A Framework for Integrating MPTCP over LWA - A Testbed Evaluation

Thomas Valerrian Pasca, Nabhasmita Sen, Venkatarami Reddy,
Bheemarjuna Reddy Tamma, and Antony Franklin
Indian Institute of Technology Hyderabad, India
[cs13p1002,cs17resch11001,cs17resch01007,tbr,antony.franklin]@iith.ac.in

ABSTRACT

Radio level integration (RLI) architectures such as LTE Wi-Fi aggregation (LWA) and LTE Wi-Fi integration with IPSec tunnel (LWIP) are gaining momentum in the context of Multiple Radio Access Technology (Multi-RAT) connectivity in 5G. It is unclear whether a transport layer solution like Multipath TCP (MPTCP) could serve better in aggregating multiple RATs than radio level aggregation, Or are these two different solutions complementing each other? In this paper, we address these questions by experimenting on a testbed. LWA testbed has been set up using OpenAirInterface (OAI) LTE base station and off-the-shelf Wi-Fi Access Point (AP). We present interesting outcomes of various experiments which can be adopted as design principles for developing 5G Multi-RAT architectures. Our findings include, (i) LWA fails to aggregate link capacities when there is congestion in the network, and (ii) Co-operative MPTCP and LWA solution is robust and achieves significant performance improvement compared to individual LWA and MPTCP, even when the network is congested and Wi-Fi channel contention is high.

KEYWORDS

LTE Wi-Fi Aggregation; MPTCP; Radio Level Integration;

ACM Reference Format:
Thomas Valerrian Pasca, Nabhasmita Sen, Venkatarami Reddy, Bheemarjuna Reddy Tamma, and Antony Franklin. 2018. A Framework for Integrating MPTCP over LWA -, A Testbed Evaluation. In *12th International Workshop on Wireless Network Testbeds, Experimental Evaluation & Characterization (WiNTECH '18), November 2, 2018, New Delhi, India.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3267204.3267215

WiNTECH '18, November 2, 2018, New Delhi, India

ACM ISBN 978-1-4503-5930-6/18/11…$15.00
https://doi.org/10.1145/3267204.3267215

1 INTRODUCTION

The exponential growth in the number of smartphones used and the traffic generated by them have become a major challenge to the telecommunication industry. International Telecommunications Union (ITU) envisions that by 2020 the requirements that a mobile network should cater will be humongous [10]. It includes 20x hike in peak data rate, 100x hike in area traffic capacity, 10x hike in connection density, and 10x low latency compared to requirements of mobile networks in the year 2015. The penetration of multi-featured electronic gadgets such as smartphones, tablets, and laptops in the market and popularity of mobile applications (native and web) developed for these devices are reasons for this humongous data demand. Also, Cisco forecasts [7] that mobile data traffic growth will continue to increase and reach 49 Exabytes per month by 2021, and annual traffic will exceed half a Zettabyte. Factors like limited availability of licensed spectrum and high cost of licensed spectrum are forcing the operators to seek for cost-effective alternate solutions. Wi-Fi operating in the unlicensed band with larger bandwidth has become a sweet spot for operators. Hence, aggregation of multiple radio access technologies (Multi-RAT) has become a key component to meet the targeted requirements for 2020.

In this work, we investigate the cellular-Wi-Fi aggregation solution. Specifically, we have considered LTE and Wi-Fi aggregation problem. Aggregating the link capacities of these two RATs can be done at one of the following layers of the protocol stack *viz.,* Application layer, Transport layer, Network layer, and Link layer. An application can integrate two different networks by establishing two application layer streams *e.g.,* Samsung boost which launches HTTP range requests to fetch different chunks of the same file through different networks. The transport layer also can aggregate two different networks by launching two independent subflows on two paths *e.g.,* MultiPath-TCP (MPTCP) [9]. The aggregation at the network layer is carried out by flow level steering of traffic inside the operator core network *e.g.,* IP Flow Mobility and Seamless Offload (IFOM) [5]. It employs Dual Stack Mobile IPv6 (DSMIPv6) [14] to use two RATs simultaneously. Aggregation at the link layer is achieved using radio level integration architectures (RLI) proposed by

3GPP *viz.,* LTE Wi-Fi Aggregation (LWA) [3] and LTE Wi-Fi integration with IPSec tunnel (LWIP) [4]. These RLI architectures allow steering of packet/flows/bearers across LTE and Wi-Fi links dynamically based on channel conditions, load, link delay, etc.

Aggregation at different layers of the protocol stack exhibits different performance benefits. This paper investigates the aggregation at the transport layer and link layer since aggregation at these layers is of high interest in the context of 5G Multi-RAT connectivity. Also, this paper answers the following questions:

(1) Does transport layer solution such as MPTCP aggregate multiple RATs better than radio level integration solution such as LWA?
(2) Does MPTCP complement and support radio level aggregation when combined?
(3) How do MPTCP and LWA react to packet losses in the network?
(4) How do MPTCP and LWA react to high contentions in medium access?
(5) Does a co-operative MPTCP and LWA solution withstand packet losses and high contentions?

The paper is organized as follows, Section 2 details the background of different Multi-RAT aggregation architectures. In Section 3, a co-operative Multi-RAT architecture and its components are described. Section 4 describes the testbed setup and its configurations. In Section 5, the performance of different Multi-RAT architectures are evaluated, and conclusions are derived. Finally, Section 6 summarizes the findings and suggests the future scope.

2 MULTI-RAT AGGREGATION : BACKGROUND

This section describes the background of link layer and transport layer aggregation of LTE and Wi-Fi networks.

2.1 LTE Wi-Fi Interworking

3GPP proposed various LTE/Wi-Fi interworking strategies from Rel.8 to Rel.13: Rel.8 - Proxy Mobile IP (PMIP) based mobility and access network discovery and selection function (ANDSF), Rel.9 - enhanced ANDSF, Rel.10 - IP Flow mobility, Rel.11 - location based selection of gateway for WLAN and Rel.12 - WLAN network selection, Multiple PDN connections, and IP preservation. From Rel. 8 to Rel. 12, 3GPP access network was connected to non-3GPP access network through standard interfaces. In case of an untrusted non-3GPP network, S2b interface is used between WLAN and evolved PDN Gateway (ePDG) for interworking. The User Equipment (UE) attached to non-3GPP access is authenticated at ePDG before connecting to the Evolved Packet Core (EPC), and an IPSec tunnel is established between UE and ePDG. In case of trusted non-3GPP access, S2a interface between WLAN and P-GW [1] is used where the UE connects to P-GW without any IPSec tunnel. In Rel. 12, Network-Based IP Flow Mobility (NB-IFOM) and LTE/Wi-Fi Aggregation (LWA) were introduced for efficient LTE/Wi-Fi integration. In NB-IFOM, Wi-Fi is brought into operator's network either as trusted or untrusted non-3GPP access. P-GW or UE decides to map between flows and access links (e.g., LTE or Wi-Fi) dynamically.

In case of LWA, LTE small cell eNB (SeNB) and Wi-Fi AP are tightly integrated at RAN level. Radio level integrated architecture has the following advantages:

- EPC need not manage Wi-Fi separately, and it is controlled directly by the SeNB inside LWA node.
- Radio level integration allows effective radio resource management across Wi-Fi and LTE links.
- LTE acts as the licensed-anchor point for UE's communication with the network.

2.2 LWA

LWA realizes aggregation of LTE and Wi-Fi at PDCP layer of LTE eNodeB. An interface, X_w, exists between SeNB and Wi-Fi AP to realize this aggregation. LWA supports various granularity of steering the traffic across LTE and Wi-Fi links, *viz.,* switched bearer and split bearer. Switched bearer switches a bearer of a UE completely from LTE interface to Wi-Fi interface, whereas split bearer splits an existing bearer at the granularity of packets/flows across LTE and Wi-Fi interfaces. In case of a split bearer, packet re-ordering is carried out using Dual Connectivity (DC) re-ordering procedure [2]. Aggregation at the PDCP layer requires modifications at the protocol stacks of UE and eNB. The purpose of realizing aggregation at PDCP layer is to achieve (1) In-sequence delivery of packets to higher layers, (2) Robust Header Compression (RoHC), and (3) Encryption of the packets sent through Wi-Fi interface. In-sequence delivery is required for aggregation because in case of split bearer at packet level any out-of-order packets have to be reassembled and delivered to the higher layer in order. RoHC further enhances the aggregation capacity by compressing the IP header of packets sent through the Wi-Fi interface. Legacy LTE encryption function provides encryption for data sent through Wi-Fi interface at the PDCP layer, and this eliminates the need for additional encryption at Wi-Fi interface.

2.3 Multipath TCP

Multipath TCP (MPTCP) is a transport layer solution which enables simultaneous use of multiple interfaces *viz.,* Wi-Fi and LTE. MPTCP uses multiple paths to deliver the segments corresponding to one end-to-end connection. MPTCP implements congestion control algorithms which are developed obeying the following principles: (a) MPTCP should not get more throughput than single path TCP in case of shared bottleneck, (b) The performance of all the MPTCP subflows together should be at least that of regular TCP on any of the paths used by an MPTCP connection, and (c) MPTCP should prefer efficient paths to deliver the larger fraction of the traffic. The packets sent through different paths are reordered at the receiver.

In spite of its significant benefits, MPTCP miserably fails in many cases. MPTCP offers higher throughput and robustness compared to single path TCP, but when the path characteristics such as RTT and loss rates become diverse, then the performance is affected significantly. This makes MPTCP inefficient in reacting to the path diversities [13]. Also, MPTCP congestion control algorithms are very conservative in the growth of their congestion window obeying to the first design principle [8], even when no bottleneck link exists. MPTCP suffers from larger reordering buffer at the receiver. These challenges prevent MPTCP from acting as a standalone solution for aggregating multiple links.

3 INTEGRATION OF MPTCP OVER LWA

This section describes the integrated MPTCP and LWA solution in order to efficiently aggregate LTE and Wi-Fi links under challenging link and network conditions. Fig. 1 shows the integration architecture of MPTCP over LWA (MLWA). Initially, MPTCP establishes two subflows across LTE and Wi-Fi links on observing the presence of multiple interfaces, revealed by the option *MP − CAPABLE*. A subflow through LTE interface is subjected to LWA operation, whereas the subflow through Wi-Fi remains undisturbed.

LWA is realized by integrating LTE and Wi-Fi at their radio protocol stacks by using X_w interface. Link Aggregation Layer (LAL) does the orchestration of traffic steering across LTE and Wi-Fi links. LAL is implemented at PDCP layer of LTE protocol stack and it does the downlink steering of packets across LTE and Wi-Fi links. LAL is also responsible for collecting link-level information about LTE and Wi-Fi, which will be used for steering the traffic. In this work, LWA employs Wi-Fi link to be used only in the downlink to minimize contentions on Wi-Fi channel. Whereas LTE is used in both uplink and downlink, *i.e.,* for the downlink TCP data packets of LWA and the corresponding TCP ACKs are sent through LTE uplink. PDCP layer at UE employs reordering function to minimize the out-of-order packet delivery to higher layers.

3.1 Traffic steering in LWA

LAL of LWA supports steering at packet level/split bearer which involves steering packets of a flow across LTE and Wi-Fi links at LWA node. Packet-level steering can be done

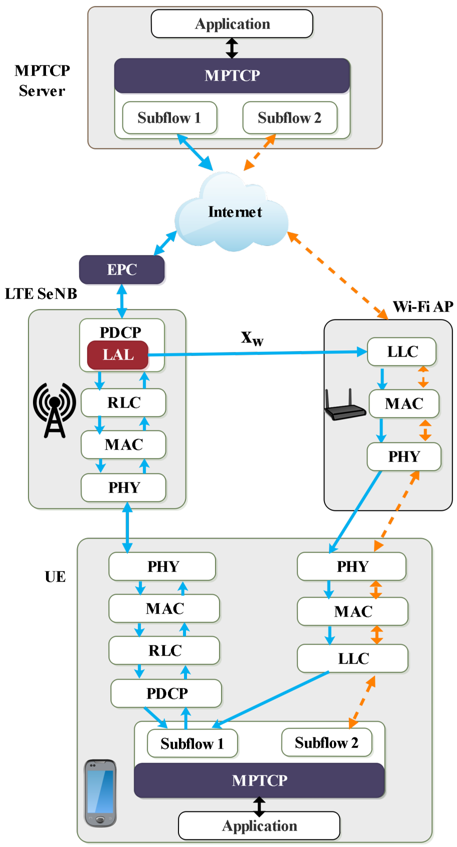


Figure 1: Architecture for Integrating MPTCP over LWA (MLWA).

based on link metrics *viz.,* PHY throughput, depletion rate of LTE and Wi-Fi buffer, and link rate. For instance, if ratio of PHY throughputs of LTE and Wi-Fi $(x : y)$ is taken as metric to steer the packets, then for every $x + y$ packets x packets will be sent through an interface, and y packets will be sent through the other interface. PHY throughput can be obtained from observed Signal to Interference plus Noise Ratio (SINR), Modulation and Coding Scheme (MCS), and bandwidth of corresponding links in real-time [17].

3.2 Dynamic traffic steering

Traffic steering across LTE and Wi-Fi links is still in its infancy. Static steering is employed initially to steer the traffic across LTE and Wi-Fi links [16], which involves a fixed number of packets to be sent over LTE and Wi-Fi links based on link parameters. The challenge with static steering is its inability in capturing the working principles of different links. For instance, LTE operating with round-robin based

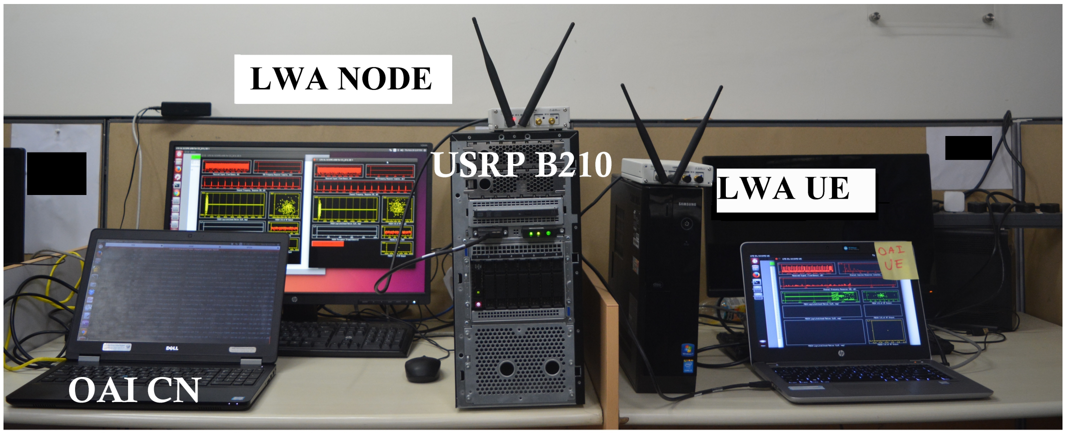


Figure 2: LTE Wi-Fi Aggregation testbed.

MAC scheduler delivers packets in an expected duration under good channel conditions. Whereas in case of Wi-Fi, the channel contention, the packet length of other users, and transmission rate of other users decide the packet delivery time of Wi-Fi, even though the Wi-Fi link is good for the targeted user. The time-varying packet delivery causes more out-of-order packet delivery to the destination, even though there exists packet reordering solution. A dynamic packet steering solution is introduced in this work to minimize number of packets delivered out-of-order and to aggregate the two link rates effectively.

Dynamic packet steering solution, that runs at LAL, takes inputs such as link round trip time (LRTT) of LTE and Wi-Fi, and the packet loss rate of LTE and Wi-Fi links. LRTT is obtained by sending probe packets on corresponding links. Probing packets which are originated at PDCP layer of LWA node (ICMP packets are used) are sent over LTE and Wi-Fi links. The UE on receiving the probe packets sends the probe responses back to LWA node. The probe packets are in order of few bytes, which are generated at an interval of $3msec$ to get the link information more accurately. A smoothed LRTT (SLRTT) estimator is used to calculate the steering ratio. $SLRTT = (1 - \alpha) \times LRTT + \alpha \times SLRTT$, where α is the smoothing factor. The value of α is determined by probe packet interval P_i, where, $\alpha = 1/P_i$. The probe response for the probe packet received through Wi-Fi interface of UE is rerouted through LTE interface to reduce contentions.

The steering window can be of fixed size or variable. Steering window size is the sum of packets sent through LTE and Wi-Fi links in one cycle. For instance, if $x : y$ is the steering ratio across LTE and Wi-Fi, $x + y$ corresponds to steering window size and time unit spent to send $x + y$ packets is referred to as a cycle. A fixed steering window does not change the sum of x and y, whereas the steering window with variable size allows variation in it. This work employs variable steering window at LWA node.

4 TESTBED SETUP FOR MULTI-RAT AGGREGATION

This section describes the testbed setup for LWA, MPTCP, and MLWA. Fig. 2 shows LWA prototype and its components.

LWA testbed setup consists of LWA-eNB, LWA-UE, and EPC. The testbed can be set up without using S1-interface, *i.e.,* the testbed can also be set up without EPC. LWA-eNB and LWA-UE are Linux machines which run Ubuntu 14.04 with low-latency kernel. The implementations of LWA-eNB and LWA-UE are built on top of OpenAirInterface (OAI) platform [12], which offers Software Defined Radio (SDR) based software implementation of LTE written in C. Ettus USRP B210 boards were used as RF transceivers. In LWA setup the LTE-eNB is connected to off-the-shelf 802.11g Wi-Fi AP through Ethernet cable. 802.11g is preferred in these experiments in order to have comparable link rates across LTE and Wi-Fi. The LWA-UE is associated with the same Wi-Fi AP. The LTE is configured to operate on band 7, where the downlink and uplink frequencies are 2.68 GHz and 2.56 GHz, respectively. LTE operates with 5 MHz bandwidth which corresponds to 25 Physical Resource Blocks (PRB). PDCP reordering time at the LWA-UE is set to 2 × Max(LRTT of Wi-Fi, LRTT of LTE).

MPTCP is set up by importing MPTCP Linux kernel V3.18.20 at the file server and V4.9.60 at the UE, respectively. The file server is connected to LTE network and Wi-Fi AP through local area network (LAN). To evaluate the performance of MPTCP, we employ the *lowest RTT first* scheduler, *opportunistic link increase algorithm (OLIA)* as MPTCP congestion control algorithm, and *ndiffports* as path manager. *ndiffports* path manager creates 'n' subflows across every pair of IP

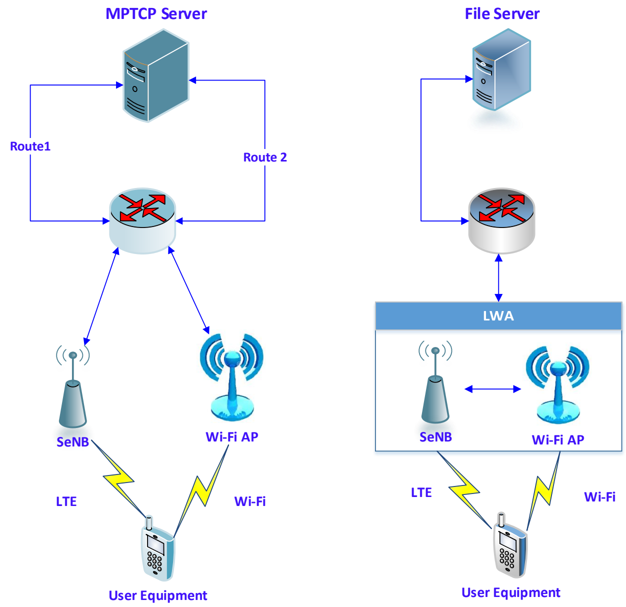


Figure 3: Experimental setup of MPTCP and LWA.

addresses. This experiment uses one subflow for every pair of IP addresses. The source code of LWA is made open [15].

5 PERFORMANCE EVALUATION

This section describes the setup considered for experimenting with different aggregation architectures *viz.,* LWA, MPTCP, and MLWA. Fig. 3 shows the outline of the setup and its components. A file server is setup by launching Apache web service on a Linux machine to evaluate the performance. To emulate an internet like scenario, backhaul delay of 80 ms [6] has been introduced at the Ethernet interface of the file server with the help of *netem* network emulator [11]. The performance of aggregation architectures is evaluated by conducting file download operations of various file sizes *viz.,* 16, 32, and 64 MB. Table 1 captures various parameters used in these experiments. The aggregation architectures are evaluated under the following three challenging scenarios:

(1) Network congestion in the backhaul.
(2) Contention on the Wi-Fi channel.
(3) Mixed: network congestion and channel contention.

The experiments are conducted by varying packet loss rates (which mimics network congestion), file sizes, and channel contentions under different scenarios. Each experiment is repeated for multiple trials. In total, 972 experiments have been conducted to make concrete conclusions.

Table 1: Experimental Parameters

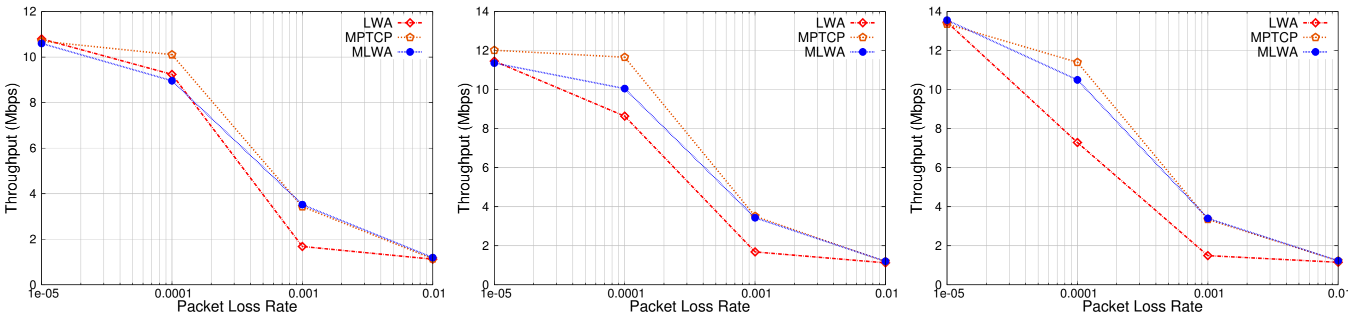
Parameter	Value
LTE eNB bandwidth	5 MHz
LTE downlink, uplink frequency	2.66 GHz, 2.54 GHz
Number of resource blocks	25
Wi-Fi transmit power	20 dBm
LTE MAC Scheduler	Round Robin
Wi-Fi frequency, bandwidth	2.4 GHz, 20 MHz
Wi-Fi standard	IEEE 802.11g
Backhaul delay	80 msec
Packet loss rate	$10^{-4}, 10^{-3}$, and 10^{-2}
Download file size	16, 32, 64 MB

5.1 Network Congestion Scenario

The network congestion is emulated by introducing packet loss at the Ethernet interface of the file server using *netem* tool. Experiments are conducted by varying the packet loss rates *viz.,* no loss, 0.01%, 0.1%, and 1% (0, 10^{-4}, 10^{-3}, 10^{-2}), to observe the reaction of different aggregation architectures to network congestion.

5.1.1 Throughput vs. Packet loss rate: Fig. 4 shows variation in observed throughput by varying packet loss rates for different file sizes. As the network congestion increases, MPTCP efficiently handles the network level packet losses compared to LWA and MLWA. Hence, it achieved the highest throughput. LWA could not achieve comparable throughput because there exists only one congestion window (single TCP) for the end-to-end connection, whereas MPTCP manages a separate congestion window for each subflow. On observing packet losses, the congestion window is reduced significantly in the case of LWA. In summary, when congestion in the network is low, the aggregation architectures exhibit different phenomenon, however as the congestion in the network increases, they achieve similar performance.

5.1.2 Congestion Window: Figs. 5a-5c show, the variation in congestion window growth for LWA, MPTCP, and MLWA architectures for downloading a 64 MB file with packet loss rate of 10^{-4}. On observing packet losses, the growth of LWA congestion window is hindered significantly. Following are some of the interesting observations from the plots (1) Congestion window for LWA grows faster due to dynamic traffic steering solution employed, whereas MPTCP grows conservatively, (2) LWA can deliver its maximum benefits for the small file downloads (which will be heavily used in web browsing and real-time services), and (3) The ratio of the total number of packets sent through LTE and Wi-Fi is in the

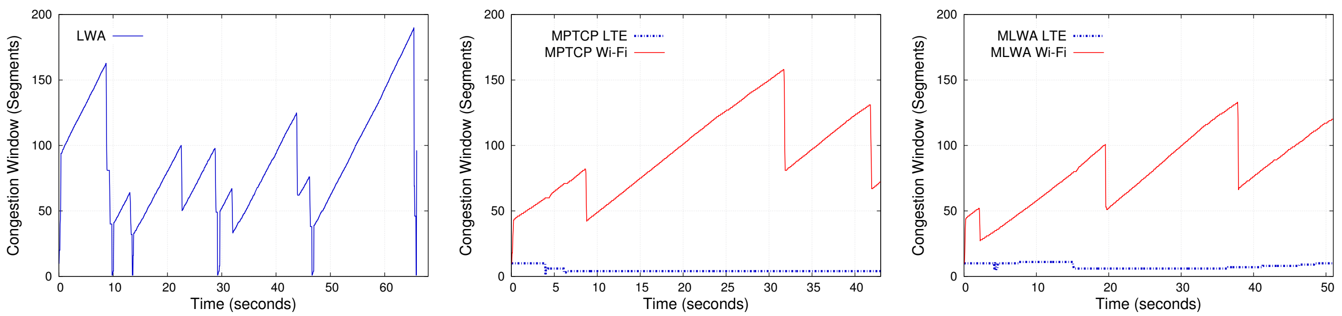


(a) File size is 16 MB.

(b) File size is 32 MB.

(c) File size is 64 MB.

Figure 4: Throughput observed in case of LWA, MPTCP, and MLWA by varying congestion losses in the network.



(a) Congestion window for LWA.

(b) Congestion window for MPTCP.

(c) Congestion window for MLWA.

Figure 5: Congestion window observed for one 64 MB file download with 10^{-4} loss rate.

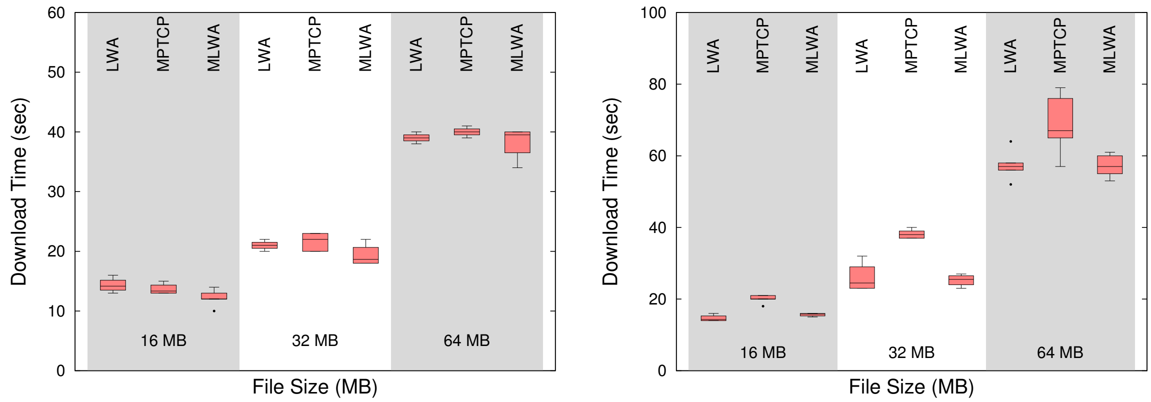
order of 1 : 4, and 1 : 27 in case of LWA and MPTCP, respectively. These reveal that MPTCP is inefficient in aggregating multiple links.

5.2 Channel Contention Scenario

A controlled contention environment was set up to evaluate the performance of LWA, MPTCP, and MLWA with different levels of contention. The contention in the Wi-Fi network is introduced by connecting 2 to 4 laptops to the same Wi-Fi AP. Each of those laptops was continuously sending UDP packets at 1.5 Mbps in uplink using iPerf tool. The contention in the network created by using two laptops and four laptops are considered as low and high contention scenarios, respectively. The channel busy time described in subsection 5.2.2 captures the level of contention on the Wi-Fi channel.

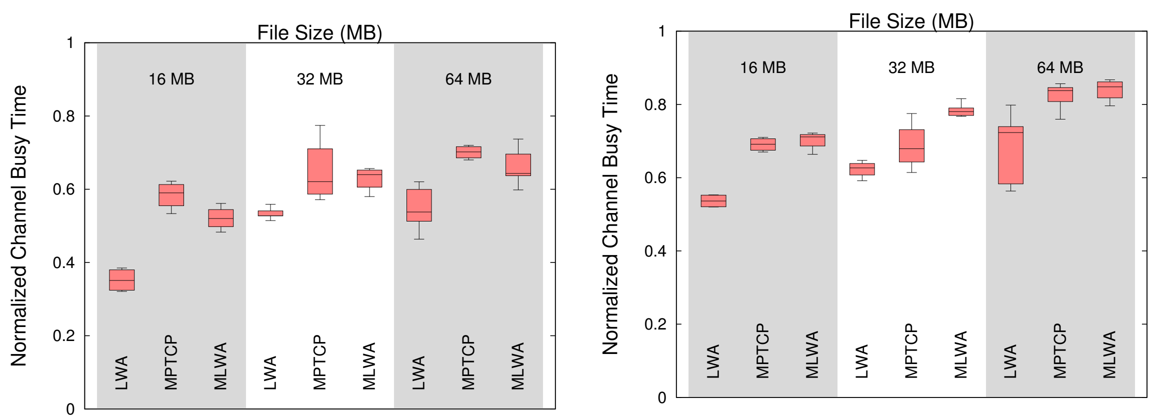
5.2.1 Download time vs channel contention: Time to download files of sizes 16, 32, and 64 MB under low and high contentions scenarios are shown in Fig. 6a and Fig. 6b, respectively. MPTCP performs well when the contention in the network is low, but it performs poorly compared to LWA when there is high contention in the network. This is because the uplink ACK packets in MPTCP which are sent through Wi-Fi interface suffers high contention, whereas TCP ACKs do not suffer any contention in case of LWA. Since LWA employs both LTE and Wi-Fi links to send TCP data packets in downlink, but in uplink it uses only LTE link, which does not suffer from any contention. Hence, LWA achieves higher throughput. MLWA achieves the best performance in low contention scenario and comparable performance with that of LWA in high contention scenario.

5.2.2 Channel busy time: Channel busy time in low and high contention scenarios are captured in Fig. 7a and Fig. 7b, respectively. The reason for the poor performance of MPTCP is due to high contentions which can be observed in Fig. 7a. LWA reduces channel contentions in the network by allowing the UE to send uplink packets through LTE and thereby it facilitates improved transmission opportunities to other Wi-Fi stations in the network. MLWA achieves high throughputs in both high and low contention scenarios because it uses the merit of MPTCP in low contention scenario (which employs different congestion regulation mechanism per subflow), and it uses LWA feature (no uplink contention) in case of high contention scenario.



(a) Low contention. **(b) High contention.**

Figure 6: Time to download observed in case of LWA, MPTCP, and MLWA by varying file sizes.



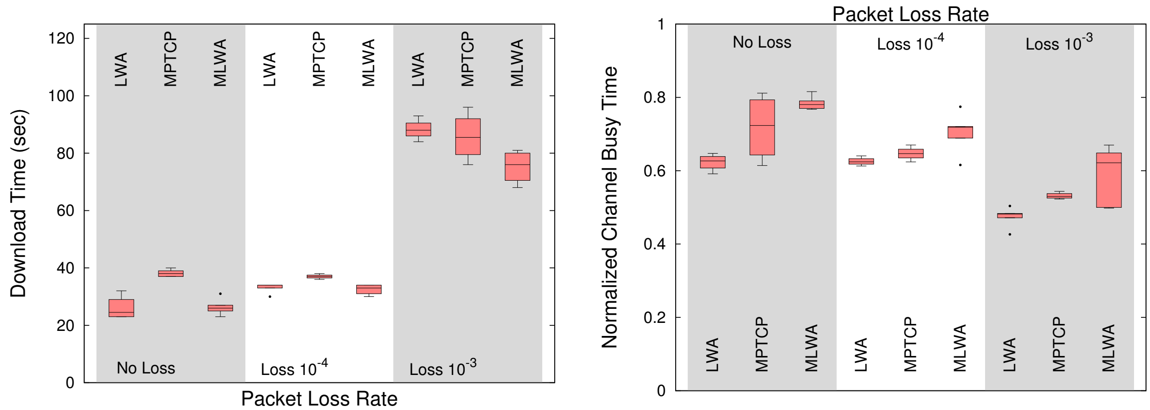
(a) Low contention. **(b) High contention.**

Figure 7: Channel busy time observed on Wi-Fi channel when one 32 MB file was downloaded.

5.3 Mixed: Network Congestion and Channel Contention Scenario

The more challenging scenario is considered to evaluate the full potential of LWA, MPTCP, and MLWA. The experiment is conducted with high channel contention for a file download of size 32 MB with different packet loss rates of 0, 10^{-4}, and 10^{-3}. The motive behind this experiment is to check the robustness and agility of LWA, MPTCP, and MLWA to aggregate multiple links in case of different congestion losses and tolerate high channel contention. From Fig. 8a, it can be observed that LWA outperforms MPTCP in high contention scenario when the network congestion is low. As packet loss increases LWA performance degrades, and it performs poorly compared to MPTCP even though it does not suffer from channel contention. MLWA performs equivalently to LWA when there is no loss with high contention, and it outperforms MPTCP and LWA when the packet loss rate is more with high contention. This is because, in high contention scenario, LTE subflow of MLWA which is split over LTE and Wi-Fi link does not create contention for Wi-Fi subflow of MLWA which sends all the TCP Acks over Wi-Fi. Thereby a co-operative operation between LTE subflow and Wi-Fi subflow of MLWA has improved the performance, which is captured in Fig. 8b. When the congestion loss rate was increased to 10^{-3}, LWA and MPTCP exhibit a similar performance in terms of download time, but LWA still preserves lowest channel contention as shown in Fig. 8b.

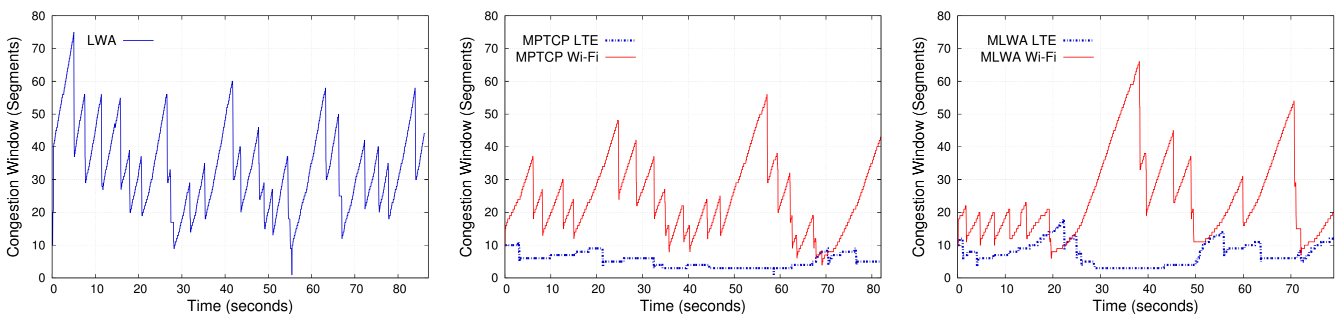
Figs. 9a, 9b, and 9c show the congestion window growth of LWA, MPTCP, and MLWA when the packet loss and channel contentions are high. It can be observed that a significant amount of traffic is sent through MLWA LTE subflow as



(a) Time to download.

(b) Channel busy time.

Figure 8: Performance observed for 32 MB file download with network congestion and high channel contention.



(a) Congestion window for LWA

(b) Congestion window for MPTCP

(c) Congestion window for MLWA

Figure 9: Congestion window observed for 32 MB file download with 10^{-3} loss rate and high channel contention.

compared to MPTCP LTE subflow. This is the key enabler for the improved performance of MLWA.

6 CONCLUSIONS

This work presented the integrated architecture of MPTCP over LWA (MLWA) and evaluated its performance in challenging environments. All the experiments were conducted in a testbed using OpenAirInteface (OAI), an open source LTE platform. From the conducted experiments, the following inferences could be drawn, (i) In case of high network congestion, MPTCP is an ideal solution to be used which can effectively handle the network level losses, (ii) LWA fails to aggregate link capacities when there is congestion in the network, (iii) LWA is well suitable when the download files are of smaller size (less than 1 MB- Web traffic), (iv) When the channel contentions are high, LWA not only improves the performance of its users but it also improves overall performance of all users on the Wi-Fi channel, and (v) MLWA is robust and exhibits significant performance when the congestion losses and channel contentions are very high.

The experiments revealed that the transport layer solution and radio level interworking solutions are complementing each other and co-operation between these two solutions in any scenario is better than at least one of their performances. As a notable point in 5G Multi-RAT design, to aggregate multiple links effectively where the link rates are diverse, an efficient radio level interworking solution should be used. A co-operative solution is needed to achieve better end-to-end performance. The work can be further enhanced by providing enhanced bi-directional co-ordination between MPTCP and LWA, which can improve the performance very significantly.

ACKNOWLEDGMENTS

This work was partially supported by the projects "Converged Cloud Communication Technologies" and "Low Latency Network Architecture and Protocols for 5G Systems and IoT", MeitY and SERB, Govt. of India. We thank Himank Gupta for his help in setting up the testbed.

REFERENCES

[1] 3GPP. 2009. *Architecture enhancements for non-3GPP accesses.* Technical Report 23.402.

[2] 3GPP. 2013. *Study on Small Cell enhancements for E-UTRA and E-UTRAN; Higher layer aspects.* Technical Report 36.842.

[3] 3GPP. 2017. *LTE-WLAN Aggregation Adaptation Protocol.* Technical Report 36.360.

[4] 3GPP. 2017. *LTE-WLAN Radio Level Integration Using Ipsec Tunnel (LWIP).* Technical Report 36.361.

[5] 3GPP. 2018. *Network-Based IP Flow Mobility (NBIFOM).* Technical Report 23.161.

[6] Yung-Chih Chen et al. 2013. A measurement-based study of Multi-Path TCP performance over wireless networks. In *Proc. of Internet Measurement Conference.* ACM, 455–468.

[7] Cisco. 2017. Global Mobile Data Traffic Forecast Update, 2016 - 2021. (2017). https://goo.gl/F1WDVU

[8] Simone Ferlin et al. 2016. Revisiting congestion control for multipath TCP with shared bottleneck detection. In *Proc. of INFOCOM.* IEEE, 1–9.

[9] Alan Ford et al. 2013. *TCP Extensions for Multipath Operation with Multiple Addresses.* Technical Report 6824. https://tools.ietf.org/html/rfc6824

[10] ITU. 2015. IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond. (2015). https://www.itu.int/

[11] Linux network developers. 2016. Network Emulation. (2016). https://wiki.linuxfoundation.org/networking/netem

[12] Navid Nikaein et al. 2014. OpenAirInterface: A flexible platform for 5G research. *ACM SIGCOMM Computer Communication Review* 44, 5 (2014), 33–38.

[13] Swetank Kumar Saha et al. 2017. Multipath TCP in Smartphones: Impact on Performance, Energy, and CPU Utilization. In *Proc. of Mobility Management and Wireless Access.* ACM, 23–31.

[14] Hesham Soliman. 2009. *Mobile IPv6 Support for Dual Stack Hosts and Routers.* Technical Report 5555. https://www.rfc-editor.org/rfc/rfc5555

[15] Santhapan Thomas. 2018. LTE Wi-Fi Aggregation. (2018). https://github.com/ThomasValerrianPasca/eNB_LWA

[16] Santhappan Thomas et al. 2017. A real-time performance evaluation of tightly coupled LTE Wi-Fi radio access networks. In *Proc. of ANTS.* IEEE, 1–6.

[17] Xiufeng Xie et al. 2016. piStream: Physical Layer Informed Adaptive Video Streaming Over LTE. *GetMobile: Mobile Comp. and Comm.* 20, 2 (2016), 31–34.