-alive messages, configuring CA results in 17 mA average current increase during RRC connected state inactivity periods. Depending on the UE background activity, this could translate into 3 % to 8 % reduction of the UE's stand-by battery life.

I. Introduction

Downlink (DL) Carrier Aggregation (CA) has been introduced in 3GPP Long Term Evolution (LTE) release 10 [1]. This feature allows the User Equipment (UE) to receive data from up to five different Component Carriers (CCs). While each CC is backwards compatible with previous LTE releases, a CA-capable UE can potentially aggregate the CCs to achieve a total bandwidth of up to 5x20 MHz = 100 MHz. This obviously helps increase the data rates, but it can also bring additional benefits in terms of frequency diversity by aggregating CCs on different frequency bands with different propagation properties such as band III (1.8 GHz) and band V (850 MHz). Finally, the use of CA can also be beneficial in scenarios with fragmented spectrum since the CA-capable UEs can aggregate those spectrum chunks to boost the data rates.

Supporting CA will induce a more complex UE design both in terms of receiver and transmitter RF [2], but also increased baseband processing due to channel estimation over a larger bandwidth or different CCs, higher data rates, etc.. So far little work has been published on how this will affect the UE battery life, which is crucial for user satisfaction [3]. When CA was standardized in 3GPP some contributions, such as [4], [5], discussed the effect on UE complexity and battery life, but without quantifying the current consumption. Since then researchers have estimated the current consumption of CA UEs by extending empirical models based on measurements on LTE release 8 UEs. In [6] DL CA current consumption was studied by increasing the bandwidth and number of RF chains of a previously established single-chain model, while [7] presented a similar study for uplink (UL) CA by combining measurements on multiple release 8 power amplifiers. Both studies showed that if CA provides a significant throughput increase then energy can be saved, but until now the conclusions have not been validated by real measurements.

Since no commercial CA devices have been available, the verification of the theoretic models has not been possible until recent dates. This, however, changed with the launch of the first commercial CA-capable device in summer 2013 [8] and therefore we present, to our best knowledge, the first independent current consumption and throughput measurements on a commercial CA UE.

Our objective is to provide a detailed analysis on how CA affects UE throughput and current consumption in relevant scenarios such as FTP file transfer and web browsing sessions, but also examine how CA may affect UE current consumption when CA is configured but unused. This information can also be useful for network operators to determine how to setup their network to ensure longer UE battery life, and thereby improve user satisfaction.

The article is structured as follows: section II presents an overview of CA in LTE, and discusses how it impacts the UE's current consumption. In section III the measurement setup is described, and in section IV the related results are presented. Finally a discussion and conclusion is given in sections V and VI respectively.

II. Carrier Aggregation in LTE

Two main scenarios are defined for LTE CA: intra-band, with either contiguous or non-contiguous CCs, and inter-band in which the CCs belong to different frequency bands. Each CC is backwards compatible, which means the control and data signaling complies with release 8 and has the same numerology. Consequently a release 8 UE is still able to use a single CC of a network that also supports CA. The bandwidth of each CC is also limited to what was specified for the single-carrier band, for example maximum 20 MHz for band III and 10 MHz for band V [9].

The inter-band scenario is the most challenging from a UE perspective, because the multiple separated bands require multiple receive and transmit chains, each with a Local Oscillator (LO) tuned to the band's carrier frequency. The large number of frequency bands specified in 3GPP LTE (more than 20 for single-carrier FDD) entails that there are numerous

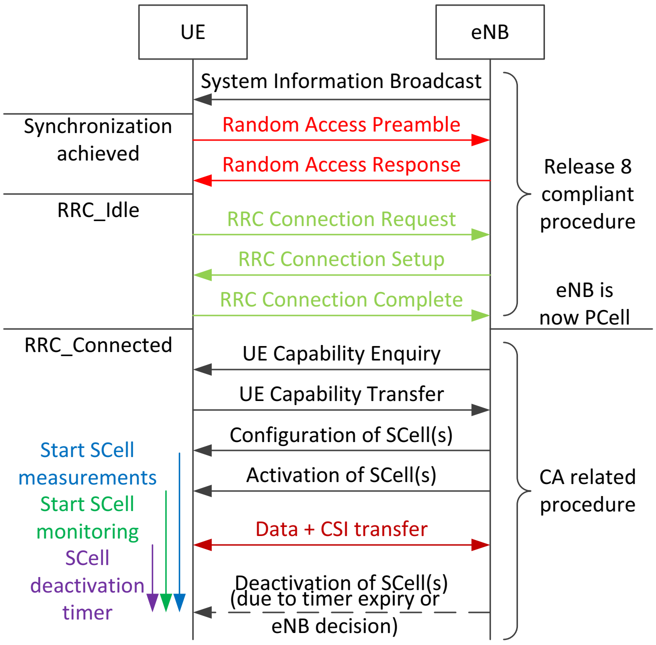

Fig. 1: Procedure for connecting a CA UE to an eNodeB.

combinations for inter-band CA. The number of standardized combinations has already increased from 1 to 21 between release 10 (version 10.13) and release 11 (version 11.7) [9] causing major challenges for chipset designers, who have to deal with a multitude of coexistence issues and coupling of LOs [2]. This affects both cost and current consumption of the UE. From a baseband processing perspective the CA scenario has little effect on the current consumption [2], because the throughput is the defining metric for the current consumption regardless whether single-carrier or a CA scenario is considered. Furthermore, the UE's energy consumption per transferred bit actually decreases when incrementing DL and UL throughput in regular release 8 devices [10]. This is also expected to be the case for CA UEs.

When the CA UE is switched ON and performs the network selection procedure, it will connect to a single CC, known as Primary Cell (PCell), following normal release 8 procedures as illustrated in Figure 1. After the UE has become RRC_Connected the network will request the UE's capabilities, and then configure a certain number of additional CCs to the UE. The CC configuration depends among other things on the UE capabilities and Quality-of-Service requirements [1]. These additional CCs are called Secondary Cells (SCells) and when they are configured the UE may have to periodically monitor the receive power level of the SCell(s) causing an increase in current consumption. Once configured, the SCells may be activated by the network, using an "Activation/Deactivation MAC Control Element" [11], when e.g., a certain data buffer threshold is met. The exact activation algorithm is not standardized and therefore vendor specific. For each active CC, the UE continuously monitors the control channels and reports channel state information (CSI) needed for scheduling purposes. Monitoring and reporting SCells is costly power wise due to the additional RF chains and baseband processing required. Therefore 3GPP standardized a timer-based deactivation mechanism for SCells [11]. The timer, known as "sCellDeactivationTimer", is restarted whenever the

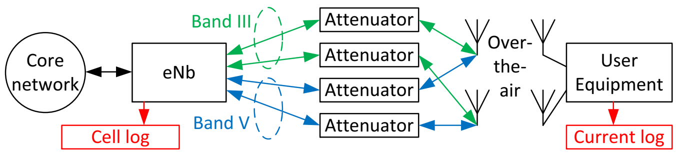

Fig. 2: Block diagram of the measurement setup.

UE receives an UL grant or DL assignment, and upon expiration the UE must deactivate the SCell, discontinue the control channel monitoring and the CSI reporting. The SCell can also be deactivated by the network using the aforementioned MAC Control Element. Finally, the network can command the UE to release a specific SCell.

III. Measurement Setup

The test environment for this study was designed to measure both performance and battery usage of a commercial device under emulated realistic network conditions in a laboratory environment. A commercial CA-capable smartphone, and a state of the art LTE end-to-end network including eNodeB and Enhanced Packet Core (EPC) equipment were used. The eNodeB included two radio modules transmitting in band III (1.8 GHz) and band V (850 MHz) respectively, which enabled 10+10 MHz downlink inter-band carrier aggregation, i.e. configuration CA_3-5 [9], or single-carrier configurations up to 20 MHz in band III or 10 MHz in band V. Intra-band CA configurations were not tested due to lack of support from the UE. All the tests were done using open loop 2x2 Multiple-input Multiple-Output (MIMO) in both bands. Over the air transmission was done by combining the signals from each band through two general purpose antennas, as described in Figure 2. Furthermore, each of the four radio paths (two for each band) was connected to an independently configurable attenuator which allowed setting up different path loss imbalance between carriers.

The current consumption was measured with an external, constant 4 V DC supply which was connected directly between the battery and the input power pins of the UE. Additionally, cell logs with sub frame resolution (1 ms) were collected for throughput and packet scheduling analysis.

For most of the tests, based on file data transfer, the display was switched OFF after the application was initiated in order to reduce the impact of current consumed by the display. However, when testing more interactive services such as web browsing or YouTube, the display was kept on during the duration of the test.

The scope of the testing was divided in four scenarios:

A. *Impact of carrier aggregation activation*

This test was designed to analyze the impact of having CA configured or activated when there is no active data transmission. I.e. current consumption was monitored during the time where the RRC inactivity timer is running after a file download finishes. The percentage of time spent on RRC inactivity timer becomes relevant when there are a high number of short transmissions, such as keep-alive messages, during long stand-by periods. Connected mode Discontinuous Reception (cDRX) was used in all the measurements.

B. *Large data transmission*

This test was based on the download of a 1 GB file using FTP. Two different current consumption measurements were

TABLE I: Estimated single-carrier (SC) and CA current consumption using the power model from [6].

Setup	SC 10 MHz	SC 20 MHz	CA 10+10 MHz
Throughput [1]	51.0 Mbps	92.0 Mbps	96.7 Mbps
Receive current consumption	398 mA	445 mA	487 mA
Current difference		11.8 %	22.4 %
Energy (1 GB, 185 s)	391 J	282 J	275 J
Energy difference		-27.8 %	-29.7 %

[1] Throughput numbers are based on the measurement results in Figure 5.

taken. The first one considered only the active download time, while the second was measured during a constant time window given by the slowest download. The purpose of the latter was to make a fair comparison between 10 MHz, 20 MHz and 10+10 MHz CA by capturing the current consumption of both the active reception and the following idle period.

C. Multiple application performance

Different application traffic profiles were tested with and without CA in order to identify the likelihood that certain traffic patterns will trigger CA usage. The multi-application profile includes web browsing across different web sites, a Skype video call and watching standard quality and high definition (HD) YouTube videos.

D. Impact of radio conditions

The final step in the analysis consisted in studying how different radio conditions on each CC affect the probability of CA being used, and how a coordinated packet scheduler and carrier selection algorithm can dynamically use both CCs in an efficient manner.

E. Theoretical Current Consumption Estimation

To estimate what can be expected from the measurements the power model from [6] is applied to scenario B presented above. In this scenario the UE is receiving a 1 GB file via FTP. The receiver current consumption depends mainly on the channel bandwidth and the throughput, and therefore an increase of 12-22 % is estimated; see Table I, for the 20 MHz and 10+10 MHz cases compared to the 10 MHz. When the UE is not receiving data it can enter a low-current sleep mode which is the key to save energy. Because of the increased data rate in the 20 MHz and 10+10 MHz cases the UE is able to enter the sleep mode faster and therefore the power model predicts that energy consumption over a period, defined as the longest time it took in all the setups to receive the file, will be reduced 28-30 %.

Note that the absolute values are not realistic because the devices have improved significantly since the model was proposed. Furthermore, the idle current value does not match the one measured later because it depends on the paging cycle settings and UE implementation details. In section IV the actual current consumption is measured and in section V compared with the simulated predictions.

IV. Measurement Results

In this section the average current consumption and throughput measurement results for the four scenarios defined in section III are presented.

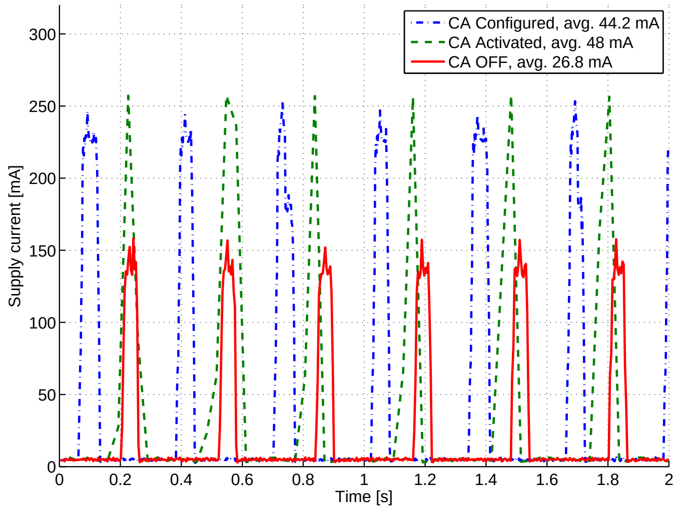

Fig. 3: Average current consumption during RRC inactivity timer with DRX.

A. Impact of carrier aggregation activation

The current consumed by the UE during RRC inactivity periods with 320 ms DRX cycle is shown in Figure 3. When CA was activated the average current increased by 79 % (21mA) compared to single-carrier 10 MHz, since the UE has to monitor the PDCCH and transmit periodic CSI reports for both carriers. The increment was reduced to 65 % (17 mA) when CA was configured but not activated. In this case the UE only has to monitor the PDCCH and send CSI reports of the PCell. The higher current level compared to single-carrier measurements seems to indicate that during DRX cycles, the UE is actually switching ON and OFF radio capabilities for both bands, although it is only required to monitor the PCell.

B. Large data transmission

Figure 4 presents the UE current consumption for a 1 GB FTP transfer. The red bar shows that with CA, the current consumption during the active transmission time, i.e. while the file was downloaded, increased by 61 % compared to 10 MHz single-carrier. Furthermore, a similar increase was observed for 20 MHz single-carrier, indicating that current consumption increase is mainly related to the amount of resource blocks used. In other words, the baseband processing load seems to have a higher impact on the current consumption than the use of multiple RF chains.

However the higher throughput achieved when using CA allowed finalizing the data transfer and moving to RRC idle state approximately twice as fast, as illustrated in Figure 5. The green bar in Figure 4 represents the average current during a constant time window of 185 s, which is given by the slowest file download (the 10 MHz, No CA case). The averaged results over the time window show 13 % energy efficiency improvement compared to single-carrier 10 MHz, because the UE can enter a low-current sleep mode while in RRC idle.

C. Multiple application performance

In this scenario popular applications were executed on the UE to see if they would trigger the usage of CA. It was observed that relatively low bit rate applications such as web browsing, Skype video call or even standard quality YouTube

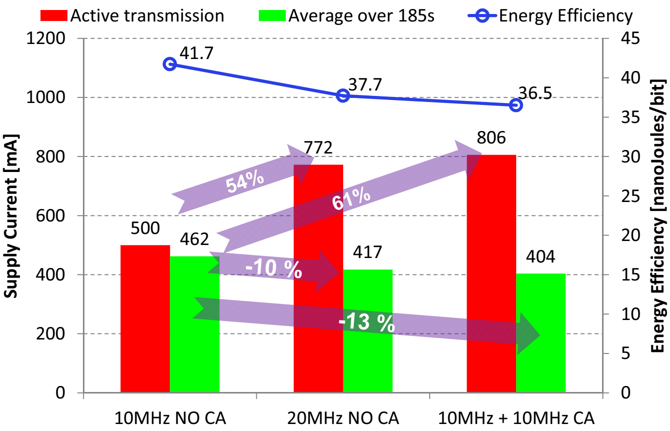

Fig. 4: Average current during 1 GB FTP download.

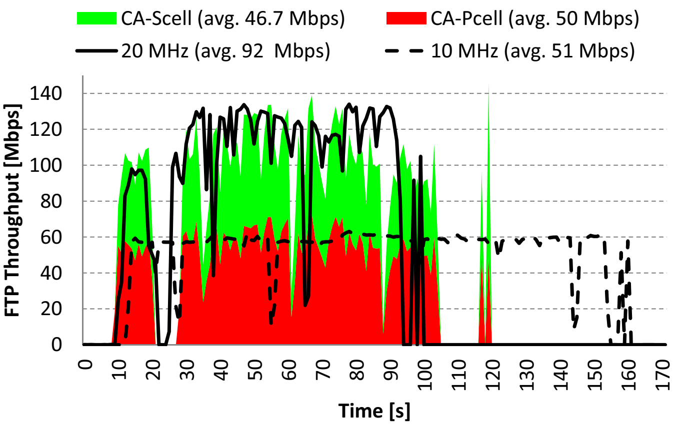

Fig. 5: Throughput vs. Time during 1 GB FTP download.

videos (750 kbps) were unlikely to trigger the activation of CA when UE was in good radio conditions and there was low load in the cell. CA was still configured at RRC level, but if the amount of buffered data was small, it was generally transmitted using only the PCell. Only HD YouTube video (2 Mbps) seemed to trigger the usage of CA in some occasions.

D. Impact of radio conditions

The same YouTube HD video was downloaded in good and bad radio conditions. Additionally, two cases were tested where the PCell was either stronger or weaker than the SCell. Bad radio conditions were generated by attenuating both PCell and SCell by 30 dB. Asymmetric conditions implied a 9 dB additional attenuation on either of the CCs. Figure 6 shows the throughput and Physical Resource Block (PRB) allocation on both PCell and SCell in bad radio conditions. In this scenario both CCs were used by the packet scheduler, allocating up to an aggregated number of 100 PRBs during the initial video buffering time, and achieving a peak rate of 6 Mbps. After that, the PRB share among the PCell and SCell was approximately 50 %. Even with a similar allocation of resources, the throughput achieved in the PCell was higher due to better quality experienced in band III, which allowed the usage of higher modulation and coding scheme.

Table II summarizes the throughput and PRB usage on the PCell and SCell during the HD YouTube video playback. It can be observed how the stronger CC provides the higher throughput, even if that CC is the SCell. This represents the

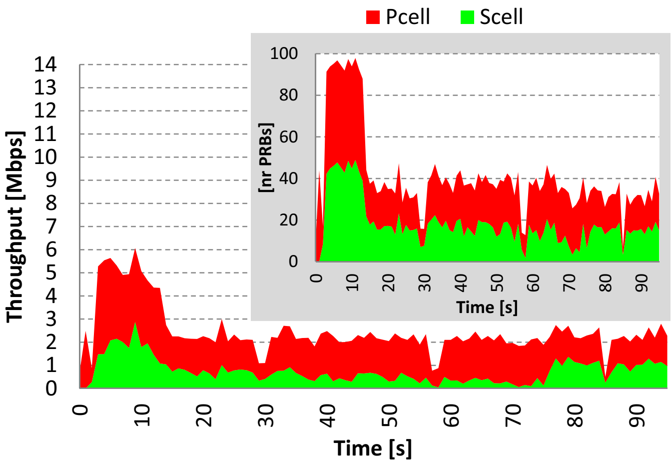

Fig. 6: HD YouTube video throughput and PRB usage in bad radio conditions. Note the results of the two cells are stacked.

TABLE II: Average throughput, PRB usage and current consumption per CC for HD YouTube video streaming.

	Good RF			Bad RF			Asymmetric RF	
	10 MHz band III	10 MHz band V	10+10 MHz CA	10 MHz band III	10 MHz band V	10+10 MHz CA	Pcell band V weaker band III	Pcell band V stronger band III
Average Throughput [Mbps]								
PCell	2.7	2.1	2.2	2.0	2.1	1.7	2.5	0.4
SCell			1.0			0.8	0.0	2.2
Total	2.7	2.1	3.2	2.0	2.1	2.5	2.5	2.6
Average PRB Usage [# of PRBs]								
PCell	2.9	1.8	1.5	22.3	33.5	22.7	13.8	2.4
SCell			0.7			18.2	1.1	2.2
Total	2.9	1.8	2.3	22.3	33.5	40.9	14.9	4.6
Average Supply Current [mA]								
	450	476	502	773	831	936	726	735

ability of the packet scheduler and carrier selection algorithm to assign resources dynamically and efficiently on each CC depending on the given channel conditions. Examining the last row of Table II it can be seen that with HD YouTube video the current consumption increased between 12 % and 21 % when 10+10 MHz CA was used, compared to single-carrier 10 MHz. The increase was more significant in bad radio conditions as a higher number of PRBs were used to cope with the video bit-rate requirements. In general, the total current consumption highly depends on the radio conditions of each CC.

V. Discussion

LTE DL CA provides higher peak data rates, improves scheduling flexibility and brings inherent inter-carrier load balancing in multi-carrier LTE deployments.

In this analysis it was evaluated how CA is capable of reducing the average UE current consumption over a period of time when transferring large files. This enables network operators to use fragmented spectrum (10 + 10 MHz) instead of a contiguous 20 MHz band without harming the UE battery life.

However, with bursty traffic which doesn't benefit from the larger peak throughput, the additional cost of activating two (or

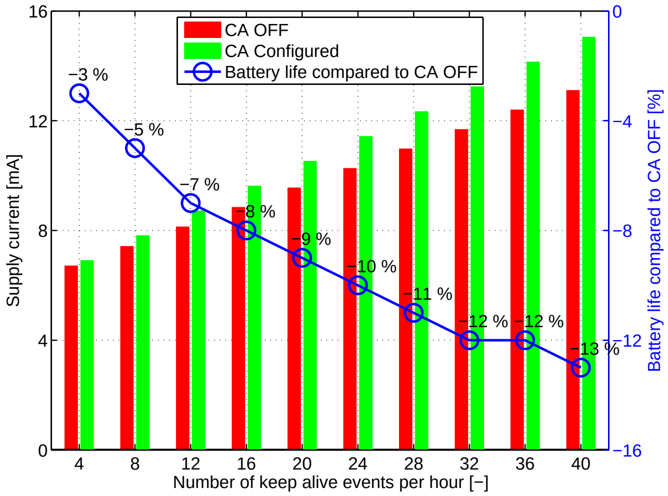

Fig. 7: Stand-by current estimation vs. keep-alive activity.

more) receivers and monitoring different carriers may have a negative impact on the UE's stand by time. This increase is however not very different of what is observed when using 20 MHz of contiguous spectrum. An advantage of CA over 20 MHz single-carriers could come from intelligent decision on whether configuring CA can provide the most benefit.

Figure 7 shows an estimation of the average current consumption and the battery life compared to single-carrier 10 MHz for an UE in stand-by mode with varying number of keep-alive events. The model assumes that one keep-alive event consists of a short 1 s transaction of only a few packets, followed by 10 s where the inactivity timer is running, and finally, the transition to the RRC_idle state. The current consumption in idle state is set to 6 mA based on measurements on the test UE, while the other current consumption values are based on Figure 3.

The amount of background traffic that one UE generates depends significantly on the operating system and the applications which are installed and running on that UE. Based on our internal studies, a much optimized smartphone with only basic services configured may generate as few as 2 to 4 events per hour, which would translate into a 3 % battery life reduction, while an average smartphone with multiple applications installed may have 15 or more events per hour, yielding an 8 % stand-by battery life reduction. Note the calculations are based on a 2600 mAh battery.

Finally the 1 GB FTP download measurements showed that the power model from [6] is too optimistic when compared to the measurements on the selected commercial device. The model predicted a current consumption increase of 22 % when using CA, but the measurements showed the instantaneous increase is more than 60 % and therefore an updated power model is proposed future work. Fortunately the measurements also confirmed that CA can provide higher data rates, and therefore the conclusion stating that the battery life can be prolonged due to increased sleeping opportunities is still valid.

It is also important to note that receiver's current consumption previously has been reported to contribute with less than 10 % of the total UE current consumption [10], and therefore an increase even as big as 60 % may not be as significant in the total perspective. This is however a very device specific observation because the total current depends heavily on the choice of the power amplifier and display components.

VI. Conclusion

In this study we presented the first current consumption measurements on a commercial Carrier Aggregation (CA)-capable smartphone, and showed that CA can decrease the average current consumption thanks to increased data rates. Comparing 10 MHz single-carrier and 10+10 MHz CA we observed a 90 % data rate increase in the given conditions, which resulted in 13 % lower current consumption when normalizing measurements over a common time window. The main reason is that the CA smartphone can move faster to a more energy efficient state as the data reception ends earlier with the provided higher data rates.

Our results also showed that configuring and activating CA can result in up to 21 mA current consumption increase compared to single-carrier transmission during RRC inactivity periods. For small data transactions, such as keep-alive message transmissions, this can result in up to 8 % battery lifetime reduction with typical keep-alive patterns.

Other studied traffic types, such as web browsing, or VoIP/video call are unlikely to trigger CA usage, especially in good radio conditions and empty cells since these applications are not too demanding in terms of data rates.

Finally, CA performance with a YouTube video streaming application was also evaluated. Results showed that downloading a high-definition video can increase the current consumption between 12 % and 21 % compared to 10 MHz single-carrier transmission depending on the radio conditions. It was also observed that the ability of the packet scheduler and carrier selection algorithm to efficiently allocate resources on each CC maximizes the performance.

Acknowledgement

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