Software-based Implementation of LTE/Wi-Fi Aggregation and Its Impact on Higher Layer Protocols

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***Abstract*—Due to the fast growing of data consumed in mobile devices through cellular networks, solutions that provide higher data rates are an important target for the mobile networking community. One such solution is the aggregation of mobile technologies (most commonly LTE) with wireless LAN solutions (most commonly Wi-Fi). Seeing its potential impact, 3GPP has devised the LTE/Wi-Fi Aggregation (LWA) specification, which defines a tight coupling between eNBs and Wi-Fi Access Points (APs). In this paper, we implement and evaluate an LWA solution, and compare its performance to the one for full offloading (only Wi-Fi) and no offloading (only LTE) through physical experimentation. The developed prototype LWA solution is based on open source and commodity hardware, which promises a low-cost and easily implementable LWA solution. Aggregation and offloading process are managed by the eNB, therefore, the core network remains intact without any modification. Physical experiments are done to detail the network performances for all these three policies for TCP and UDP traffic and both for uplink and downlink connections. In TCP transmissions with LWA policy, the different delays between Wi-Fi and LTE links causes the performance degradation because of the out-of-order arrivals of the segments. For this, we evaluate a solution where an artificial delay is added to reduce the number of out-of-order packets.**

***Index Terms*—LTE, 4G mobile networks, LTE Wi-Fi Aggregation.**

I. INTRODUCTION

Spectrum is a key element in mobile networks and with more data being sent on the network and with each user having multiple devices, the burden on the limited spectral resource is immense. Adding to this the 5G use cases such as heterogeneous multi-RAT networks makes the need to exploit unlicensed spectrum an urgent necessity. To cope with mobile data explosion [1], one of the promising solutions is to intelligently utilize multiple access radios in an aggregated manner. The idea is that when there does not exist a single radio access technology (RAT) that offers sufficient bandwidth to meet an application's requirement (e.g., users at the cell edge), two or more RATs are integrated seamlessly so that the application is able to experience a scaled-up capacity [2], [3]. In fact, it is expected to be the key driver for 5G systems to efficiently use heterogeneous wireless networks in an integrated manner [4]. From an operator's perspective, it is preferable to have as little change as possible to existing core network and RAN by means of a simple software update [5].

Two promising candidate technologies to meet multi-RAT aggregation objectives are LTE and Wi-Fi. Wi-Fi is a mature access technology and is evident with the ubiquitous deployment of Access Points (APs) for both enterprise and home users. These factors make Wi-Fi a very practical choice for femto-cell deployment in future 5G heterogeneous network (HetNet) scenarios.

Broadly speaking, multi-RAT aggregation in LTE can be performed at the Radio Access Network (RAN) layer (i.e., between the eNodeB and UE at IP, PDCP, RLC, MAC or PHY layers of the protocol stack), the EPC core, or the Application layer. At the PDCP layer, we have LTE + LTE (Dual connectivity, split radio bearer) and LTE/Wi-Fi Aggregation (LWA) standardized in 3GPP Rel. 13. Albeit its standardization, LWA has not been evaluated in detail for the performance improvements it promises or the implementation challenges it brings. In this study, we target these two objectives, and first we provide LWA implementations both for UE and eNB using open-source LTE and Wi-Fi implementations along with commodity hardware such as generic purpose processors (GPPs), software-defined radio (SDR) and Wi-Fi adapters. The developed LWA implementation is evaluated through physical experiments, focusing specifically on its effect on the higher layer protocols, specifically TCP and UDP. The challenges LWA brings for these protocols are portrayed through comparative performance analysis both for downlink and uplink aggregation, using the no-aggregation (i.e., only LTE or only Wi-Fi) connections as benchmarks. Our implementation focuses on Collocated LWA architecture of 3GPP, where the Wi-Fi Access Point (AP) is collocated with eNB.

As per the LWA scheduler, we evaluate a simple one that changes between LTE and Wi-Fi interfaces sequentially for each PDCP PDU. We show that the TCP performance suffers significantly due to the out-of-order segments caused by delay and data rate differences between the interfaces. The TCP performance is improved by adding an artificial delay to compensate the delay difference issue. The UDP performance evaluations provide a good benchmark for the potential performance improvement by LWA. To the best of our knowledge, this is the first study in the literature to evaluate the higher layer protocol performance with an

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underlying open-source LWA software solution in such detail.

II. RELATED WORK

In [5], a method to achieve LTE-Wi-Fi aggregation at a femto BS is proposed. TCP flows are an essential performance bottleneck for any real time application (eg. video streaming, FTP file transfer). The Link Aggregation algorithm proposed distributes a TCP traffic flow to LTE and Wi-Fi links based on the Modulation and Coding Scheme (MCS) and Physical Resource Block (PRB) usage of the LTE link.

The authors study two packet distribution algorithms viz., Radio Resource Usage (RRU) based distribution algorithm with Weighted Round Robin (WRR) and RRU with Token Bucket Algorithms (TBA). The difference is the way in which the data rate in the LTE link is restrained below the target data rate required by the application. The Link Aggregation (LA) control module decides how the flows are split between LTE and Wi-Fi, by generating a packet distribution ratio between LTE link and Wi-Fi link based on the terminal's MCS, PRB usage of the LTE link and the transfer data rate. As the LTE link becomes congested, decided by the measurement of PRB used and the LTE congestion threshold defined by the system, the IP flows are switched to the Wi-Fi link in an ascending order of frequency usage efficiency of the LTE link (i.e. MCS) so as to decrease the LTE PRB usage.

The Token Bucket Algorithm works by having a Token Bucket Counter (TBC) that switches the IP packet between the LTE and Wi-Fi link on a packet-by-packet basis. In the Received Data Rate (RDR) approach, the femto cell BS distributes the packets based on the available data rate of the LTE link and the Wi-Fi links. Authors conclude that the packet distribution algorithm using RRU with TBA/WRR outperforms Received Data Rate (RDR) packet distribution algorithm while also being more responsive to changes in network conditions. However, the work has been performed using proprietary simulation software, the details of which have not been provided, and hence the reproducibility of the results is a major bottleneck for future research. In comparison, in this work, we provide a software-based implementation of an LWA solution, which can be reproduced with commodity hardware and open-source projects.

In [7], LTE-W is defined as the service to integrate LTE and Wi-Fi. Two steps are defined: i) mode selection, i.e. deciding which UE(s) in the LTE cell must receive the LTE-W aggregated service based on intra-cell fairness (eg. cell edge users might be given priority over cell centre users) and ii) split scheduling of bearers (basic unit of aggregation in the paper) among LTE and Wi-Fi.

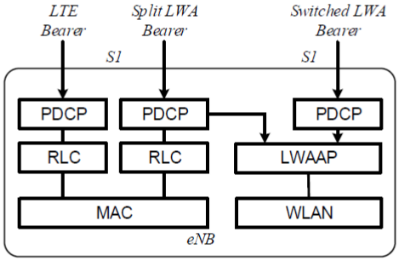

Fig. 1. LWA Radio Protocol Architecture for the Collocated Scenario [13]

In mode selection, LTE-W internally decides who should be served by either of LTE or LTE-Wi-Fi aggregation considering intra-cell fairness rather than just following users' intention of aggregation. An intra-bearer scheduling algorithm at PDCP is proposed that splits a bearer's traffic into LTE and Wi-Fi links. However, LTE-W Services are supported only for Non-Guaranteed Bit Rate(GBR) bearers. Evaluations have been done using NS-3 LENA, an open source software platform for LTE simulations and hence are reproducible. However, the results confine to a purely simulated environment and are devoid of a real time hardware implementation. In our work, in comparison, we have used commodity hardware, which can be easily procured, thereby saving cost, and implemented the LWA solution using real-time LTE and Wi-Fi software.

III. LWA SPECIFICATION AND ITS OPEN-SOURCE IMPLEMENTATION

A. Specification

LTE-WLAN Aggregation (LWA) is a feature of 3GPP Release-13 which allows a mobile device to be configured by the network so that it utilizes its LTE and Wi-Fi links simultaneously. Unlike other LTE/WLAN interworking methods (e.g. S2b and LWIP), which also allow using LTE and WLAN simultaneously, LWA has the capability to split a single bearer (or a single IP flow) at sub-bearer granularity while accounting for channel conditions. This capability allows all applications (e.g. video streaming and file download) to use both LTE and WLAN links simultaneously without any application-level enhancements, thus promising significant performance gains.

The specification defines both user plane and control plane architectures for two scenarios: Collocated and Non-collocated LWA. In the former, the Wi-Fi AP is collocated with and is controlled by eNB. Hence, for the latter, a protocol is defined for eNB and Wi-Fi AP messaging, namely Xw. In this paper, we focus on a collocated scenario, where each Wi-Fi AP are associated to a specific eNB. In the user plane, LTE and WLAN are aggregated at the Packet Data Convergence Protocol (PDCP) level. A new sublayer is defined for this, namely LWA Adaptation Protocol (LWAAP) as shown in Fig. 1. At eNB, LWAAP adds the bearer ID to the PDCP packets and transmits it through LTE or Wi-Fi interfaces. In the control plane, eNB is responsible for LWA activation, de-activation and the decision as to which bearers are offloaded to the WLAN. The interface selection algorithm is not defined in the specification.

B. Implementation

For the purpose of network performance evaluations, our prototype implements the LTE and Wi-Fi links both at the eNB and UE side, while an aggregation module at PDCP manages the selection of the RAT to be used per packet.

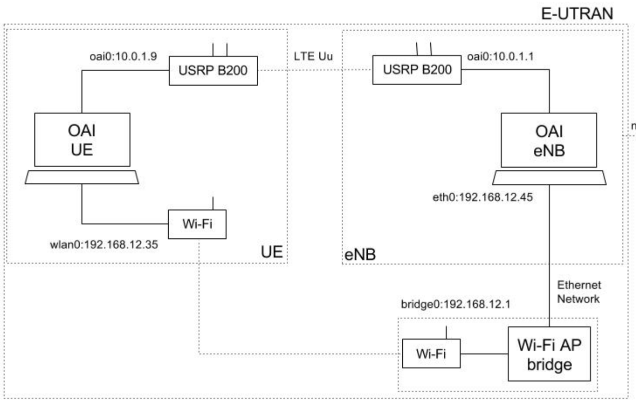

Fig. 2. Testbed implementation of the LWA solution.

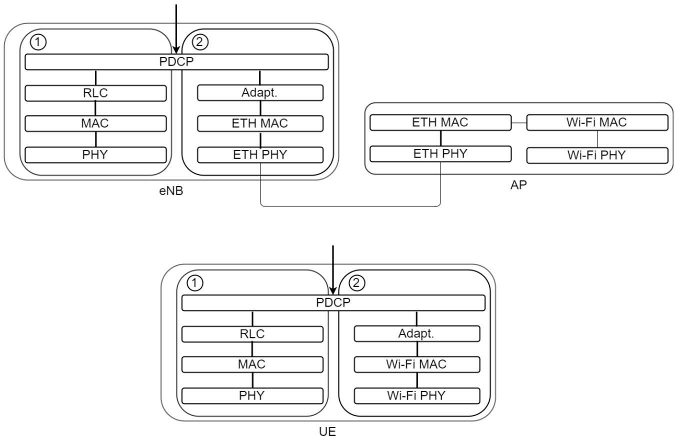

Fig. 3. The LWA protocol stack implemented.

The implementation is built on the open source solutions: 1) For LTE, the Open Air Interface project [9] is used, which provides a Software Defined Radio (SDR)-based software implementation for both UE and eNB, along with softwarized EPC. 2) For Wi-Fi, we use `hostapd` [10], which is a software that allows to convert a Linux device into a fully configurable Wi-Fi access point.

Open Air Interface (OAI) is a software implementation of 3GPP LTE standards in C, running under real-time Linux and optimized for x86 architecture processors. It is LTE release 8.6 compliant and supports a subset of release 10 features. Although there are other open source LTE implementations such as srsLTE, we chose OAI for its wide community support.

Hardware setup implemented is shown in Fig. 2, wherein two functional communication links are executing independently: LTE and Wi-Fi links between the eNB and the UE. All LTE and Wi-Fi communication hardware is commodity hardware. Specifically, the eNB and UE baseband processing is done on PCs with Intel i5 processors, the radio hardware used is Ettus USRP B200 for LTE communication and off-the-shelf Wi-Fi adapters for Wi-Fi communication.

Since LWA implementation does not change anything at EPC level, we used the option of noS1 in OAI, which emulates the EPC connection on eNB. Hence, the LTE link is formed with OAI UE software and the OAI eNB software with the noS1 interface option.

We chose and implemented the collocated LWA option in the following way. The Wi-Fi link has an intermediate device acting as AP that executes the hostapd. eNB is connected to this Wi-Fi AP through Ethernet network. As a result, the Wi-Fi AP has a direct connection with eNB, i.e., the Wi-Fi AP has been integrated to evolved UMTS Terrestrial Radio Access Network (E-UTRAN). In order to avoid/minimize modifications on the current infrastructure, and to have an implementation as transparent as possible, Wi-Fi AP is used in bridge mode. Thus, in AP device Wi-Fi interface connected to the UE is bridged with the Ethernet interface connected to the eNB. With this, the Wi-Fi packets are manipulated at eNB through Ethernet captures. Moreover, the Wi-Fi network is not using any secret key and uses an open authentication system, which allows a fast attachment. As specified in LWA specification, such setup requires eNB-based authentication.

The aggregation (or its choice) is implemented at PDCP layer, hence, the developed protocol stack includes layers of both technologies LTE and Wi-Fi with PDCP layer as common layer between them Fig. 3 illustrates the protocol stack both at the eNB and at the UE side. When and IP data packet arrives to PDCP layer, a PDCP header is added obtaining a PDCP PDU. If that PDU will be sent through Wi-Fi, an adaptation header (LWAAP header) is added which is required to recognize unequivocally each PDCP PDU. After that, the data packet continues to the next layer where an Ethernet header is added including MAC address of UE, then the information is sent through Ethernet network to Wi-Fi AP configured in bridge mode. With this configuration, Ethernet header is converted to Wi-Fi header and finally data is sent by physical Wi-Fi interface.

Three policies are implemented for the choice of aggregation and offloading:

a) No Offload policy: This policy implies a standard LTE transmission without intervention of Wi-Fi technology, and hence the name *No Offload*. The protocol stack traversed is the standard LTE one: IP data packet is sent through PDCP layer and continue to RLC, MAC, and PHY, i.e., the traffic follows Path-1 of the protocol stack shown in Fig. 3.

b) Offload policy: In this case, the radio bearer is switched to Wi-Fi, which means that the data traffic passed from upper layers to PDCP layer is sent only through Wi-Fi interface. For this, an adaptation layer is required to identify the radio bearer, the RNTI information, etc. to identify the targeted receiver and the bearer. After that the data is sent through lower layers of Wi-Fi link. The policy is named as (Wi-Fi) Offload policy, following Path-2 of protocol stack shown in Fig. 3. In this policy, only the user plane data is sent through this path, LTE control plane communication is still carried out through the LTE interface.

c) Aggregation policy: In this policy, the radio bearer is split between lower layers of LTE and Wi-Fi technologies.

Fig. 4. Hardware setup of the LWA testbed implementation.

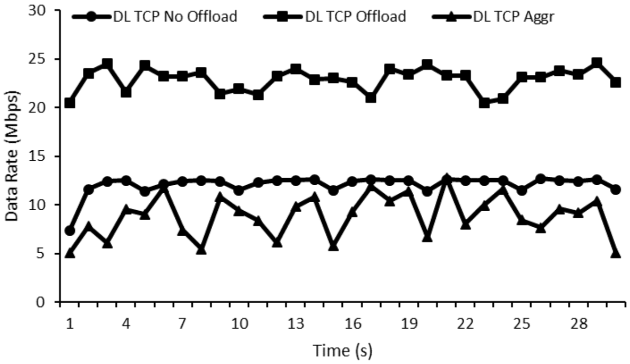

Fig. 5. Downlink TCP throughput, where LTE uses 25 PRBs.

An efficient methodology to decide how many packets to send from each interface or when to change the interface is a future research topic. In this paper, we implement and evaluate a simple methodology, which defines that even numbered PDUs are sent through LTE and odd numbered PDUs are sent through Wi-Fi. Hence, the data traffic follows Path-1 and Path-2 of Fig. 3 sequentially.

IV. PHYSICAL EXPERIMENTATION RESULTS

We set the system up as described in Fig. 2, with the resulting system being displayed in Fig. 4.

The Wi-Fi connection is established using a IEEE 802.11g connection at 2.4 GHz ISM band. The LTE Band 7 is used for the LTE connection, which uses an FDD multiplexing with central frequency for downlink being 2.68 GHz and that of uplink being 2.56 GHz. The default PRB size used in the evaluations is 25 PRBs. The UE and eNB SDRs are connected directly with attenuators of 40dB added to both RX/TX pair.

We evaluate the performance of the system by applying each of the developed policies No offload, Offload, and Aggregation, in a lapse time of 30 seconds. The performance is measured per second and the time-based performance results are presented in the following to show the fluctuations in the performance during the tests. Since the LTE connection medium is RF cable, the fluctuations in the No Offload policy have been found negligible as expected. Nevertheless, the fluctuations in the Wi-Fi link performance are also found to be limited, due to the close distance between Wi-Fi AP and STA, i.e., a much higher RSSI link than the other co-existing Wi-Fi interferers.

The performance metric evaluated is the data rate, assessed by the iperf tool running between the UE and eNB. The comparative performance analysis of Aggregation policy is done for both TCP and UDP type of traffic and both for uplink and downlink communication.

A. Downlink TCP

We first analyze the effect of the three policies on the TCP performance, which is the dominant transport layer protocol used in Internet. According to [8], TCP dominates the Internet traffic (95.3% flow-wise and 97.2% byte-wise), with majority of the remaining traffic in UDP. Fig. 5 shows the data rate obtained in downlink with TCP traffic according to the different policies applied.

The data rate obtained in Downlink TCP traffic on Offload policy (only Wi-Fi) is 22.87 Mbps, followed by the transmission done on LTE interface (No offload policy) with 12.07 Mbps. However, the data rate obtained when the traffic is sent by alternating between the Wi-Fi and LTE interfaces (Aggregation policy) is lower than the two other policies: 8.85 Mbps. In line with the observations from the literature (e.g., [12]), the low data rate obtained is found to be because of: a) different delays incurred by the interfaces, and ii) different link speeds, resulting in out-of-order segments, which degrades the TCP data rate considerably. Although reordering functions at PDCP layer have been tried in the literature [12], the TCP performance is found to get worse when a delayed PDU blocks all the ones already received in the PDCP buffer.

Fig. 6 shows the performance obtained when the number of PRBs are increased to 50 (i.e., the bandwidth is increased to 10 MHz bandwidth) in No offload and Aggregation policy, instead of 25 PRBs (and 5MHz bandwidth, respectively). In this case, the LTE data rate is twice of the one obtained with 25 PRBs (Fig. 5) as expected, which gives comparable data rate to Offloading (Wi-Fi only) policy. However, the Aggregation policy with TCP also gets its data rate doubled, yet this data rate is still lower than both other two policies. This clearly shows the effect of different delays on the interfaces on the TCP performance.

Later, in this paper, we evaluate a solution to make the latencies on both interfaces comparable and show its effect on TCP performance.

B. Downlink UDP

Fig. 7 shows the data rate obtained in downlink with UDP traffic, with the three policies evaluated. In downlink UDP traffic, the referential data rate is 12.44 Mbps achieved in the transmission over LTE interface (No Offload policy). The two policies implemented surpassed the benchmark performance, being the transmission over Wi-Fi the one that achieved the

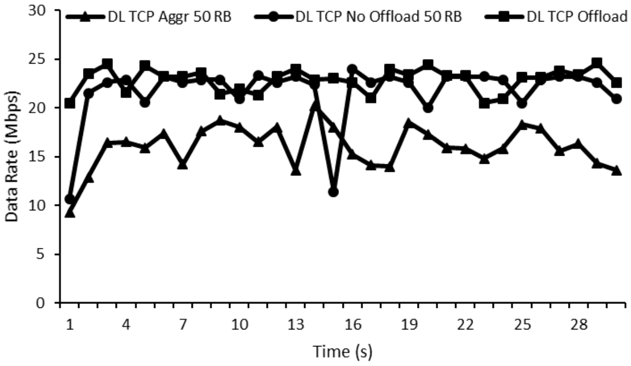

Fig. 6. Downlink TCP throughput, where LTE uses 50 PRBs.

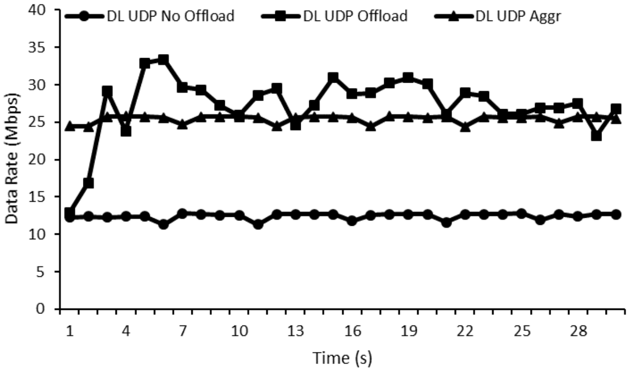

Fig. 7. Downlink UDP throughput, where LTE uses 25 PRBs.

highest data rate with 27.27 Mbps, followed by the traffic aggregation transmission with 25.41 Mbps.

The UDP protocol does not perform packet order control, which allows a better data rate of 25.41 Mbps than the one obtained in the aggregation policy of TCP, i.e., 8.85 Mbps (Section IV-A). According to iperf tool, around 50% of datagrams received by UE arrived out of order, which is expected due to the sequential switching between interfaces. These data rate values can be considered as the raw throughput that can be achieved by the policies without any congestion or rate control applied at the transport layer. Hence, these values are the upper limits that can be achieved by the TCP connections for our tests. Note the gap between the UDP and TCP data rates, which show the criticality of an efficient policy selection method for TCP connections.

Fig. 8 shows the throughput performance obtained, when 50 PRBs (i.e. 10 MHz bandwidth) are used for the LTE connection. Data rates are twice of those obtained with 25 PRBs (see Fig. 7) as in the downlink TCP case. The data rate of around 50 Mbps achieved by the Aggregation policy is the highest data rate achieved among all the tests in this study, showing the promising feature of the Aggregation policy.

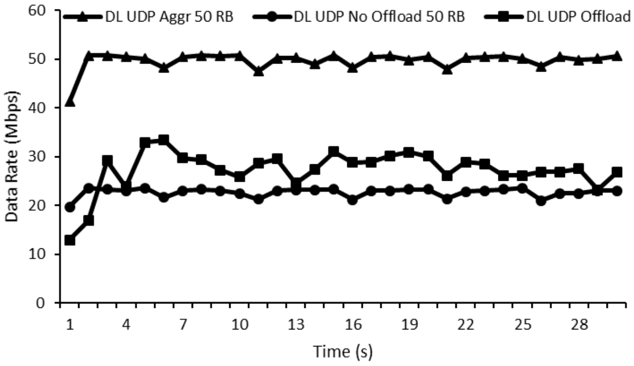

Fig. 8. Downlink UDP throughput, where LTE uses 50 PRBs.

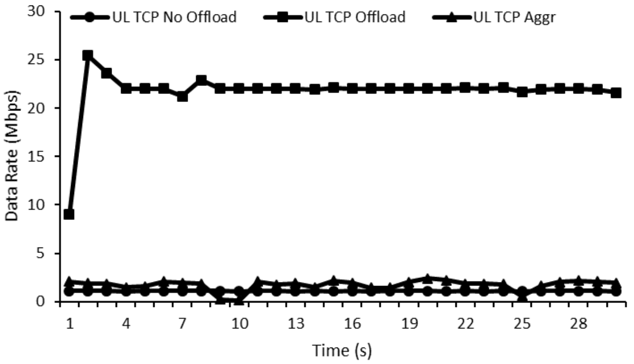

Fig. 9. Uplink TCP throughput, where LTE uses 25 PRBs.

C. Uplink TCP

Fig. 9 shows the data rate obtained in uplink with TCP traffic, according to the different policies applied. In uplink, the data rate achieved in transmission over only LTE interface (No Offload policy) with TCP traffic is 1.09 Mbps. This low value is due to the MAC scheduler employed by OAI eNB software, which limits the physical resources assigned to uplink connections. The asymmetric resource assignments are common in LTE due to the asymmetry between the data rate demands of downlink and uplink communication. The Offload and Aggregation policies surpassed the No Offload policy performance, former achieving the highest data rate of 21.71 Mbps. Nevertheless, the Aggregation policy resulted in a low data rate (1.73 Mbps), again, due to the two reasons provided for low performance in downlink TCP performance.

Fig. 10 shows the data rates obtained, where LTE connection uses more physical resources (i.e. 50 PRBs). In the case of No Offload policy, 1.68 Mbps was obtained being a very similar value to the one obtained with the use of 25 PRBs. In Aggregation policy, however, an average of 3.01 Mbps represents 73% of improvement compared to the use of 25 PRBs. This increase shows the crucial effect of lower data rate connection on the overall TCP performance.

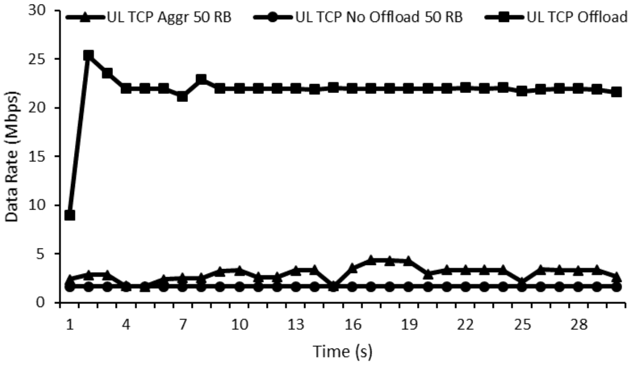

Fig. 10. Uplink TCP throughput, where LTE uses 50 PRBs.

TABLE I
RTT VALUES FOR LTE AND WI-FI INTERFACES

	UL	DL
Wi-Fi	8.78	9.24
LTE	23.4	24.6
Artificial Delay Added	7.31(x2)	7.68(x2)

D. TCP Performance under Artificially Added Delay

Finally, the delay effect between the Wi-Fi and LTE interfaces is evaluated when the Aggregation policy is applied to TCP. The *netem* tool is used to add delays artificially to Wi-Fi and Ethernet interfaces at UE and eNB machines, respectively, to increase the Wi-Fi delay. In each interface, half of the difference between LTE and Wi-Fi link Round Trip Times (RTTs) is applied to make them have similar delays, as listed in Table I. Note that, RTT measured during UL and DL experimentations yield similar values as expected, and both are presented for completeness of the measurement information.

Fig. 11 shows the performance improvement in downlink compared to the one obtained without delay applied to LTE and Wi-Fi interfaces. TCP throughput increases from 8.85 Mbps to 21.06 Mbps, which quantify the criticality of delay difference between interfaces on TCP performance. This indicates that an intelligent bearer split method is crucial for LWA to not hinder the achievable TCP throughput performance.

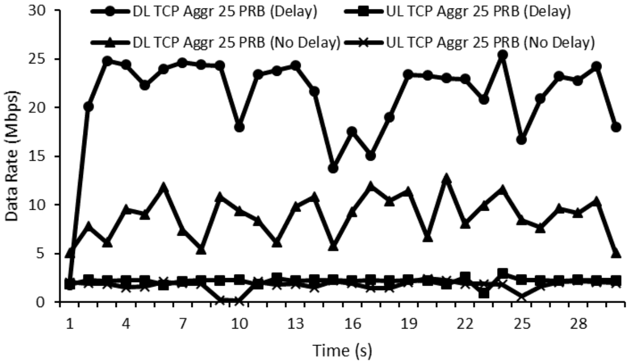

Fig. 11. TCP throughput for Aggregation policy with artificial delay adjustment.

V. CONCLUSIONS

In this study, a collocated LWA prototype was implemented based on open source and commodity hardware. The aggregation is done at eNB, therefore, the core network remains intact without any modification. The switch or split of the bearers according to the chosen aggregation policy is done in PDCP layer, which is the common layer between LTE and Wi-Fi.

Using LWA, a substantial improvement in the data rate is evidenced for UDP traffic, since UDP has no control of the order arrival packets, the datagrams received out-of-order are around 50%. However, data rate detriments with aggregation for TCP due to the difference of delays and temporal data rates between the Wi-Fi and LTE links, causing the arrival of packets in a non-sequential way. We provided and evaluated a solution to mitigate the delay difference problem which improved the TCP performance for aggregation policy noticeably. The evaluations show that LWA is promising in improving aggregate data rates, however, for split bearer approach, an efficient aggregation policy is needed to not observe performance degradations.

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