Implementation of the 3GPP LTE-WLAN Inter-working Protocols in ns-3

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ABSTRACT

LTE/Wi-Fi Link Aggregation (LWA) and LTE WLAN Radio Level Integration with IPSec Tunnel (LWIP) are two approaches put forward by the 3rd Generation Partnership Project (3GPP) to enable flexible, general, and scalable LTE-WLAN inter-working in the context of 5G. These techniques enable operator-controlled access of licensed and unlicensed spectrum and allow transparent access of operator's evolved core. This article describes the design details of LWA and LWIP protocols and presents the first ns-3 LWA and LWIP implementations in ns-3. In particular, this work focuses on the adaptation and concurrent usage of different ns-3 modules and protocols of different technologies to enable the support of these inter-working schemes.

CCS CONCEPTS

• **Networks → Network protocol design**; **Network simulations**; *Network performance analysis*; • **Computing methodologies → Modeling and simulation**.

KEYWORDS

IEEE 802.11, LTE, Unlicensed LTE, Offloading, LWA, LWIP.

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1 INTRODUCTION

The dramatic increase in the number of smart phones, tablets, wearable, and other smart mobile devices has resulted in tremendous growth in traffic demands for current and future wireless networks. According to Cisco Visual Networking Index (VNI) [5], global mobile data traffic will reach 48.3 EB per month by 2021 with a growth of 46 percent between 2016 and 2021.

Motivated to achieve the required future capacity growth standardization efforts are underway at the 3GPP to enable cellular mobile networks operate over the unlicensed 2.4 and 5GHz spectrum which is currently being used by Wi-Fi and other communication systems. To date, there are five different approaches to offload data from LTE to the unlicensed bands: 1) LWA [2], 2) LWIP [2], 3) Licensed Assisted Access (LAA) [1], 4) LTE-Unlicensed (LTE-U)[4], and 5) MuLTEFire [3]. Each of these alternative methods aim to opportunistically meet the future growth in cellular traffic. However, no analysis is found in the literature comparing and ranking these according to their feasibility of implementation and performance.

In this work, we present the implementation details of LWA and LWIP protocols in ns-3 [7] to enable filling the aforementioned gap.[1] ns-3 is a discrete-event network simulator for internet systems and is developed in C++ language. It provides realistic models to mimic the behavior of packet data networks. ns-3 provides a great compromise, by combining the ability to run real applications and network protocol codes, with the flexibility, as well as the ability to simulate in a controlled network environment, easing reproducibility. ns-3 also provides support for several models and protocols such as Wi-Fi, WiMAX, LTE and Point-to-Point. The details of different ns-3 modules used and modified to implement the aforementioned techniques are provided. Both LWA and LWIP have been implemented in ns-3.27.

The remainder of this article is organized as follows. In Section 2, a detailed overview of LWA and LWIP mechanisms is presented. Sections 3 and 4 describe the implementation details of LWA and LWIP, respectively. Validation results for the two techniques are presented in Section 5. Finally, Section 6 concludes the article.

2 LTE-WLAN INTER-WORKING PROTOCOLS

2.1 LTE-WLAN Radio Aggregation

LWA was first introduced in 3GPP release 13 and combines Wi-Fi unlicensed bandwidth with the licensed LTE bandwidth, taking advantage of the high indoor availability of Wi-Fi networks. It efficiently integrates LTE and WLAN at the Packet Data Convergence Protocol (PDCP) layer of LTE. LWA aims for optimal operation

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[1] The code will be available at https://github.com/ni/NI-ns3-ApplicationExample.

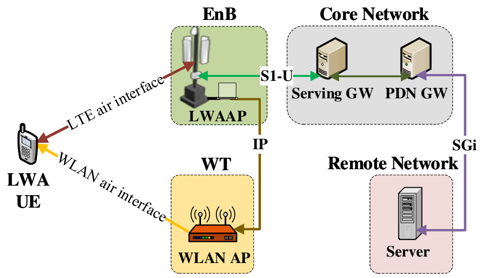

Figure 1: Network Architecture of LWA

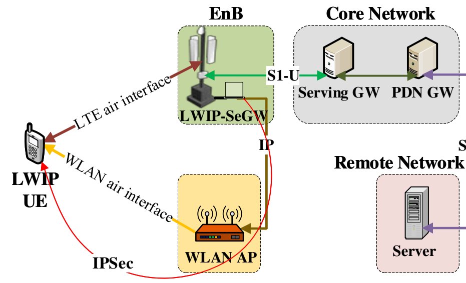

Figure 2: Network Architecture of LWIP

of licensed/unlicensed bands by allowing downlink traffic to be carried by both LTE and WLAN. In order to avoid the asymmetric contention problem of Wi-Fi, the uplink traffic is only carried through LTE. Wi-Fi APs, which act as secondary access for user data, are connected to LWA base stations and thus can leverage LTE core network functionalities without a dedicated gateway.

LWA architecture consists of Evolved Node B (eNB), LWA-aware Wi-Fi Access Point (AP), LWA-aware Wi-Fi station and User Equipment (UE). Release 13 of 3GPP LTE defines two development scenarios of LWA, namely collocated and non-collocated, through which the eNB and WLAN entities are connected. In the collocated scenario, the Wi-Fi AP is collocated and connected through an internal backhaul connection to the eNB. This deployment option is more appropriate for small cells. For the non-collocated deployment as shown in Figure 1, an optional standardized interface, called Xw, is used to connect the WLAN AP to the eNB through a WLAN Termination (WT) logical node (which can be a Wi-Fi AP or a Wi-Fi controller). This interface supports control (called Xw-C) and user (data) plane (called Xw-U). Apart from PDCP Service Data Units (SDUs), the Xw interface is also used for flow control feedback. The Xw-U interface is used to deliver LWA PDUs from eNB to WT. The eNB-WT control plane signalling for LWA is performed by means of Xw-C interface signalling. It supports the following functions: *i)* Transfer of WLAN metrics from WT to eNB, *ii)* Support of LWA for UE (establishment, management and control of user plane), and *iii)* Xw management and error handling function.

A new sublayer, called LWA Adaptation Protocol (LWAAP), that adds the Data Radio Bearer (DRB) ID to the PDCP frames and transmits it to the Wi-Fi interface is defined. This allows multiple bearers to be offloaded to the Wi-Fi network. In the control plane, the eNB is responsible for selecting the bearers to offload to WLAN and for the activation/deactivation of LWA. However, Release 13 does not specify any algorithm for the interface selection. Regardless of the deployment scenario, PDCP frames are scheduled by the eNB, where some frames are encapsulated with Wi-Fi protocol and transmitted through the Wi-Fi interface. LWA can also configure the network to allow use of both Wi-Fi and LTE simultaneously. This procedure, called split bearer, uses both eNB and Wi-Fi radio resources. On the contrary, LWA also allows switched bearers, which only utilizes the WLAN radio resources for transmission.

While using the split bearer operation, the UE supports in-sequence delivery of frames based on the reordering procedure introduced in 3GPP Release 12 for dual connectivity. This is done using a reordering window controlled by a reordering timer running at the UE. The received frames from both LTE and Wi-Fi are reordered by the aforementioned additional PDCP functionality of the LWA UE. In the uplink, PDCP PDUs can only be sent via the LTE.

2.2 LTE-WLAN Radio Level Integration

The foundation of 3GPP LWIP release 13 was set by Wi-Fi boost, which realized the first implementation of downlink switching of Internet Protocol (IP) layer connectivity. The basic aim of LWIP was to readily adopt and supplement LTE without making any major changes to the WLAN infrastructure. Figure 2 shows the network architecture of the LWIP scheme.

Traffic splitting in LWIP is performed above the PDCP layer, and data path bypasses all LTE protocols. The LWIP aggregation scheme involves the use of an Internet Protocol Security (IPSec) tunnel to transfer PDCP SDU packets from eNB to UE via WLAN infrastructure. IPSec is an end-to-end security framework (which includes a set of protocols and algorithms for mutual authentication) that operates at the network layer by extending the IP header of the frames. That is, in the IPSec tunnel mode, the entire IP packet is protected by inner and outer IP datagrams. The inner headers specify the communication endpoints whereas the outer IP header defines cryptographic end-points. Since the IPSec connection is unconcerned of WLAN deployments, the LWIP solution supports legacy WLAN deployments more easily than LWA (that requires software as well has hardware additions).

While the LWIP scheme is used, the Radio Resource Control (RRC) and signalling messages, which are exchanged between eNB and the UE, are carried over the LTE interface. A new protocol, called LWIP Encapsulation Protocol (LWIPEP), is specified for the transfer of user plane data. LWIPEP is also used for identification of the data bearer identity to which the LWIPEP SDU belongs. The traffic splitting is performed above the PDCP layer and the data path going towards WLAN is only passed through LWIPEP layer (and is bypassed by the LTE protocols below the PDCP layer). The LWIPEP protocol allows forwarding frames of different DRB using the IPSec tunnel configured for the UE. It is important to note here that no reordering procedure is employed at the UE (since aggregation is done above the PDCP layer) and all LWIP bearer data is forwarded.

Since LWIP is transparent to the WLAN, the flow control mechanisms used in LWA are not applicable. Also, the Xw interface and WT nodes are not required. However, due to security issues, the IPSec tunnel is terminated into a dedicated gateway, called Security Gateway (SeGW), which can be deployed at the eNB.

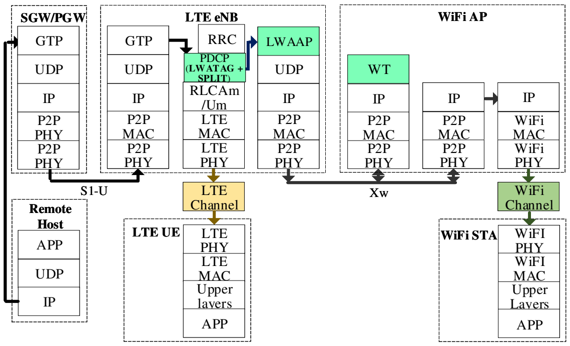

Figure 3: LWA ns-3 Implementation

The eNB is responsible for activating and deactivating LWIP operations based on UE measurement reporting. The main drawback of this scheme is that the IPSec tunneling protocol appends an IPSec header to the Downlink IP packets that travel from eNB to UE via the WLAN network.

3 IMPLEMENTATION OF LWA IN NS-3

As highlighted in Section 2, the key concept of LWA is that it enables routing packets by using the PDCP layer in the eNB as convergence layer (i.e. a UE in *RRC-Connected* mode is configured by the eNB to utilize radio resources of LTE and WLAN). The control plane connection remains with LTE, whereas the data can be routed via both eNB and WLAN. In order to explain how this architecture was simulated in ns-3, we refer to Figure 3, which shows the interconnection between different network devices. In this work, we focus our study on the implementation of LWA defined in Release 13 which considers the downlink only.

Before initiating simulation, the PDCP layer of LTE eNB can be commanded to activate/deactivate offloading of data. If LWA is fully activated, the data flow from eNB to UE is stopped and the data is diverted towards the Wi-Fi AP. This procedure is accomplished by using the event triggering capabilities of callback functions.

3.1 Assumptions

In our implementation, we make the following assumptions:

(1) A non-collocated LWA scenario is assumed, where the LTE network is connected through a WT to an already existing Wi-Fi network.
(2) We assume an ideal Xw-C interface where there is no error in communication and setting up.
(3) No mobility model is considered.
(4) The Wi-Fi AP can accommodate traffic of normal Wi-Fi stations as well as the station used by LWA.
(5) Wi-Fi station is already configured and associated with an AP.

3.2 Implementation Details

In this section, we describe the sequence of actions that take place during the simulation of our LWA protocol implementation in ns-3. As shown in Figure 3, multiple network components corresponding to different technologies (LTE, PointToPoint, Wi-Fi) are used together. First, any traffic initiated between the remote host and the UE within the EPC model attempts to follow the direct path. However, the downlink traffic can be managed, based on LWA being partially or fully activated. In case of full LWA being used, all the traffic is forwarded to the Wi-Fi network. Whereas for partial LWA, some packets are allowed to flow through LTE while others are diverted towards the Wi-Fi network. As shown in Figure 3, two main mechanisms representing LWA implementation at the PDCP layer are: LWA Tag and Split. If partial or full LWA is activated, all the packets that are to be passed to the Wi-Fi network are tagged to maintain their identity. In the split part, all frames with LWA tags are passed to the P2P link to be forwarded to Wi-Fi. All the other non LWA tagged frames are forwarded to the RLC layer. Modifications within the PDCP class along with the design detail of LWA in ns-3 main file are depicted in Figure 4. This flowgraph provides a detailed description and the subsequent flow of packets of the new additions that connect LTE and Wi-Fi networks in ns-3 (the parts highlighted in green in Figure 3 correspond to code additions). The implementation of the LWA architecture is explained next.

3.2.1 Packet generation at the remote host and transfer to PDCP layer. The remote host of the EPC model in ns-3 provides IP-based service to a single UE. An OnOff/PacketSink application (that mimics a Voice Over IP traffic flow) is used to transfer a burst of UDP packets over a Client/Server configuration from the remote host to the UE. The Ipv4StaticRoutingHelper class is used to create a static routing table to enable a connection between the remote host and the UE through the eNB. The sequence number of generated packet is attached to the packet as a header (called *SeqTsHeader*).

3.2.2 LWA data flow differentiation. In ns-3, attributes are used to organize, document and modify the default values used by the various components of the models. In-order to inform the PDCP layer of the eNB about the activation or deactivation of LWA, a new attribute is added. This attribute is called *lwaactivate*. Add attribute binds the member variable *pdcp_decision* to a public string

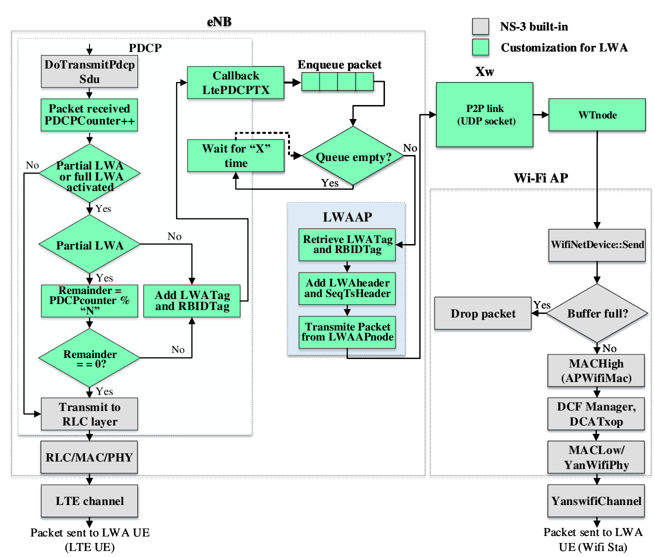

Figure 4: Activity Diagram of LWA Implementation

PDCPDecLwa. It is important to mention here that the value of variable *pdcp_decision* is accessible in the attribute namespace, which is based on string "PDCPDecLwa" and TypeId name ns3::LtePdcp. This variable *pdcp_decision* is used to activate and deactivate the LWA connection at the start of the simulation. As highlighted in Section 2.1, the LWA technique also allows the partial use of both LTE and Wi-Fi technologies together so as to enable in-sequence combining of packets at the UE. The *pdcp_decision* variable can take values: *i)* 0 - LWA deactivated, *ii)* 1 - Partial LWA (LTE+Wi-Fi) and *iii)* 2 - LWA activated (Wi-Fi only).

These states are also used to mimic the split and switched bearer operations of LWA (a *pdcp_decision*=1 indicates split bearer while *pdcp_decision*=2 indicates the switched bearer option).

As described in Figure 4, the first stage of the flowgraph resolves the activation of LWA. If LWA is not activated by setting *pdcp_decision*, the received packet is passed to the TransmitPdcpPdu function so as to be fowarded to RLC layer.

3.2.3 RBID and LWA activation status tags. When partial or full LWA is activated using *pdcp_decision*, all packets are tagged with the corresponding RBID and LWA status information before being enqueued for transmission from LWAAP node. Two new tags are created by sub-classing from the abstract base class ns3::Tag (i.e. LWAtag and LCIDtag). LWAtag includes the LWA activation status and LCIDtag contains the logical ID of the bearer (RBID is derived from LCIDtag). This procedure is represented by the entity "Add LWATag and RBIDTag" in Figure 4.

3.2.4 Flow control in LTE PDCP layer. Packets upon arriving at the PDCP layer with *pdcp_decision* variable assigned a value corresponding to full LWA activate, are tagged and are enqueued for transmission over the Wi-Fi infrastructure. On the other hand, if the variable *pdcp_decision* is assigned a value corresponding to partial LWA activate, the modulo operator is used to decide the percentage of packets that are to be send to Wi-Fi AP and the eNB. This is represented by "$Remainder = PDCPcounter\%"N""$ in Figure 4. The variable N can decide the percentage of split and is set to a fixed value of 2. Thus, when partial LWA is activated, the traffic flow is equally split between LTE and Wi-Fi networks. In order to allow in-sequence delivery of frames at the LWA UE upper layers, each packet arriving at the PDCP layer of eNB is already assigned a sequence number. This number is embedded within a 12 bytes header called $SeqTsHeader$. The sequence number along with RBID information can be used to aggregate data at the UE.

To gain access to packets at the PDCP layer, we utilize the ns-3 tracing system which relies on the callback and attribute system. A new trace source, called TxPDUtrace, is added in the PDCP layer, which gives access to the LWA packet (i.e. $Lte\_pdcpDlTxPDU$) and is used for the collection of the actual transmission. To extract frames from the PDCP layer of eNB, a trace sink function (called $Lte\_pdcpDlTxPDU$), is used to correspond directly to a callback function. That is, whenever a packet is tagged with LWAtag and LCIDtag, the trace callback function $LtePdcp :: m_pdcptxtrace$ at the PDCP layer is triggered and the packet is passed to the $Lte\_pdcpDlTxPDU$ function. This packet (with both header and data contents) is copied and enqueued in the buffer for transfer to the Wi-Fi network through a Xw (P2P) link. This procedure is represented by "Callback LtePDCPTX" box in Figure 4.

It is important to mention here that the above mentioned callback function is used only for LWA tagged frames and these frames are not passed to the RLC layer of the LTE eNB.

3.2.5 Packet generation to LWAAP. In 3GPP LTE, a typical Transmit Time Interval (TTI), which refers to the duration of a transmission over the radio link, is set to 1 ms [6]. For a timely and accurate transmission of frames from LTE eNB to Wi-Fi AP, the buffer is continuously observed after every "X" interval. The value of this interval is kept below the aforementioned TTI (i.e. $X = 0.1ms$). Therefore, whenever a packet is placed in the buffer, it is immediately transferred to the source of the UDP socket at the LWAAPnode. These procedures are represented by "Enqueue packet", "Queue empty" and "Wait for "X" time" entities in Figure 4.

3.2.6 Packet formulation by LWAAP and transmission to the Xw link. As described above, RBID and sequence number of a packet are important parameters that can enable the aggregation of flow at the UE. Information regarding the sequence number is passed along, when the packet is copied along with $SeqTsHeader$. RBID and $lwaactivate$ information is first extracted from tags and then added as header to be transmitted over the Xw interface.

As described in the LTE Release 13 standard, the LWAAP entity generates LWAAP PDUs containing a RBID identity. To forward the RBID and LWA status information, a new 2 bytes header named $LwaHeader$ is defined. In the next stage, the packet is sent to the source of the UDP socket installed at the LWAAPnode. The above highlighted steps are shown in the LWAAP entity in Figure 4.

3.2.7 Data forward from LWAAPnode to the Wi-Fi station through the Wi-Fi AP. The downlink flow of a packet from the LWAAPnode to Wi-Fi station is accomplished by creating a source destination socket. The Xw interface in the simulation is assumed to be a P2P link created between the LWAAPnode and the WTnode. Wi-fi AP is also connected to the WT through a P2P link.

The LWAAPnode is set as a source socket and the Wi-Fi station as the destination sink. Both sockets are identified using IPv4 addresses. For synchronization between sockets, the port number for both is kept equal. To create the routing database and initialize the routing tables for connection between the P2P node, Wi-Fi AP and Wi-Fi station, the Ipv4GlobalRoutingHelper class was used.

3.2.8 Packet reception at Wi-Fi station. The packet received at the destination socket of the Wi-Fi station includes the $SeqTsHeader$ and the $LwaHeader$ headers. This information can be used to aggregate packets at the application layer of the UE.

With the help of Table 1, a comparison between implemented functions of LWA in ns-3 with 3GPP LWA standard is provided. As highlighted in the table, most of the specifications of LWA provided by 3GPP Release 13 were implemented in ns-3. LWA was controlled at the eNB and the splitting of frames was performed at the PDCP layer. The *pdcp_decisionlwa* variable enabled the ns-3 implementation to support split and switched bearer functionality. Since the implementation of a method to aggregate data at the PDCP layer has been left as future work, no changes were made at the ns-3 LTE UE.[2] As mentioned in Section 3.1, it was assumed

[2]The aggregation of flows at the PDCP layer required modifications to the core of the ns-3 LTE module and was considered out of scope of our current work.

Table 1: ns-3 LWA Implementation/3GPP Feature Checklist

Attributes	ns-3 LWA	3GPP standard LWA
eNB control	Yes	Yes
Connecting layers	PDCP	PDCP
Offloading granularity	Split or Switched Bearer	Split or Switched Bearer
Upgrade in LTE network	eNB and UE	eNB
Aggregating flows at UE PDCP	No	Yes
New network entities in LTE	LWAAP and Xw-U	LWAAP and Xw
Additional interface for flow control	Xw-U	Xw-U
Xw control plane interface	No	Xw-C
WT connection establishment	No	Yes
New network nodes in Wi-Fi	WT	WT
WLAN measurements	No	Yes
WLAN security	No	WLAN native 802.1x EAP/AKA
WLAN traffic direction	Downlink	Downlink

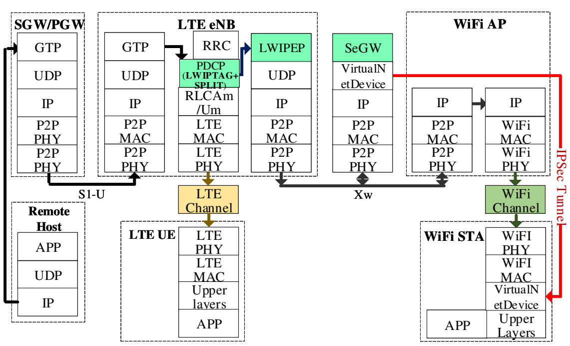

Figure 5: LWIP ns-3 Implementation

that an ideal control plane (Xw-C) was available between eNB and WT. Therefore, WLAN measurements, support for establishment, modification and error handling mechanism were not considered.

4 IMPLEMENTATION OF LWIP IN NS-3

In LWIP, an IPSec tunnel is used to transmit downlink traffic from eNB to the UE through a Wi-Fi AP. Similar to LWA, the UE in LWIP has a RRC connection to the eNB. Unlike LWA, packets in LWIP can not be simultaneously transmitted to both LTE or WLAN link. In ns-3, the IP networking for end-to-end connectivity for end users (that contains UE, SGW/PGW and remote host) does not involve the use of IP stack at the eNB in the EPC model. In order to counter the aforementioned problem and to gain access to PDCP SDUs (IP packets), the LWIP protocol was designed to follow the same methodology used in Section 3.2 for LWA to extract frames at the PDCP layer. Similar to LWA implementation, the PDCP layer of LTE eNB can be commanded to activate/deactivate the offloading of data. If LWIP is activated, the complete flow from LTE to UE is stopped and the data is diverted towards the Wi-Fi AP. The aforementioned procedure is accomplished by event driven triggering technique. An IPSec tunnel is created on which IP packets are tunneled over UDP/IP. For the ns-3 implementation, since the same LWA mechanism is leveraged, Xw interface was used. This is also justified by the fact that the implemented Xw-U interface was only responsible for transfer of packets.

4.1 Assumptions

In our implementation, we make the following assumptions:

(1) The non-collocated scenario is assumed, where LTE network is connected through SeGW to an already existing Wi-Fi network.
(2) We assume an ideal Xw-C interface where there is no error in communication and setting up.
(3) No mobility model is considered.
(4) Wi-Fi station is already configured and associated with an AP.
(5) The LWIP tunnel between the LWIP SeGW and the Wi-Fi station is already established through Wi-Fi infrastructure.
(6) The IPSec tunnel uses authentication but no encryption.

4.2 Implementation Details

In this section, we describe the sequence of events that take place during the simulation of the LWIP protocol in ns-3. Figure 5 indicates that multiple network components corresponding to different technologies (LTE, PointToPoint, VirtualNetDevice and Wi-Fi) are used together to develop the LWIP protocol. An IP tunnel is created using a VirtualNetDevice that wraps UDP packets with new IP headers. First, any traffic generated from the remote host to the UE attempts to follow the direct path. However, if the downlink traffic is to be forwarded to the Wi-Fi network, a secure tunnel is used to funnel the data to the LWIP UE (i.e. the Wi-Fi station). The details of modifications within PDCP classes and the interconnection between different classes is highlighted in Figure 6. This flowgraph provides a detailed description and the subsequent flow of packets over the new network nodes/modules added to connect LTE and Wi-Fi networks through the IP tunnel (the parts highlighted as ns-3 additions in Figure 5). The implementation of the LWIP architecture is explained next.

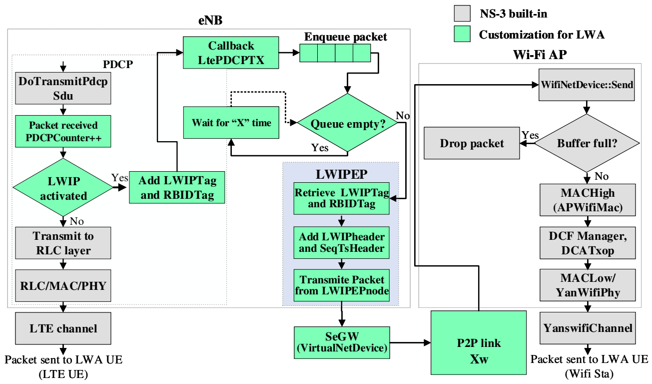

Figure 6: Activity Diagram of LWIP Implementation

4.2.1 Packet generation at remote host and transfer to PDCP layer. Similar to the LWA implementation, an OnOff/PacketSink application is used to transfer a burst of UDP packets over a Client/Server configuration from the remote host to the LTE UE.

4.2.2 LWIP data flow differentiation. In order to inform the PDCP layer of the eNB about activation or deactivation of LWIP, a new attribute is added. This attribute, called *lwipactivate*, associates with the mechanism to access the underlying member variable (i.e. *pdcp_decision*), which is used to activate and deactivate the LWIP connection. The variable *pdcp_decision* can take the following values: *i)* 0 - LWIP deactivated and *ii)* 1 - LWIP activated.

At the start of the simulation, the Config::SetDefault method is used to override the initial (default) value of the PDCPDecLwip attribute. As described in Figure 6, the first stage of the flowgraph is used to take a decision about the activation of LWIP. If LWIP is not activated by setting *pdcp_decision*, the received packet is passed to the *TransmitPdcpPdu* function to be forwarded to the RLC layer.

4.2.3 RBID and LWA activation status tags. Similar to LWA, when *pdcp_decision* variable is assigned a value corresponding to LWIP activate, all packets are tagged with the corresponding RBID and LWIP status information before being enqueued for transmission from LWIPEP node. The LCIDtag defined for LWA is reused. However, for LWIP status, a new tag (called LWIPTag) is defined. This is shown as the entity "Add LWIPTag and RBIDTag" in Figure 10.

4.2.4 Flow control in LTE PDCP layer. Packets upon arriving at the PDCP layer with *pdcp_decision* variable assigned a value corresponding to LWIP activate, are tagged and are enqueued for transmission over the Wi-Fi Infrastructure. In order to allow in-sequence delivery of frames at the LWA UE upper layers, each packet arriving at the PDCP layer of eNB is already assigned a sequence number. This number is embedded within a 12 bytes SeqTsHeader. In order to extract the LWIP tagged frames from the PDCP layer, the same approach described in Section 3.2.4 was used.

4.2.5 Packet generation to LWIPEP entity. The procedure described in Section 3.2.5 is used to transfer packets to the LWIPEPnode.

4.2.6 Packet formulation by LWIPEP and transmission to SeGW link. As mentioned in Section 2.2, the responsibility of LWIPEP module is to generate user plain data along with the bearer identification. Similar to LWA, RBID and lwip activate information is first extracted from tags and then added as header to the packet to be sent over the Xw interface. A new 2 bytes header named $LwipHeader$ is defined that contains lwip activate status and bearer ID information. This stage is represented by LWIPEP entity in Figure 6.

In the next phase, the packet is transferred to the SeGW from LWIPEPnode for transmission over the IPSec tunnel.

4.2.7 Data forward from SeGW to Wi-Fi station through IP tunnel. To create an IP tunnel, extra virtual interfaces were installed over the SeGW link and the Wi-Fi station (i.e. an interface with a new address set to 11.0.0.1 was installed over the P2P link and the interface with address 11.0.0.254 was installed over the Wi-Fi station). Thus, the flow of packets would be between 11.0.0.x (i.e. the tunnel) instead of the actual IP addresses (10.0.x.y for P2P and 192.168.x.y for the Wi-Fi network). The use of VirtualNetDevice at the SeGW represents a contact point towards external Wi-Fi network. This is the point where the secured IPSec tunnel is initiated. A tunnel class is created that uses callback functions to create virtual UDP source and destination sockets over the VirtualNetDevice. These sockets are used to transmit the IP encapsulated LWIP packets from SeGW to Wi-Fi station. The Xw interface defined for LWA is re-used to provide a connection between SeGW and Wi-Fi AP.

4.2.8 Packet reception at Wi-Fi station. The packet received at the destination at the Wi-Fi station include the $SeqTsHeader$ and the $LwipHeader$ headers. This information can be used to aggregate packets at the application layer of the UE.

With the help of Table 2, a comparison between implemented functions of LWIP in ns-3 with 3GPP standard is provided. As highlighted in the table, most of the specifications of LWIP provided by 3GPP Release 13 were implemented. Activation and deactivation of LWIP mechanism was controlled by the eNB. Due to the problem of non-existing IP stack at the eNB, the splitting of IP packets was performed at the PDCP layer. The *pdcp_decisionlwip* variable enabled the ns-3 implementation to support switched bearer functionality. Since the implementation of a method to aggregate data at the IP layer has been left to future work, no changes were made at the ns-3 LTE UE. As mentioned in Section 4.1, it was assumed that an ideal control plane (Xw-C) was available between SeGW and Wi-Fi AP. Therefore, the details of WLAN measurements, support for establishment, modification and error handling mechanism were not considered. Although LWIP can be configured to deliver both uplink and downlink data over the WLAN, we focused our study on the implementation particularly for downlink communication.

5 PERFORMANCE EVALUATION

In this section we describe the definition of the evaluation scenarios and the collection of results. We have evaluated the aggregated capacity achieved by using LWA and LWIP, how they compare in terms of efficiency and different effects associated to having Wi-Fi interferer networks in the vicinity. Parameters used are listed in Table 3, for LWA and LWIP Wi-Fi transmissions we have considered IEEE 802.11ac physical layer parameters with no MIMO and no aggregation. Simulations are run for 100 seconds and have been repeated 10 times. We use Constant Bit Rate (CBR) UDP sources

Table 2: ns-3 LWIP Implementation/3GPP Feature Checklist

Attributes	ns-3 LWIP	3GPP standard LWIP
eNB control	Yes	Yes
Connecting layers	PDCP	IP (PDCP SDU)
Offloading granularity	Switched Bearer	Switched Bearer
Upgrade in LTE network	eNB	eNB
Aggregating flows at UE IP	No	Yes
New network entities in LTE	LWIPEP and SeGW	LWIPEP and SeGW
New network nodes in Wi-Fi	None	None
WLAN measurements	No	Yes
WLAN security	No	WLAN native 802.1x EAP/AKA
WLAN traffic direction	Downlink	Downlink plus uplink

Table 3: Simulation Parameters

Wi-Fi Parameters	Value	LTE Parameter	Value
MCS	8 (78 Mbps)	MCS	28
Tx power	30 dBm	Tx power	30 dBm
Bandwidth	20 MHz	Tx Bandwidth Configuration $[N_{RB}]$	25 (5 MHz)
RTS/CTS	Disabled	Noise figure	5

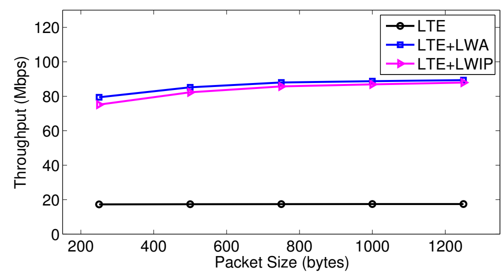

Figure 7: LTE Aggregated Capacity using LWA and LWIP

We start by comparing the efficiency of LWA and LWIP in the unlicensed spectrum. To do so we simulate 1 eNB, 1 Wi-Fi AP and 1 Wi-Fi STA and 1 UE while the eNB generates downlink traffic towards the UE. In order to evaluate the network efficiency we saturate both the LTE and the Wi-Fi channels. That is, we make sure that there is always a packet to transmit by the eNB and the Wi-Fi AP. In this way we can compare LWA and LWIP maximum capacity. In the absence of interference from other networks, we would expect LWIP to be able to augment LTE capacity in a lower degree than LWA due to the extra headers of the IPSec tunnel, which reduce the effective information that can be transmitted at each Wi-Fi transmission attempt. Results are plotted in Figure 7 which shows LTE throughput when LWA and LWIP are not activated plus the aggregated capacity obtained by using LTE along with LWA and LWIP with varying packet sizes. Note that since we are assuming saturated conditions here, the use of partial or full LWA does not make any effect on the throughput results. Thus, we have opted to show full LWA results only.

As it can be observed in Figure 7, for the parameters considered, the use of LWA and LWIP allows to substantially increase the aggregated capacity. Note that we have used IEEE 802.11ac parameters and that the Wi-Fi throughput obtained can be as higher as 78 Mbps. We can observe, as we introduced before, that the use of LWIP results in slightly lower throughput than LWA. This is due to the extra headers of the IPSec tunnel. We can observe in the figure as well the effect of increasing the packet size (effective data transmitted per packet). Increasing the packet size in Wi-Fi results in more throughput as more data is transmitted per channel attempt, making the access more efficient by compensating overhead, both in terms of headers and channel access inefficiency (such as empty channel duration due to DIFS, SIFS and backoff slots). What can be observed in the figure is the combined effect of this trend (increased throughput with longer packet sizes) and LWIP higher inefficiency if compared to LWA. Note that LWIP higher inefficiency due to overheads is more notable for small packet sizes. For longer packet sizes the extra added overhead introduced in LWIP becomes negligible as the channel access becomes more efficient.

Now, we evaluate the effect of having a Wi-Fi network interfering with the LWA and LWIP link and analyze the effect of increasing number of uplink transmissions in the Wi-Fi network. Thus, effectively evaluating how LWA and LWIP perform under contention. Figure 8 shows the throughput of the LTE link as well as the throughput achieved by the LWA connection (not aggregated with LTE now to better compare with Wi-Fi) and the aggregated throughput achieved in the Wi-Fi interferer network. The transmit power has been now set to 15 dBm, packet size has been set to 500 bytes for both Wi-Fi and the LTE and the carrier sense threshold has been set to -72 dBm. Simulation time has been set to 10 s.

We can observe in Figure 8 that the throughput of LWA and LWIP decreases as the number of uplink Wi-Fi transmitters increases. This is due to the channel access of Wi-Fi which provides fairness per device. We cannot see a proportional division of resources among all devices (2, 4 and 6 Wi-Fi transmitters plus the LWA/LWIP AP)

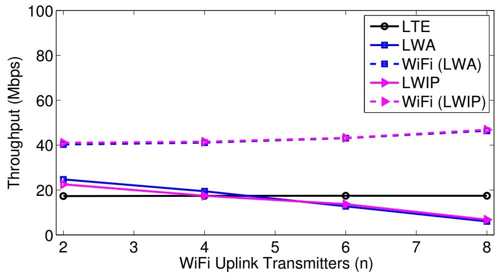

Figure 8: Throughput Achieved in the LTE and LWA Link when a Wi-Fi Interferer Network is Placed in the Vicinity

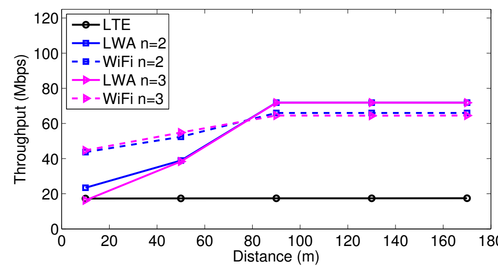

Figure 9: Throughput Achieved in the LTE and LWA Link when a Wi-Fi Interferer Network is Placed in the Vicinity

due to the fact that by default ns-3 prioritizes AP channel access. However, even using higher priority we can see in the figure that the LWA and LWIP throughput substantially decreases with contention from the Wi-Fi network. An interesting effect as well is the fact that the inefficiency of LWIP due to having to transmit extra headers becomes negligible as the number of Wi-Fi interferers increases. We believe this is caused by this extra overhead now becoming negligible when compared to channel access inefficiency due to contention. It is also worth noting that the throughput capacity now obtained whith the LWA and LWIP connection is smaller than that of the LTE link, even tough the LTE bandwidth is set to 5 MHz and the bandwidth of the Wi-Fi side is set to 20 MHz but needs now to be shared with a coexisting Wi-Fi network.

In the following, we evaluate the effect of having a Wi-Fi network interferer and analyze how the effect of the interference changes by increasing the distance among two networks (Wi-Fi and LWA link) as well as by increasing the transmission power of both the Wi-Fi interferer network and the LWA connection. Figure 9 shows the throughput of the LTE link as well as the throughput achieved by the LWA connection (not aggregated with LTE now to better compare with Wi-Fi) and the aggregated throughput achieved in the Wi-Fi interferer network. The number of Wi-Fi transmitters (in the uplink only) is considered to be equal to n=2 and n=3. The transmit power is now set to 15 dBm, packet size has been set to 1000 bytes for the LWA link and Wi-Fi network and the carrier sense threshold has been set to -72 dBm. The three log-distance propagation pathloss (with path-loss exponents $\alpha_1 = 2$ and $\alpha_2 = \alpha_3 = 3.5$) model is used in the 5.19 GHz Wi-Fi band. Results are only shown for LWA as LWIP will perform similarly as seen in Figure 8.

As it can be observed in Figure 9 when the two networks are close together the throughput achieved is considerably reduced as they now share the channel resources and create contention. As long as we increase the distance among them the throughput improves until the point at which they no longer interfere with each other. As can be seen for small distances the throughput achieved by LWA is higher when the Wi-Fi interferer competes with 2 nodes instead of 3. Similarly, the throughput of the LWA link is approximately half the one achieved by the Wi-Fi network with n=2. It is worth noting that the contrary effect will be obtained by increasing LWA receivers. However, we do not observe a complete proportional division of resources according to the number of users of the network due to the fact that the LWA device is an AP and some channel access parameters give priority to AP transmissions by default in ns-3. This is why LWA link transmissions are somehow benefited in the unlicensed spectrum sharing with Wi-Fi in this results. Interestingly, we can see in this figure as well that with Wi-Fi interference now throughput becomes comparable to the one obtained in the LTE link, even though the Wi-Fi channel bandwidth is considered equal to 20 MHz and the LTE one is set to 5 MHz for these simulations.

6 CONCLUSIONS

In this article, we present the design details of our implementation of LTE-WLAN offloading techniques (i.e. LWA and LWIP) proposed in Release 13 by 3GPP. We provide details of the two techniques and provide a step-by-step description of different aspects of the implementation, which are validated through simulation results. First, we analyse the efficiency of LWA and LWIP implementation under saturation conditions. Results indicate substantial increase in the aggregate capacity for LTE-WLAN interworking schemes in the absence of interference. However, LWIP is found to be less efficient due to IPsec tunnel overheads. Next, the impact of interfereres originating from neighbouring Wi-Fi cell to the primary WLAN network (supporting LWA/LWIP) is observed. Important outcome is that for amicable operations, the primary cell should be selected with fewer interfering nearby stations. Future work includes comparison to LAA in ns-3 and our implemented LWA/LWIP techniques.

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REFERENCES

[1] 3GPP. 2015. Feasibility Study on Licensed-Assisted Access to Unlicensed Spectrum; V.13.3.0, Section 22A.1, document TS 36.889.
[2] 3GPP. 2016. Evolved Universal Terrestial Radio Access (E-UTRA) and Evolved Universal Terrestial Radio Access Network (E-UTRAN); Overall Description; Stage 2, V.13.3.0, Section 22A.1, document TS 36.300.
[3] MulteFire Alliance. 2018. MulteFire Release 1.0 Technical Paper, A New Way to Wireless.
[4] Huawei. 2014. U-LTE: Unlicensed Spectrum Utilization of LTE.
[5] Cisco Visual Networking Index. 2017. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021. White Paper.
[6] M. Nohrborg. [n. d.]. LTE Overview. http://www.3gpp.org/technologies/keywords-acronyms/98-lte
[7] ns-3 project. [n. d.]. The Network Simulator- ns-3. www.nsnam.org