LWIR: LTE-WLAN Integration at RLC Layer with Integrated LTE-WLAN Scheduler for Efficient Aggregation

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Abstract

Mobile data traffic has seen an exponential growth in the past few years with the similar trend expected to continue. Long Term Evolution (LTE) as a standalone cellular networking technology will not be able to keep pace with the increasing traffic demands. In the meanwhile, Wireless LAN (WLAN) has proven itself as an economical wireless access technology. 3GPP has thus been encouraged to standardize the integration of WLAN with LTE. LTE-WLAN integration at Radio Access Network (RAN) level offers tighter link level aggregation with enhanced system performance compared to other WLAN inter-working and offloading mechanisms. Having LTE as the anchor for both networks, it provides unified control over both networks without any changes in LTE Core Network (CN).

In Rel-13 [1], 3GPP has standardized two RAN level aggregation architectures, LTE-WLAN Radio Level Integration using IPsec Tunnel (LWIP) at IP layer and LTE-WLAN Aggregation (LWA) at PDCP layer of LTE protocol stack. But both LWIP and LWA are prone to some issues. Having no re-ordering scheme at IP layer, LWIP does not support split bearer (packet-level) traffic steering. Traffic steering means transmitting data at different granularity (i.e., packets, flows or bearers) across different radio interfaces available at user handsets. On the other hand, because of high delay on Wi-Fi network, LWA is not able to achieve good throughput, especially for TCP flows. To address these problems, we have developed a new LTE-WLAN RAN Integration architecture at RLC layer (LWIR) for both collocated and non-collocated scenarios. In collocated scenario, both LTE small cell (SeNB) and Wi-Fi AP are placed in a same integrated AP. In non-collocated scenario, Wi-Fi AP is connected to an LTE cell through X_w-interface.

The proposed LWIR architecture is furnished with an Integrated LTE-WLAN Scheduler (ILWS) which performs scheduling for both LTE and WLAN RANs and improves the fairness and system resource utilization. LWIR enables byte stream level traffic steering which gives finer control over data than flow-level and packet-level traffic steering as more than one packet can be aggregated and steered on one of the networks. ILWS is also embellished with five different bearer selection schemes for Wi-Fi, which provide efficient traffic steering by smartly choosing a bearer to steer some of its data onto Wi-Fi link based on its available bandwidth. LWIR architecture with ILWS for both the scenarios is implemented in NS-3. Using extensive simulations, we have evaluated the performance benefits of proposed architecture and also compared with existing LWIP and LWA architectures.

Our novel, all-encompassing LWIR architecture is demonstrated to be significantly better and more effective than LWIP and LWA architectures. It has been seen that the proposed LWIR with ILWS has significantly better performance in terms of system throughput than LWA packet-level traffic steering scheme. In LWIR, almost 37% throughput improvement has been seen compared to best existing solution LWIP (flow-level).

Contents

Chapter 1

Introduction

In recent years, rapid adoption of smartphones with high-quality and data-intensive services has spawned an over-abundance of bandwidth related issues on cellular networks with the current capacity of licensed spectrum. LTE networks are inherently constrained by the limited bandwidth of the licensed spectrum. This has shifted mobile operator's interest to offload data traffic from bandwidth constrained licensed networks onto available unlicensed spectrum networks. WLAN is playing an increasingly important role as a supplement in unlicensed spectrum by allowing opportunistic cellular data offload. 3GPP has developed several solutions for data offloading onto WLAN networks such as Access Network Discovery and Selection Function (ANDSF) and IP Flow Mobility (IFOM). But these conventional solutions do not provide tighter integration of both LTE and WLAN at Radio Access Network (RAN) level. Also, determining when to switch between the radios and how much data to steer onto Wi-Fi is a tedious task. Hence, there is an essential need for a mechanism that can efficiently shift loads between LTE and Wi-Fi by adjusting the steering rate dynamically. Hence, 3GPP came up with LTE-WLAN aggregation architectures at RAN level at different layers of LTE protocol stack for tighter integration. Figure 1.1 shows the network architecture for LTE-WLAN aggregation. An important element of aggregation is that it does not require any new Core Network (CN) nodes, interfaces and signaling. In Figure 1.1, the connection of WLAN to the CN (i.e, EPC) is shown to illustrate the fact that the same WLAN network can be used to provide offloading services using such interfaces which were standardized by 3GPP before Rel-13 [1]. As shown in Figure 1.1, LTE base station (evolved Node B or eNB) and Wi-Fi Access Point (AP) are connected through X_w-interface in non-collocated scenario. In collocated scenario, both eNB and Wi-Fi AP are tightly integrated at RAN level in the same box.

1.1 3GPP on RAN Level Aggregation

Recently, 3GPP has standardized some LTE-WLAN aggregation architectures at RAN Level at different layers of LTE protocol stack. LTE-WLAN Radio Level Integration using IPsec Tunnel (LWIP) at IP layer and LTE-WLAN Aggregation (LWA) at PDCP layer are two link aggregation architectures proposed by 3GPP in Rel.13 [1]. These architectures have sparked a keen interest in the research community as they offer reliable connectivity and tighter link level aggregation with remarkably enhanced throughput. An eNB that can schedule packets to be delivered on LTE and

Wi-Fi radio links, is currently the best choice for data steering on unlicensed spectrum as it does not require a great deal of changes in the current architecture of LTE.

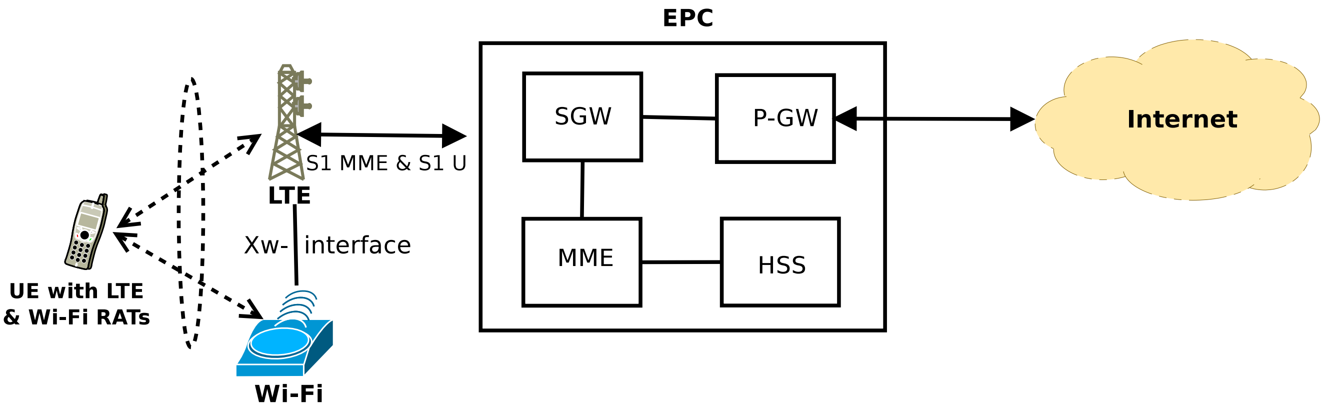

Figure 1.1: Network architecture for LTE-WLAN aggregation [2]

As most of the LTE User Equipments (UEs) are already equipped with Wi-Fi, both LTE and Wi-Fi radios can be used simultaneously under one IP layer sharing the same CN as shown in Figure 1.1. At the eNB, a tunneling architecture can be enabled to pick frames from any particular layer of LTE protocol stack and steer them as Wi-Fi payloads. A similar logic can also be implemented at the UE side just with a software update which puts the data from Wi-Fi MAC back into the LTE bearers.

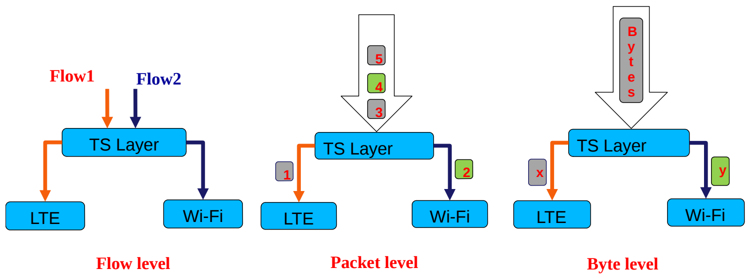

Figure 1.2: Traffic Steering Schemes

Traffic steering means transmitting data at different granularity (i.e., packets, flows or bearers) across different radio interfaces available at user handsets. There are two possible traffic steering schemes as discussed below:

- **Switched Bearer:** It is a bearer-level offloading scheme in which a complete bearer is offloaded from LTE interface to Wi-Fi interface. Flow-level steering comes under this scheme.

- **Split Bearer:** It is basically the packet-level steering scheme in which packets belonging to the same flow are sent across different available interfaces.

In split bearer steering, some packets are put into the Wi-Fi queue just after going through the IP layer in LWIP and PDCP layer in LWA. The packets going in the Wi-Fi and LTE have to wait in the Wi-Fi MAC and RLC layer queues, respectively. Waiting time in these queues is different due to scheduling delay in LTE and contention delay in Wi-Fi. As a result, packets reach out-of-order on the UE side. In LWIP, there is no re-ordering mechanism at IP layer which leads to a high number of out-of-order packets at the receiver side. This situation drives to a lot of triple DUPACKS (3DUPACKS) in the case of TCP, resulting in poor system performance and less throughput. On the other hand, LWA does have re-ordering mechanism which adds to the delay as packets now have to wait at the PDCP layer for re-ordering. This is mainly caused because of the existence of queues after the steering point.

There is an another issue that has so far remained largely unaddressed. While steering data onto the Wi-Fi network, careful selection of the bearers to pick data from plays an important role to maximize the achievable throughput. However, selecting the most adequate and reasonable user or bearer from the enormous set of all UEs, for traffic steering to Wi-Fi network, is a tedious task. Further, the absence of such user/bearer selection schemes in the existing research literature that could aid a network administrator in making such crucial choices, makes it worse.

1.2 Overview of Our Work

In this work, we aim to alleviate problems with LWA and LWIP by proposing a fresh LTE-WLAN integration architecture at RLC Layer (LWIR) with an Integrated LTE-WLAN Scheduler (ILWS) which does scheduling for both the networks. Both collocated and non-collocated scenarios have been considered. The ILWS is also equipped with five newly proposed user selection schemes which select most adequate users/bearers for traffic steering over Wi-Fi network based on the user Channel Quality Indicator (CQI) and network load. The proposed work shows a significant improvement in system throughput and user fairness than the previously proposed LTE-WLAN link aggregation architectures. Experimental results to validate the proposed technical indications were collected by running an exhaustive set of NS-3 simulations.

Generally, fairness among users is taken care by scheduler in LTE. Since some data from particular bearers is steered onto the Wi-Fi, this fairness is disturbed. Thus, an LTE feedback mechanism is proposed that keeps track of data being sent on the Wi-Fi and co-ordinates with the LTE scheduler to ensure fairness.

Following are the main contributions in this thesis work:

- Proposing an LWIR architecture for efficient LTE and WLAN aggregation for both collocated and non-collocated scenarios.

- Proposing an Integrated LTE-WLAN scheduler embellished with an aggregation scheme for minimizing Wi-Fi queue delay which eventually tries to equate the delivery time of both the radios for ensuring in-order packet delivery thereby helping to achieve higher throughput especially in the case of TCP flows.

- Proposing five bearer selection schemes to aid ILWS for effective user selection to enhance utilization of both the networks.

- Extensive study of the performance of the proposed LWIR with ILWS and its comparison with LWA split bearer scheme using NS-3 simulator [3].

For the integrated AP, we will be using LWA node in case of LWA and LWIR node in case of proposed architecture, LWIR.

1.3 Thesis Outline

The rest of the thesis is organized as follows: Chapter 2 describes different aggregation architectures proposed by 3GPP such as LWIP and LWA. It gives an overview of related work and the motivation for this thesis work. In Chapter 3 the proposed aggregation architecture for collocated and non-collocated scenario has been explained. Chapter 4 describes the proposed user selection schemes used by LWIR architecture for the data steering onto Wi-Fi network. The simulation setup and results for the proposed work are discussed in Chapter 5. Conclusions and possible future work are discussed in Chapter 6. Chapter 7 shows different research outputs related to this thesis work.

Chapter 2

LTE-WLAN Aggregation: History and Motivation

2.1 RAN Level Aggregation

3GPP [4] has recognized the importance of 802.11 WLANs (aka Wi-Fi networks) by defining standards for their integration into the LTE architecture. The standards support various mobility management protocols like Proxy Mobile IPv6 (PMIPv6) [5], GPRS Tunneling Protocol (GTP) [6], and Dual-stack Mobile IPv6 (DSMIPv6) [7] for the integration. Various mechanisms to offload traffic onto non-3GPP technologies have been proposed in the 3GPP standards. Current WLAN offloading solutions are useful for service and policy management but they are not efficient for radio and system performance. They also do not allow tight control of WLAN offloading due to device centric methods. Hence, 3GPP has come up with the RAN-level Aggregation of LTE and Wi-Fi which provides following advantages:

- Dynamic resource allocation based on radio and load conditions.
- Higher system throughput.
- Unified network control and management of resources.
- Real-time load balancing and seamless handover support.
- Minimal change on CN and applications.

3GPP proposed two of such solutions: LWIP and LWA as shown in Figure 2.1 and Figure 2.2.

2.2 Motivation and Related Research Work

An architecture with tightly coupled LTE and Wi-Fi having only one CN for both interfaces have been firstly proposed in [9]. This tight interworking apprehends the potential of finer control over multiple radio interfaces. It determines the possible decision making and flow steering solutions based on the link condition and states. Understanding the potential of tighter interworking [10], many architectures have been proposed for interworking between LTE and Wi-Fi. 3GPP is already

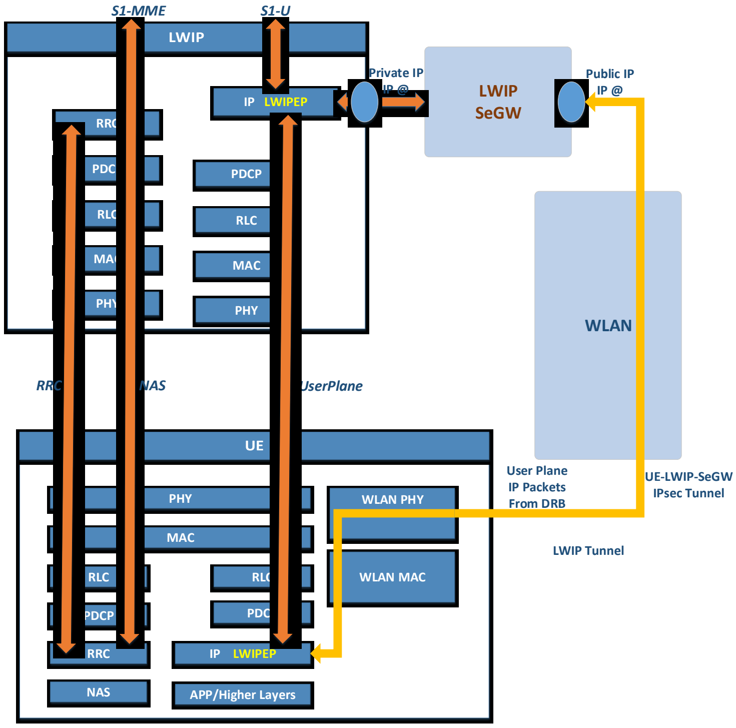

Figure 2.1: 3GPP proposed LWIP Architecture[8]

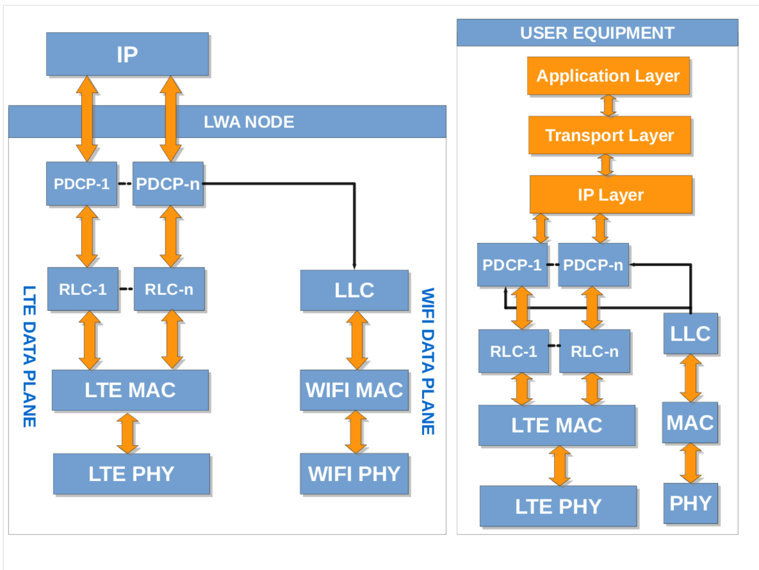

Figure 2.2: 3GPP proposed LWA Architecture[8]

working on two RAN level aggregation architectures. First, LWIP which is an IP layer aggregation scheme and second, LWA which does traffic steering at PDCP layer of LTE protocol stack. LWA has been discussed first in [11].

Architecture for collocated and non-collocated LWA and LWIP has been discussed in [12] and [13]. LWIP does not require any changes to the protocol stack of UE. This makes it available to the existing commercial UEs to readily use these architectures with the availability of LTE and Wi-Fi interfaces. On the other hand, LWA requires modifications in protocol stacks at both UE and eNB. Unlike LWIP, in LWA PDCP layer ensures in-order packet delivery to higher layers, which is required to minimize the out-of-order delivery caused by packet-level traffic steering in split bearers. It achieves in-order packet delivery using Dual Connectivity (DC) procedure [14]. Qualcomm proposed an RLC layer aggregation [15] and compared App-level throughput for both RLC-level aggregation and Multi-Path TCP in the collocated case. They claimed RLC layer to be the most promising approach for LTE-WLAN aggregation. But the aggregation architecture is not included in this work and the amount of data to be transferred to the Wi-Fi network is still an unaddressed and open issue.

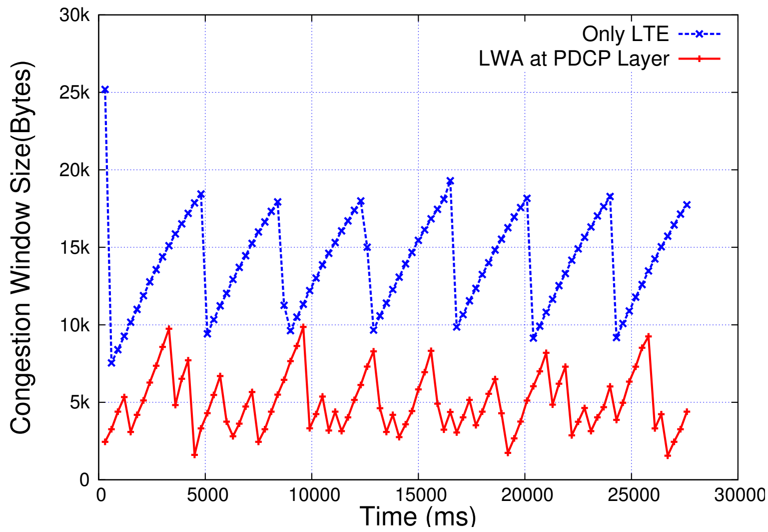

Figure 2.3: Congestion window growth in only LTE and LWA at PDCP layer

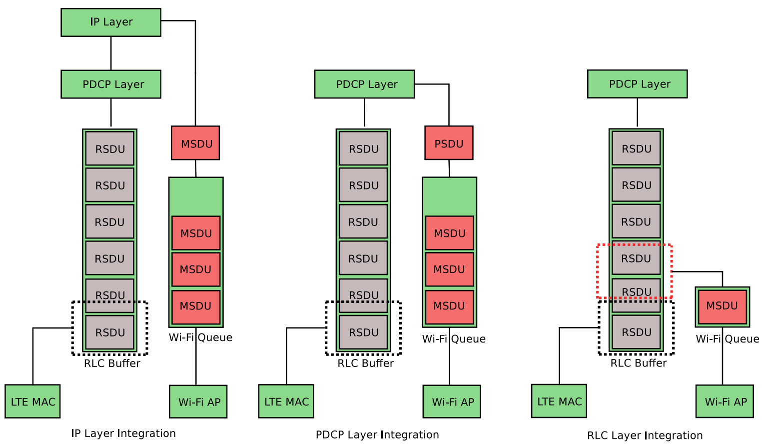

Figure 2.4: Data Steering at Different Layers of Protocol Stack

All these previous works (in RLC and PDCP layer aggregation) rely on the assumption that the problem of out-of-order can be taken care by re-ordering at PDCP/RLC layer. This can reduce TCP 3DUPACKS, but since the re-ordering mechanism is triggered more frequently, it leads to waiting of the packets before going to the higher layer. Thus, TCP is not able to grow the congestion window due to frequent timeouts and it, in turn, effecting the throughput the throughput negatively. To support the claim, we performed a study to understand these effects with a fully loaded network with 30 users having one downlink TCP flow and the result of those can be seen in Figure 2.3. The congestion window of a TCP flow from such network in two different steering schemes has been shown. In the first scheme, all traffic is offloaded to only LTE network, while in second, the traffic is steered at PDCP layer with 50% traffic offloaded to Wi-Fi. The re-ordering timer at PDCP is set as 50 msec. Despite this, it can be seen that the congestion window drops its size frequently in LWA.

There are no queues in LTE after RLC queue. This implies that sequential packets travelling from Wi-Fi and LTE will get transmitted almost at the same time. This will reduce the out-of-order delivery at UE side and hence will reduce the delay caused by the re-ordering mechanism. If Wi-Fi picks packets from any layer above RLC, it is similar to picking bytes from the tail of the RLC queue and more waiting time due to Wi-Fi queues as shown in Figure 2.4. This means that both the channels are picking data from different ends of the queues and this causes the extra delay because there is already some data queued up in Wi-Fi queue. Both the factors will cause out-of-order delivery of data. Having said that, RLC re-transmission and re-ordering also ensures the reliability of the flows.

Chapter 3

Proposed LWIR Architecture

In this chapter, the proposed LWIR architecture, working of ILWS and different module of ILWS will be discussed for both the collocated and non-collocated scenarios.

The proposed LWIR architecture realizes the LTE-WLAN integration at RLC layer with a newly introduced integrated scheduler ILWS. As shown in Figures 3.1 and 3.2, both LTE and Wi-Fi radios share the same IP layer. The packets coming from the common IP layer go through the PDCP layer and get enqueued into the appropriate RLC buffer according to its bearer. Following are some design factors which were taken into consideration in LWIR architecture:

- *Bearer Selection for Wi-Fi*: Opportunistic or round-robin selection of user/bearer for data steering will not guarantee maximum system throughput and fairness among users. The user which should be selected to transmit the data on Wi-Fi depends on factors such as link quality, load, and CQI of each user. ILWS outfitted with five different user/bearer selection schemes for Wi-Fi.

- *Level of Steering*: In RLC buffer, the data resides in byte format. Hence, traffic steering is done at byte stream level at this layer. Byte stream level integration gives more liberty and assures a closer integration than flow and packet-level. It provides a finer control on the volume of data to be sent on Wi-Fi. Byte stream level steering permits us to merge multiple packets into one before steering to Wi-Fi and thus enabling utilization of the channel to its fullest capacity. Different sizes of byte stream can be selected for the transmission over Wi-Fi according to the link condition.

- *How much data to steer?*: Placing extra data in Wi-Fi queue will again drive unnecessary waiting which eventually causes out-of-delivery and performance degradation. With ILWS's data steering module, the solution for this problem has been discussed.

Generally, the LTE MAC layer keeps extracting data from the RLC buffers as and when they are scheduled. In addition to this, some data can be steered to Wi-Fi link as per the opportunity. The newly proposed ILWS takes care of fairness with the maximum possible utilization of Wi-Fi, without disturbing the traditional of LTE scheduler. The architecture and working of ILWS differ a bit in collocated and non-collocated scenarios. The LWIR architecture and working of ILWS are as follows:

3.1 LWIR: Collocated Scenario

In the collocated scenario, both SeNB and Wi-Fi AP reside in a single box (LWIR Node). The LWIR architecture outfitted with ILWS for collocated scenario is shown in Figure 3.1. The LWIR node furnished with LTE SeNB and Wi-Fi AP share a common IP layer. Packets coming from the common IP layer goes through the PDCP layer and get enqueued into the appropriate RLC buffer according to its bearer. The scheduling of the LTE interface follows the legacy LTE scheduling. Hence, the LTE MAC layer keeps extracting data from the RLC buffers as and when they are scheduled by ILWS. But, in addition to this, the ILWS also does scheduling for the Wi-Fi link. Whenever the Wi-Fi MAC gets the channel access the ILWS selects one of the bearers (and its RLC queue) using the appropriate bearer selection algorithms which are only specified for Wi-Fi and extracts some amount of data (bytes) from the queue. As soon as the ILWS transfer some data to Wi-Fi network, it provides feedback about it to the LTE scheduler of ILWS. Hence, LTE scheduler can allocate the LTE resources knowing that some users might be served already by Wi-Fi to ensure fairness.

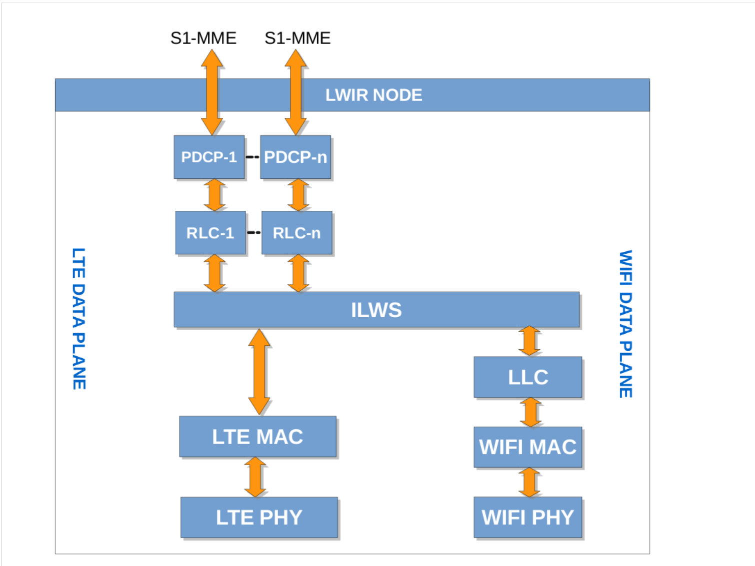

Figure 3.1: LWIR Collocated Architecture

The amount of data can be decided based on the link condition of Wi-Fi as the main goal here is to reduce the waiting time and the contention time for the packets in the Wi-Fi queue. This waiting delay occurs because the packets have to wait as there are some other packets waiting in line before the packet and the contention time is a result of the LBT in the 802.11 standards. Fetching data from RLC buffers and putting it in Wi-Fi queue to transmit only when the Wi-Fi gets channel ensures that there is only one packet in the queue at a time and no packet has to wait. In RLC buffers, the data resides in RLC Service Data Unit (RSDU) form. The IWS then tunnels this data into the Wi-Fi link by attaching Wi-Fi headers to it and sending it over the Wi-Fi MAC layer. On the receiving end, these Wi-Fi MAC frames are decapsulated and the Wi-Fi headers are removed. The extracted RLC frames are then delivered to the appropriate RLC queue using the Radio Network Temporary Identifier (RNTI) and Logical Channel Identifier (LCID) tag on the RLC frame.

As both SeNB and Wi-Fi AP resides in the same box, fetching data from RLC queues and transmitting to Wi-Fi network is as seamless as LTE network. But Wi-Fi, working on unlicensed spectrum follows LBT mechanism which causes a lot of contention as the number of users increase. Taking this fact into consideration, we have come up with the following two contention schemes for Wi-Fi of LWIR:

3.1.1 OneSized Window

When LTE data is steered over Wi-Fi link, the data first, has to wait in Wi-Fi queue. After that higher contention causes some latency in channel access. This delays the delivery of particular data on receivers end. This delay difference on both links disturbs the in-sequence delivery of packets which downgrades performance especially in TCP. Having said that, to minimize the waiting time in Wi-Fi, in this scheme, it is ensured that there is no data stuck in Wi-Fi queue just to wait for other data to transmit. Hence, in this scheme:

The ILWS always fetches some bytes from particular RLC buffer and tunnel it to Wi-Fi link in the form of a packet. This packet is added to Wi-Fi MAC queue. Only when this packet gets the channel access and is sent to the PHY for transmission, the ILWS repeats the process.

This ensures that there is only one packet in the Wi-Fi MAC queue at a time and no packet has to wait. The ILWS keeps track of the Wi-Fi channel availability and always transfer fixed size data block called Maximum Transmission Unit (MTU) from the RLC buffer selected based on user selection schemes.

3.1.2 Dummy/Packet less

Having only one packet in Wi-Fi queue removes the waiting delay. This gives a boost to the system performance when there are not many users contending for the channel. In the case of the highly crowded channel, the contention time can be higher enough to produce delay which may degrade the system performance. Hence, in this scheme the ILWS puts a pseudo/dummy packet in the Wi-Fi queue just to contend for the channel and directly fetches the MTU from RLC buffer when it gets the channel and transmits the real packet to the Wi-Fi network. Therefore, in this case, there is no extra delay at all in Wi-Fi link access. The dummy packet is then added back to the Wi-Fi Queue. And this continues for the subsequent packets.

3.2 LWIR: Non-Collocated Scenario

The LWIR architecture outfitted with ILWS for the non-collocated scenario is shown in Figure 3.2. Along with ILWS, non-collocated LWIR architecture has one newly introduced Virtual Wi-Fi Scheduler (VWS). The ILWS modules situated at SeNB and VWS at Wi-Fi AP are shown in Figure 3.2. As in collocated scenario both SeNB and Wi-Fi AP are situated in an integrated box (LWIR node). Hence, the ILWS scheduler directly can schedule for both the LTE and Wi-Fi link. But in the case of non-collocated scenario, where SeNB and WI-Fi AP are connected through X_w- interface there is extra delay added to data transmission from RLC buffers to Wi-Fi AP. Therefore, to control how much data to transmit and when to transmit, an extra module, VWS has been added to Wi-Fi AP. This keeps track of Wi-Fi MAC status and communicates with the ILWS to schedule for Wi-Fi link in such a way that it maximizes the system throughput and Wi-Fi link utilization. As shown in Figure 3.2, the packets coming from the common IP layer go through the PDCP layer and get enqueued into the appropriate RLC buffer according to its bearer. The ILWS does scheduling for both the LTE and Wi-Fi links. As mentioned earlier, the scheduling for LTE link is same as traditional LTE scheduler and there is no change in that. Hence, the LTE MAC layer keeps extracting data from the RLC buffers as and when they are scheduled by ILWS. In addition to this, the VWS requests the ILWS to schedule some data over Wi-Fi link. Hence, whenever the VWS makes a request to the ILWS, it selects one of the bearers (and its RLC queue) using the appropriate bearer selection algorithm and extracts the required amount of data (bytes) from the queue. The amount of data is decided based on the X_w-interface delay. The VWS requests the minimum possible data required for continuous transmission over Wi-Fi. The VWS keeps updating with Wi-Fi MAC status and the amount of data in Wi-Fi queue. Hence, it requests the data in such a way that it can receive the data from ILWS before all data from Wi-Fi queue is transmitted. This maintains the utilization of Wi-Fi network also. This data is in the form of an RLC frame. The ILWS then tunnels this data into the Wi-Fi link by attaching Wi-Fi headers to it and sending it to VWS through X_w-interface. Then the VWS delivers it to the Wi-Fi MAC. On the receiving end, these Wi-Fi MAC frames are opened and the Wi-Fi headers are removed. The extracted RLC frames are then returned to the appropriate RLC queue using the RNTI and LCID tag on the RLC frame.

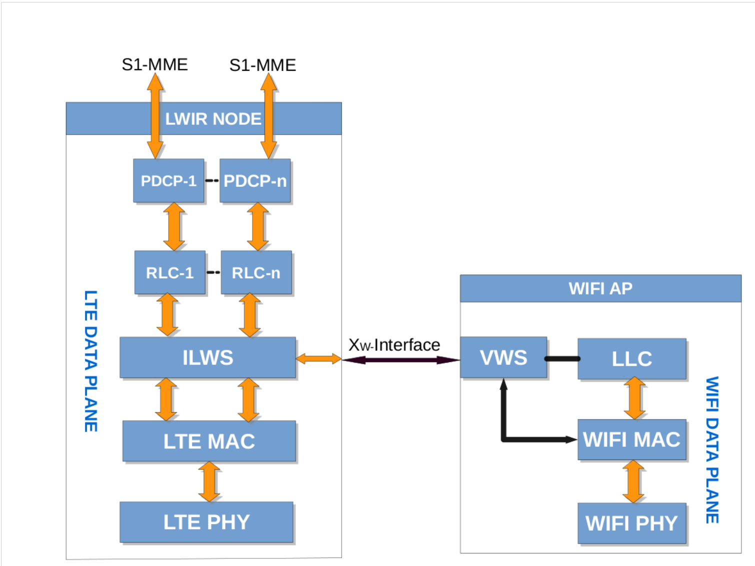

Figure 3.2: LWIR Non-Collocated Architecture

Byte stream level steering provides the option to select different MTU size, unlike other aggregation architectures. Increasing MTU size leads to efficient link utilization. As LTE is a scheduled interface (time frequency scheduled) the achievable rate is deterministic. On the other hand, Wi-Fi with probabilistic transmission, gets increased throughput by increasing the packet size. This is captured below:

$$T_{tot} = N * (T_{PktTx} + T_{Acc}) \tag{3.1}$$

For a given time duration of T_{tot}, the effective channel usage time is given by $N * T_{PktTx}$, where N is number of packets transmitted from Wi-Fi AP in T_{tot} time. T_{Acc} is the time to get the channel access in Wi-Fi.

$$T_{PktTx} \propto PacketSize \tag{3.2}$$

As the packet size (MTU) increases, the number of transmitted packet N decreases which in turn reduces the total access time $N * T_{Acc}$ and this increases the overall effective channel utilization.

In this work two MTU sizes: 1500 and 2,304 MSDU (Maximum MAC payload, the size of 802.11a) are considered. The first MTU size 1500 is taken because in the experiments the packet size is kept 1428. Hence, the transmission packet in RLC level integration is also almost equal to PDCP integration (with headers added to it). Also, 1500 bytes signify the ethernet payload size. To get maximum utilization of Wi-Fi link, we chose other MTU size 2304 bytes (Maximum MAC payload). The MTU size scales to different Wi-Fi technology (for eg. in 802.11n and 802.11ac, the ethernet frame size will be large, this holds still for those cases).

3.2.1 ILWS: Feedback (Fairness) mechanism

The legacy LTE schedulers ensure fair resource allotment among the users. Since some data from particular bearers is now getting steered onto the Wi-Fi network by Wi-Fi scheduler, this fairness is disturbed. Therefore, an extra feedback architecture is added in ILWS which keeps track of data being sent on the Wi-Fi network and co-ordinates this information with the legacy LTE scheduler architecture to ensure fairness. According to this, say the LTE scheduler decides that x amount of data should be transmitted in a particular time period. If in that time period the user gets the chance to transmit some data y through Wi-Fi, it updates the data that needs to be transmitted as x-y. This virtually combines the capacity of LTE and Wi-Fi. In this work the Proportional Fair Scheduler (PFS) is considered. In PFS the user selection priority function is:

$$P = \frac{T^{\alpha}}{R^{\beta}} \tag{3.3}$$

where T, denotes potentially achievable data rate for the station in the present time slot. R is the historical average data rate and α and β are "fairness" variable.
PFS is just taken as an example to explain the working of feedback architecture. Our work is however not limited to it and can be accommodated with all schedulers. The resource allocation depends on transmitted data in last time period. With the feedback, it does not matter from which link the data has been transmitted in the last time period. Hence, logically the scheduling is done for both the networks. Virtually, the Wi-Fi transmission is also scheduled. Hence, scheduler is aware of amount of data transmitted to Wi-Fi network unlike opportunistic offloading on Wi-Fi network with no feedback. This will improve fairness among users because if some users got the chance to transmit data on Wi-Fi network, the LTE resource can be allocated respectively.

In this chapter, LWIR architecture with ILWS is described for both collocated and non-collocated scenarios. Two contention schemes for Wi-Fi of LWIR node have been also proposed which boost the performance of system especially in case of TCP. To maintain fairness among users, the feedback architecture of ILWS has been explained by considering PF scheduler as an example.

Chapter 4

Virtual WLAN Scheduler: Bearer/User Selection Schemes

VWS is a module situated at Wi-Fi AP that communicates with the ILWS of LWIR node. It keeps track of the available data in Wi-Fi queue and according to the link delay, it maintains sufficient amount of data so that some data is always available for transmission. Whenever Wi-Fi MAC transmits some data, the VWS selects the RLC buffer based on the Bearer/User Selection algorithm for fulfilling the QoS requirement, to maximize the throughput, and to ensure fairness to all the users. The performance of LTE and Wi-Fi networks depends on many factors. Thus, selection criteria for suitable users to steer data on a particular network changes according to the requirement. Below, we propose five such user selection schemes:

4.1 Bearer/User Selection Schemes

As both the media (LTE and Wi-Fi) are available for transmission, the bearers can be chosen based on the channel condition, interference level or CQI of the user. The following CQI based schemes have been proposed:

4.1.1 Min CQI First

The users in the interference region or at the edge of the cell, will be having less CQI. The PF scheduler in this scheme would be giving more resource blocks to these users in order to cater their needs. This will lead to inefficient use of LTE resources. In such case, if these users have no interference on Wi-Fi network, the traffic can be steered to Wi-Fi network. This will lead to an efficient use of LTE resources.

4.1.2 Max CQI First

The users who are nearby base station have better signal strength from both the radios of small cell. They would get better throughput from Wi-Fi network compared to cell edge users. Hence, selecting these users will increase the traffic steering on Wi-Fi network but decrease the efficiency of LTE network. High contention on Wi-Fi network and high LTE interference for the cell edge users causes the performance degradation here. While the Wi-Fi users are nearby the AP, it can compensate the throughput which was lost by LTE because of interference if there is less contention on Wi-Fi network.

4.1.3 Max RLC Buffer First

In this scheme, as soon as the Wi-Fi AP gets the chance to transmit, it selects the RLC buffer which has the highest amount of data.

This is contrary to the previous schemes where it was not necessary that the selected RLC buffer has sufficient data whenever the Wi-Fi AP gets the opportunity. In such case, less than requested data is transmitted on Wi-Fi network. This causes under utilization of Wi-Fi capacity. This scheme ensures maximum steering to Wi-Fi capacity as it always chooses the user which has sufficient data in RLC queue and makes the best use of opportunity in Wi-Fi network. In the case of high MTU size selection, this scheme maximizes the Wi-Fi utilization and the LTE scheduler also maintains the distribution of resources.

4.1.4 Max RLC Buffer with Min CQI

As Min CQI First increased LTE efficiency and Max RLC buffer First ensures the maximum utilization of network capacity. In this scheme, only those users are eligible which have sufficient data in their RLC buffer to fulfill the request from Wi-Fi. Then among those users, the user which has the least CQI is selected for steering. If none of the users have sufficient data to transmit, then VWS goes ahead with max RLC buffer first scheme. This scheme achieves very good throughput from LTE network as the users who are in interference region or cell edge region are served by Wi-Fi. Hence, fewer resources are allocated to these users by the proportional fair scheduler.

4.1.5 Max RLC Buffer with Max CQI

Steering of user's data who has better CQI will give better throughput as the signal strength of Wi-Fi will also be good for these users. Max RLC Buffer First ensures the maximum utilization of the network capacity. Therefore, to achieve maximum advantage from both the networks, the users who have sufficient data in their RLC buffer to fulfill the request from Wi-Fi have been selected. Then out of these, the user that has the best CQI is selected. If none of the users have sufficient data to transmit, VWS goes ahead with max RLC buffer first scheme. This scheme steers comparatively more data on Wi-Fi network than Max CQI First as it first ensures maximum possible data steering. Again, because cell edge users are served by LTE, it leads to inefficient use of LTE resources.

Our LWIR architecture is not limited with only proposed user selection schemes. Any user selection schemes can be used.

4.2 Effect of RLC Modes on Bearer/User Selection Schemes

RLC Layer has following three different modes:

- **Transparent Mode (TM)**: In this case, the contents goes through this layer without any modification. Hence, there are no extra headers added to the data. No segmentation and

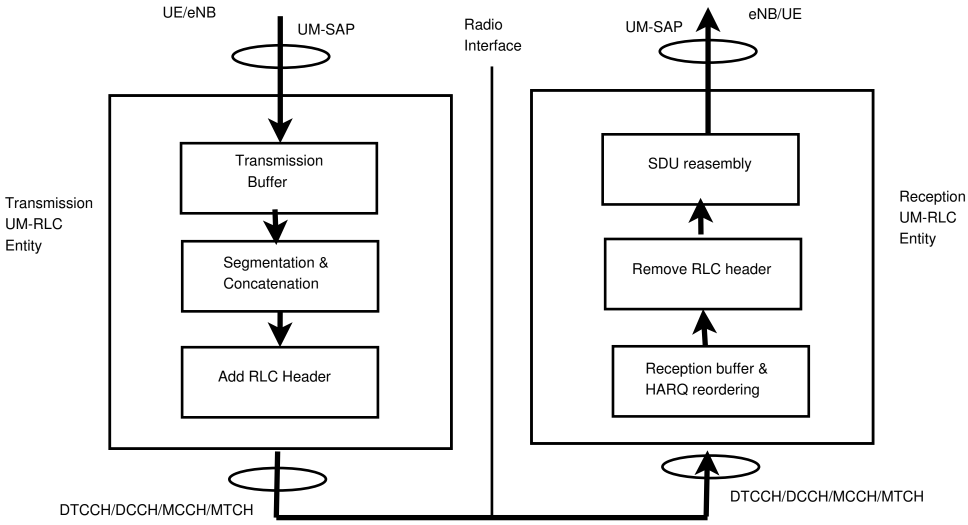

Figure 4.1: Model of two UM peer entities [16]

concatenation of data received.

- **Unacknowledged Mode (UM):** Unacknowledged means it does not require any reception response from the receiver side. Reception response simply means ACK or NACK from receiver's end. UM does buffering, segmentation, concatenation, and add RLC header at sending side and buffering, re-ordering, removing RLC header and reassembly at receiver side unlike TM.

- **Acknowledged Mode (AM):** As it's name implies it requires ACK/NACK from the receiver side. It is more like TCP packet in IP world, whereas RLC UM is more like UDP in IP world. If we see Figure 4.2, what is different from UM mode lies in the middle column, namely re-transmission buffer and RLC control procedure. After RLC transmitter does the segmentation/concatenation process, it adds RLC header and then, it creates two identical copies and transmits one copy of the data out to lower layer (MAC) and sends another copy to re-transmission buffer. If the RLC get NACK or does not get any response from the other party for a certain period of time, the RLC packet (we call this RLC PDU) in the re-transmission buffer gets transmitted again. If the RLC get ACK, the ones in re-transmission buffer would be discarded.

The proposed bearer selection schemes consider the user CQI and the data in RLC buffer as the comparison parameters. In RLC Unacknowledged Mode (UM) [16], there is only one kind of buffer per bearer (transmission buffer) as shown in Figure 4.1. Unlike RLC-UM, in RLC acknowledged Mode (AM) [16], there exist two different types of buffers (transmission, re-transmission) as shown in Figure 4.2. Along with this, there exist control data for transmission in AM. Having said that, now there are following new challenges:

- Which buffer should be selected for the comparison purpose?

- From which buffer data should be transmitted to Wi-Fi?

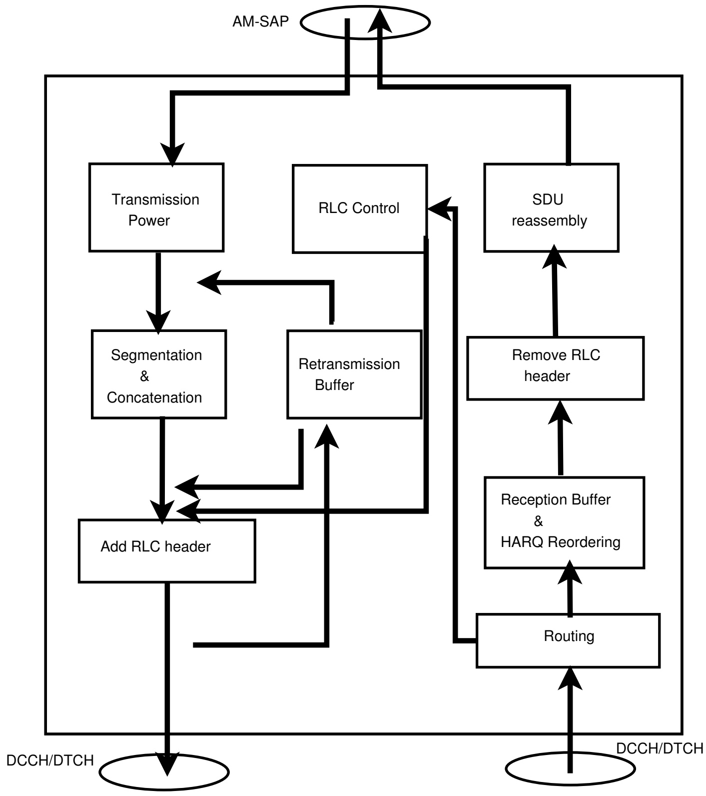

Figure 4.2: Model of an AM enttiy [16]

In this work, we are using the transmission buffer for the comparison as it is a proper resemblance to the amount of data that is to be transmitted. After user selection, there exist two options to fetch data from for that particular user:

- **Re-transmission on LTE and Wi-Fi (ROLW)**: If a user has data to re-transmit (in re-transmission), Wi-Fi network will first transmit that data. Hence, re-transmission will happen on both networks.
- **Re-transmission on LTE only (ROL)**: Fetch the data from the transmission buffer to transmit on Wi-Fi network. In this case, all the re-transmission will happen on the LTE network.

In above schemes, the amount of data transmitted will be different as for the steering, different buffers are getting selected. As mentioned earlier, for user selection decision, always transmission buffer is considered. In ROLW, we gave first priority to re-transmission buffer. If there resides some data for re-transmission, we always steer that first. But re-transmission buffer might not have always sufficient data as it totally depends on how much loss happened during the previous transmission. In ROL, always transmission buffer is selected for data steering on Wi-Fi network which mostly has more data compared to re-transmission buffer. This gives ROL edge over ROLW.

In this chapter, we studied the possible effects of different RLC modes in proposed RLC level aggregation and the user selection schemes. We only studied it with respect to two RLC modes: UM and AM and not with the TM mode.

Chapter 5

Simulation Experiments and Performance Results

We used Network Simulator-3 (NS-3) for simulation. NS consists of the family of discrete event network simulators NS-1, NS-2 and NS-3. NS-3 is the latest version of these simulators and the only one being actively developed and maintained. It is free software licensed under GNU GPLv2. Its primary goal is to be used in research. NS-3's first version NS-3.1 was released in 2008 and since then with at least 3 releases every year, has now reached NS-3.25. It is written using C++ and Python.

NS-3 is an open source simulator which supports both LTE and Wi-Fi networks. Since NS-3 contains the implementations of both LTE and WLAN, this was chosen to study the RAN level aggregation of LTE and WLAN. LWIR along with LWIP and LWA support was built into NS-3 in this work. In all the three schemes, the traffic steering is done at IP layer, PDCP layer, and RLC layer correspondingly. This chapter gives an overview of the simulation setup and results for different cases.

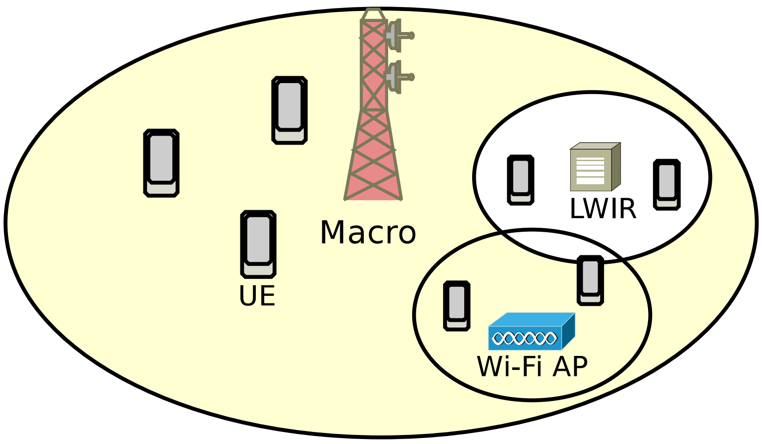

Figure 5.1: Simulation Setup

Table 5.1: Simulation Parameters

Parameter	Value
LTE Scheduler	Proportional Fair
Number of Resource Blocks	100 (50 UL, 50 DL)
Distance between UE's and LWA/LWIR node	50 m
Number of UEs per LWA node	(30)
EPC Delay	(15 msec)
Backhaul Delay	(25 msec)
IEEE 802.11 a Operating frequency, Bandwidth	5 GHz, 20 MHz
Transmission power of Macro	46 dbm
Transmission power of SeNB	16 dbm
Transmission power of Wi-Fi AP	16 dbm
Distance between Macro and LWIR Node	300 m
Distance between LWIR Node and Standalone Wi-Fi AP	100 m
Packet Size	1428 Bytes
UDP Data Rate per User	3.7 Mbps
Number of seeds	10
Simulation duration	30 seconds
Distance between LWIR Node and Wi-Fi AP	10 m
X_w-Interface Delay	1 msec
X_w-Interface Loss Rate	10^{-7} bits

5.1 Simulation Setup

As mentioned earlier, we are considering Wi-Fi Only in Downlink. As shown in Figure 5.1, we have one macro eNB and one LWA/LWIR node. The experiment is conducted with 30 UEs connected with LWIR node, with each UE having 1 DL flow. To check the performance of different traffic steering schemes (aggregation architectures) this scenario is tested with TCP-based flows. To get maximum capacity, we have also tested it with UDP flows. For background traffic, there are 5 UEs connected with a macro cell eNB and running 1 DL UDP flow. To generate contention on Wi-Fi network, there are 5 UEs connected with a Wi-Fi AP, running 1 UL flow each. For maximum possible contention on both LTE and Wi-Fi, UDP flows are chosen. The other considered parameters are given in the Table 5.1. The last three parameters are only specific to the non-collocated scenario.

5.2 Results

In this section, we will evaluate the performance of proposed LWIR with different user selection approaches in collocated scenario and compare it with the LWIP and the LWA. Further, a study on the effects of the RLC-AM on this work is explained. Following this, we will evaluate the performance of LWIR in the non-collocated scenario and talk about the crucial factors which can affect the system throughput.

5.2.1 Performance Evaluation: LWIR Collocated (RLC-UM)

Figures 5.2 and 5.3 show the total throughput for the LWIR node users in different user selection schemes with different values MTU size. Here, OneSized Window is selected as the contention scheme in Wi-Fi of LWIR node. Figure 5.2 shows the UDP throughput of LWIR node. The UDP throughput

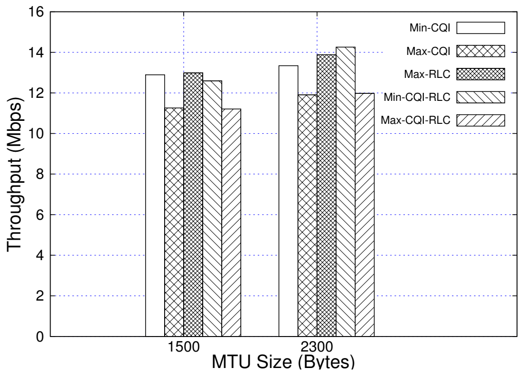

Figure 5.2: UDP Throughput for LWIR with different User Selection Schemes

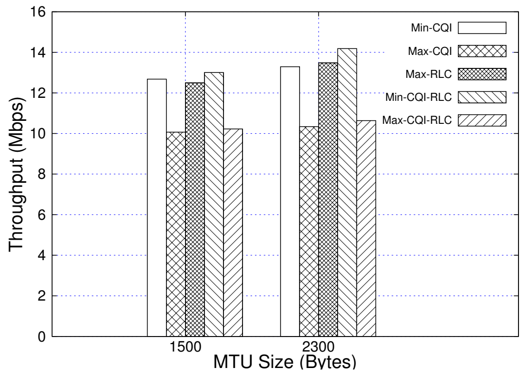

Figure 5.3: TCP Throughput for LWIR with different User Selection Schemes

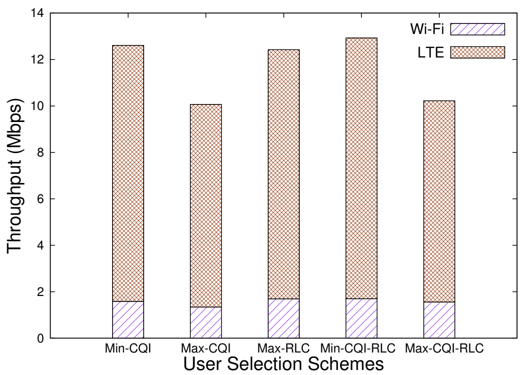

Figure 5.4: TCP Throughput Distribution for LWIR with different User Selection Schemes (MTU Size=1500)

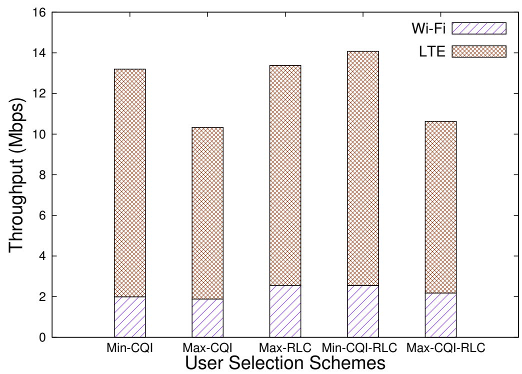

Figure 5.5: TCP Throughput Distribution for LWIR with different User Selection Schemes (MTU Size=2300)

shows the maximum achievable throughput for the current scenario in each user selection scheme as each user pumps sufficient amount of data in the network to find out the possible maximum achievable throughput. In Figure 5.3, it is clearly shown how good LWIR architecture supports the TCP performance as in all the schemes, the TCP performance nearly achieves maximum possible throughput (UDP throughput). It can be seen that increasing MTU size increases the Wi-Fi link utilization and increases the system throughput.

Figures 5.4 and 5.5 give a closer view to the performance evaluation of the user selection schemes with the throughput distribution between LTE and Wi-Fi network. Min CQI First and Max CQI First selects users for steering based on CQI. Min CQI First is serving the cell edge users by Wi-Fi which minimizes the interference effect of LTE for these users. This leads to efficient utilization of LTE resources where as the Max CQI First does the opposite. The Max RLC First is a load-aware scheme which always selects the user who has most data in its RLC buffer. Therefore, it randomly selects the users and maintains the fairness. The other two schemes are making sure of CQI and load. This leads to better throughput in Max RLC Buffer First with Min CQI First and Max RLC Buffer First with Max CQI First in comparison to Min CQI First and MAX CQI First respectively.

Figures 5.6 and 5.7 show the effect of two Wi-Fi contention schemes we proposed for LWIR node. In OneSized Window, we always maintain one packet in Wi-Fi queue. Hence, there is no

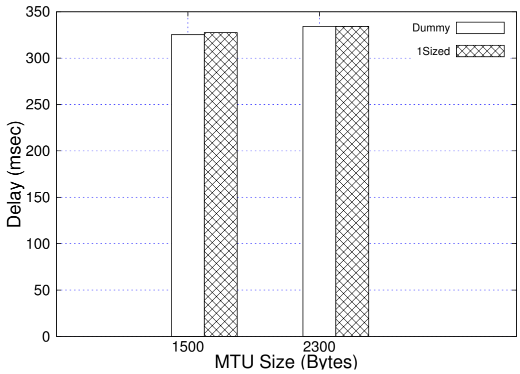

Figure 5.6: Delay Comparison with less contention on Wi-Fi Network

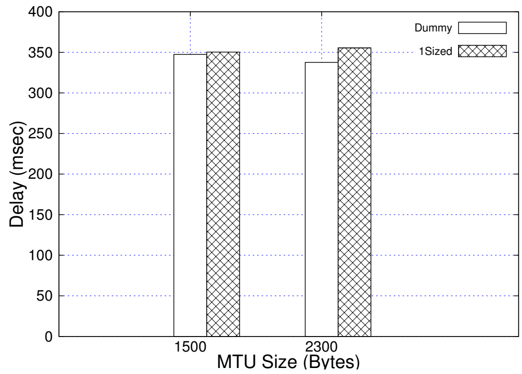

Figure 5.7: Delay Comparison with high contention on Wi-Fi Network

waiting delay in Wi-Fi queue. But if there is high contention on Wi-Fi network, this one packet has to wait in queue until its gets the channel access. But in case of dummy packet, the data is only fetched from RLC buffer when the Wi-Fi gets the channel access. Thus, there is no access delay. Figures 5.6 and 5.7 show access delay in less and high contention scenario. Although, this delay didn't improve the system throughput much, one can use both scheme depending on delay sensitivity of applications.

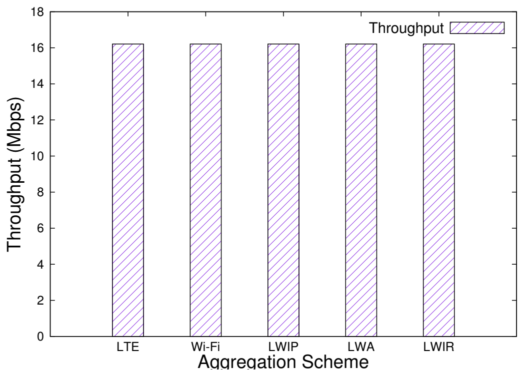

Figure 5.8: Effect on Background Macro Throughput

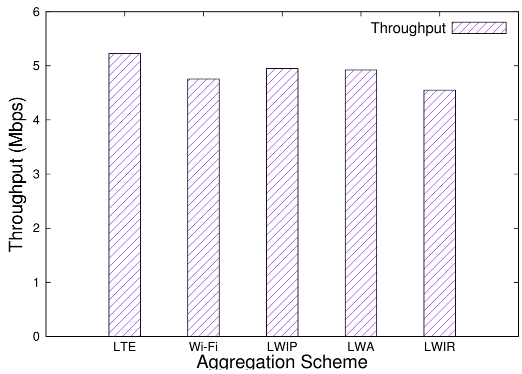

Figure 5.9: Effect on Background Wi-Fi Throughput

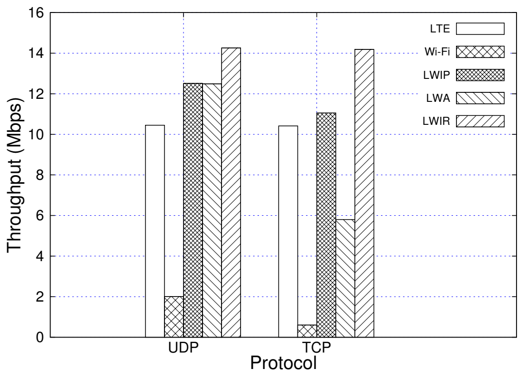

Figure 5.10: Throughput Comparison with Different Aggregation Architectures

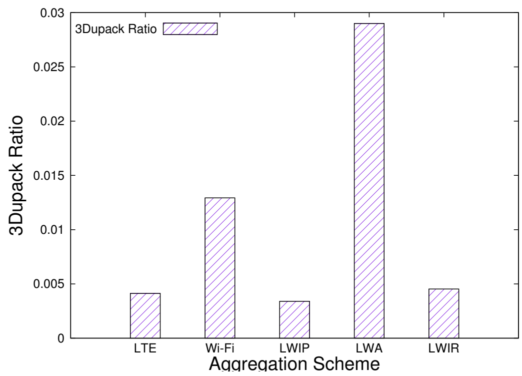

Figure 5.11: 3Dupack Instance with Different Aggregation Architectures

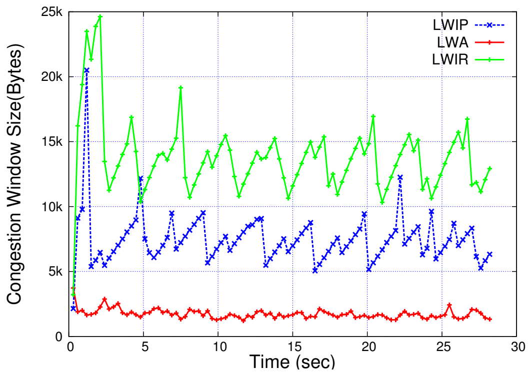

Figure 5.12: Congestion Window in Different Aggregation Architectures

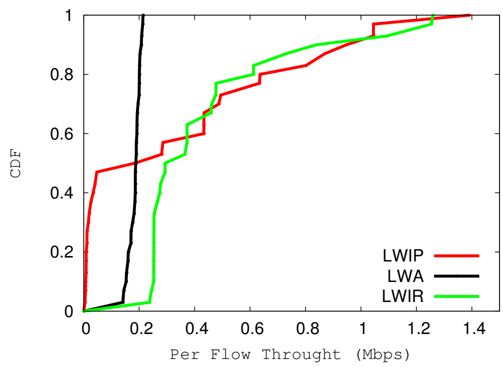

Figure 5.13: CDF of LWA/LWIR users in Different Aggregation Architectures

Figures 5.8 and 5.9 show the background traffic throughput in macro and Wi-Fi in different aggregation architectures. LTE and Wi-Fi corresponds to only LTE and Wi-Fi offloading. LWIP corresponds to the flow-based traffic steering in LWIP which steers half of the flow to Wi-Fi network. LWA corresponds to the packet-level traffic steering which transfers only 10% of the data to Wi-Fi as this ratio gives the maximum throughput. The best scheme under LWIR, Max RLC Buffer with Min CQI First is taken for the comparison. Figure 5.9 shows the effect of different aggregation architectures on traditional Wi-Fi. It is inversely proportional to throughput any scheme gets from Wi-Fi.

Figures 5.10 and 5.11 show the TCP throughput and 3DUPACK ratio comparison among different aggregation architectures. The 3DUPACKS ratio corresponds the ratio of number of 3DUPACK instances to the total number of acknowledgments. In the case of TCP flows, out-of-order delivery can cause 3DUPACKS with more frequent drops in congestion window size, which in turn leads to decline in throughput. To consider the behavior of each scheme with TCP, we have collected the throughput and the 3DUPACKS stats. We can clearly see that in LWIP flow-based scheme since complete flow is moved on one of the two network, there is very rare chance of out of order packet delivery. But in case of LWA, there is a high number of out-of-order packets. Because of this TCP causes high number of 3DUPACKS. Thus TCP is not able to achieve high throughput. It can be seen that throughput in LWIP is far better than LWA.

The main cause for LWA's poor performance is waiting delay in Wi-Fi queue. We are using LWA only in the downlink. Hence, there is no contention delay, but the waiting delay in Wi-Fi is sufficient enough to cause the out-of-order packets and TCP timeout. We can see these results in Figure 5.11. The TCP congestion window size drops frequently with out-of-order packets. On the other hand, in RLC based schemes, all the data is taken from the front of the RLC buffer. Thus, a continuous flow is maintained during transmission. Also because of OneSized Window algorithm, there is no waiting time in Wi-Fi queue. Still, as the packets are coming from two different interfaces, there will be out of order delivery as we cant ensure exactly same transmission time. But because of RLC level re-ordering logic, these 3DUPACK instances are decreased as shown in Figure 5.11 with respect to LWA. This really helps TCP flow to maintain its congestion window, leading to high throughput in TCP as shown in Figure 5.10. Figure 5.12 also supports our claim with better congestion window. We can see that LWIR shows nearly 37% of throughput improvement than LWIP aggregation scheme in case of TCP. LWA performs very poorly with respect to LWIP and LWIR. In Figure 5.13, the CDF of three aggregations is shown. Nearly 58% of users get almost double throughput in LWIR than LWIP. Clearly, LWIR is more fair and better in terms of throughput.

5.2.2 Performance Evaluation: LWIR Collocated (RLC-AM)

Figures 5.14 and 5.15 show the performance of LWIR schemes with RLC-AM mode. Figure 5.14 shows the total throughput in ROLW where re-transmission happens from both networks. We can see in Figure 5.14 that results do not follow the trend of schemes followed in RLC-UM. The Max RLC Buffer First with Min CQI First is not the best in case of MTU size 1500, because still the user selection happens based on transmission buffer, but the re-transmission buffer is given priority over it. The same result trend follows in ROL where both user selection and data transmission happen from transmission buffer. The total result is far lower than RLC-UM. This happens because of waiting for response from receiver side. This leads to a high delay which leads to high RTT time, thus slowing down the data rate in TCP. We can see the delay difference in both RLC-UM mode and RLC-AM mode for TCP in Figure 5.16.

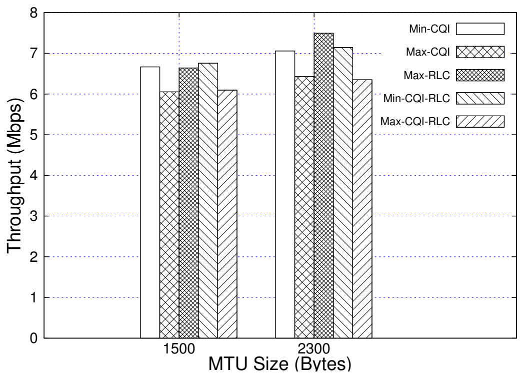

Figure 5.14: TCP Throughput for LWIR Collocated in RLC-AM (ROLW)

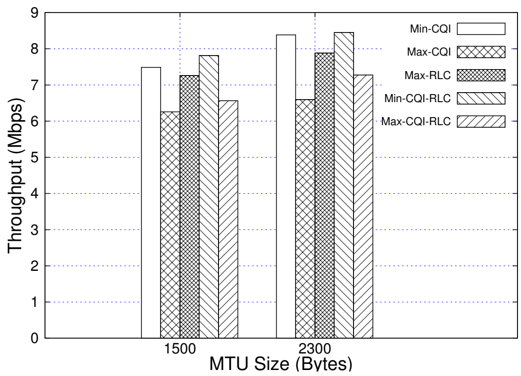

Figure 5.15: TCP Throughput for LWIR Collocated in RLC-AM (ROL)

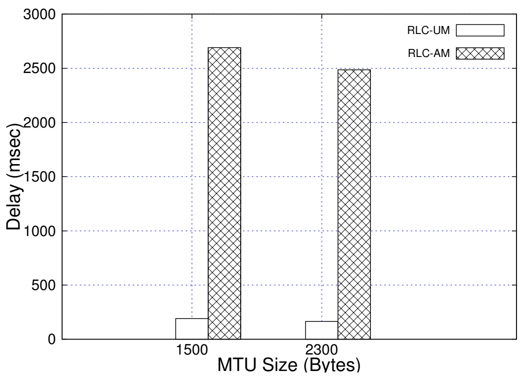

Figure 5.16: Average Delay in RLC-UM and RLC-AM

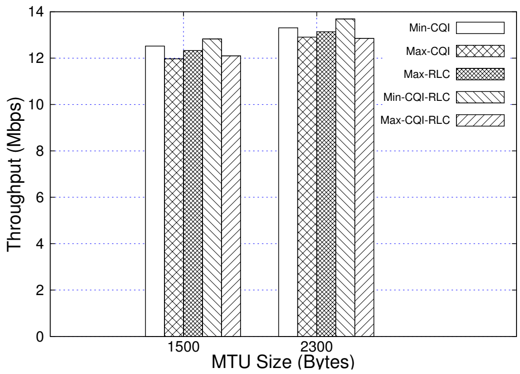

Figure 5.17: UDP Throughput for LWIR Non-Collocated Scenario

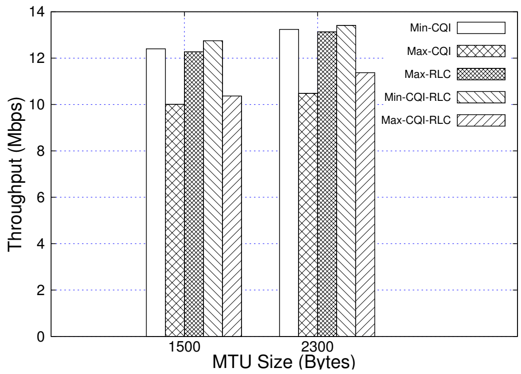

Figure 5.18: TCP Throughput for LWIR Non-Collocated Scenario

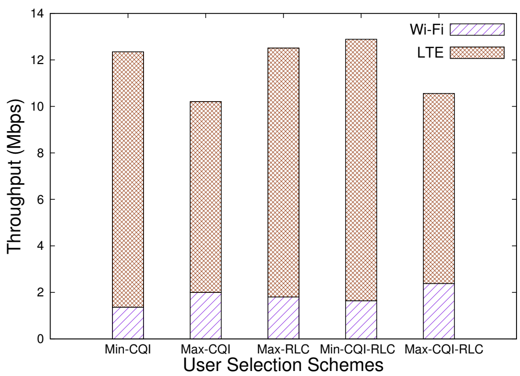

Figure 5.19: TCP Throughput Distribution for LWIR in Non-Collocated Scenario (MTU Size=1500)

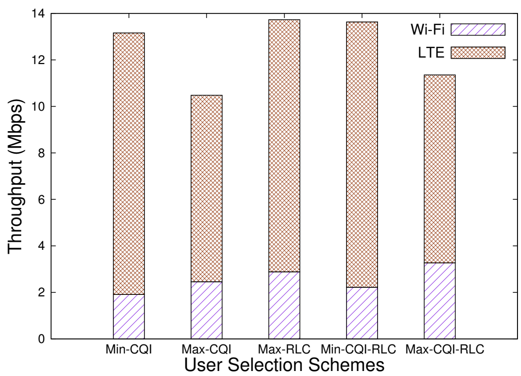

Figure 5.20: TCP Throughput Distribution for LWIR in Non-Collocated Scenario (MTU Size=2300)

5.2.3 Performance Evaluation: LWIR Non-Collocated

Figures 5.17 and 5.18 show the total throughput for LWIR node users in non-collocated scenario with different user selection schemes with different MTU sizes for both UDP and TCP. Here, unlike collocated scenario, the OneSized Window is not selected as the contention scheme in Wi-Fi connected with LWIR node through X_w-interface. Based on the delay of this interface, the VWS decides the size of Wi-Fi queue. It maintains the minimum number of packets in Wi-Fi queue such that there always remains some data to transmit in Wi-Fi queue when it gets the channel access. This ensures maximum link utilization with minimum waiting time. Figure 5.17 shows the UDP throughput of LWIR node. The UDP throughput shows the maximum achievable throughput for the current scenario in each user selection scheme as each user is pumping sufficient amount of data in the network to find out the possible maximum achievable throughput. In Figure 5.18, it is clearly shown that LWIR architecture is performing really good in non-collocated scenario also. TCP is able to achieve nearly maximum possible throughput (UDP throughput). Also, it can be seen that increasing MTU size increases the Wi-Fi link utilization and increases the system throughout.

Figures 5.19 and 5.20 give a closer view to the performance evaluation of the user selection schemes with the throughput distribution between LTE and Wi-Fi network. The only difference we can see here from the collocated scenario is the change in share of LTE and Wi-Fi distribution of each scheme because the Wi-Fi is away from LTE of LWIR node. Hence, some users are in better coverage of Wi-Fi than collocate case. This changes the possible distribution ratio.

In this chapter, we have analyzed the different stats about proposed LWIR architecture and compared it with different aggregation architectures, effects of RLC-Mode and the performance of LWIR in non-collocate scenario. The proposed LWIR is best among all previously proposed aggregation architectures in terms of both throughput and fairness.

Chapter 6

Conclusions and Future Work

In this work, the problems with current 3GPP LWA architecture especially in TCP have been analyzed. It is shown that LWA architecture causes need of frequent re-ordering and lot of waiting in PDCP re-ordering queues. We have proposed a unique RLC layer integration architecture LWIR with ILWS, an integrated LTE-WLAN scheduler which does scheduling for both LTE and Wi-Fi networks. ILWS uses five different user selection schemes to select the appropriate users to steer on Wi-Fi network and also can incorporate with other user selection schemes. The effects of different RLC modes on LWIR have been studied. LWIR has been studied thoroughly in both collocated and non-collocated scenario. We have shown that the proposed LWIR architecture with ILWS has shown almost 37% throughput improvement over the best existing architecture, LWIP with flow-based traffic steering approach. Results have proved that it is the best architecture in both split bearer and switched bearer. Proposed LWIR architecture works only in the downlink. Many more factors like Wi-Fi signal strength, load etc. can be considered for the user selection. Future work would entail the extension of the same LWIR architecture to the uplink flows. Various factors like contention and delay in communication over X_w-interface can be considered. User mobility and handover in proposed work is yet to be studied.

Chapter 7

Visible Research Output

Following are the research publications and submission related with our work:

- LWIR: LTE-WLAN Integration at RLC Layer with Virtual WLAN Scheduler for Efficient Aggregation, accepted in Globecomm (2016)
- Velocity based Dynamic Flow Mobility in Converged LTE/Wi-Fi Networks: NCC 2016
- Study or Work Item Proposal (SWIP) submitted on LTE/Wi-Fi Link Aggregation in Telecommunications Standards Development Society, India (TSDSI) by research team.

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