

The Voice of 5G for the Americas



LTE Aggregation & Unlicensed Spectrum

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PREFACE

A key industry discussion concerns the efficient use of spectrum to serve societies' connectivity requirements. A recent solution to the rising wireless data demands, and the topic of this paper, is data offloading from licensed LTE networks to unlicensed spectrum. Recent work by the 3rd Generation Partnership Project (3GPP) on offloading to the Wireless Local Area Network (WLAN) via LTE/WiFi Aggregation and using LTE directly in unlicensed spectrum are specifically discussed.

WiFi offloading is driven by the rapid adoption of smartphones which are Wi-Fi enabled and the increase in data demand from consumers. This has led to mobile operators quickly moving to offload data traffic from capacity constrained licensed networks onto available Wi-Fi networks. 3GPP has defined several WLAN offloading mechanisms which rely on the connection between the LTE core network and WLAN. The recent work on data aggregation at the LTE base station, which is discussed in this paper, allows for better control of offloading with improved system and user performance while leveraging the existing LTE features of Carrier Aggregation (CA) and dual connectivity.

The option of using LTE in unlicensed spectrum was motivated by the possibility of a more seamless and spectrally efficient method of offloading while using the same core radio technology across both licensed and unlicensed spectrum. The coexistence of deploying both LTE and Wi-Fi in the same way was studied extensively by 3GPP which concluded that the two technologies can coexist, thus allowing mobile operators the option to use either or both LTE and Wi-Fi to offload data to unlicensed spectrum.

1 INTRODUCTION

In recent years, mobile data usage has been increasing at an exponential rate by almost doubling every year and it is expected to continue. Even though advances in cellular technology have increased the performance and capacity of mobile networks, this alone will not be sufficient to meet the mobile data demand. The usage of unlicensed spectrum provides an attractive opportunity for operators to help support their subscribers by increasing network data capacity.

The conventional method for data offloading to unlicensed spectrum by operators has been using 802.11 based WLAN networks. Such networks have been deployed by either operators themselves or their partners. The residential and campus WLAN networks have also been used by end users, especially for connecting to the Internet. In order to provide an architectural framework and standardization for WLAN offloading, 3GPP has developed several solutions such as ANDSF, IFOM, and SaMOG which enable interworking with WLAN and provide data offloading through switching of data bearers to WLAN.

There have been recent methods developed within standardization bodies and industry for data offloading to unlicensed spectrum:

LWA: A new alternative for LTE and WLAN interworking is data aggregation at the radio access network, where an Evolved NodeB (eNB) schedules packets to be served on LTE and Wi-Fi radio links. This is similar to the carrier aggregation and dual connectivity features defined in Release 10 and Release 12. The advantage of this solution is that it can provide better control and utilization of resources on both links. This can increase the aggregate throughput for all users and improve the total system capacity by better managing the radio resources among users. In contrast to the previously developed offloading solutions which rely on policies and triggers, scheduling decisions for each link can be made at a packet level based on real-time channel conditions and system utilization. Furthermore, data aggregation at the Radio Access Network (RAN) can be implemented without any changes to the core network since the WLAN radio link effectively becomes part of the Enhanced Universal Terrestrial Radio Access Network

(E-UTRAN). 3GPP has approved a Release 13 (Rel-13) Work Item on LTE/WLAN Aggregation which is to be completed according to the Rel-13 schedule.¹ The term Radio Aggregation will be used to be synonymously with LTE/WLAN Aggregation at the RAN Level and also as the abbreviation for LWA (LTE WLAN Aggregation).

LAA: Another alternative for using unlicensed spectrum to complement mobile networks is the deployment of LTE itself in unlicensed spectrum. LTE has been successfully deployed in providing wireless broadband data and its usage in both licensed and unlicensed spectrum can enable operators and vendors to leverage the existing or planned investments in LTE/Evolved Packet Core (EPC) hardware at both the radio and core network and simplify User Equipment (UE) architecture.

3GPP has completed a Rel-13 Study Item on License Assisted Access LTE (LAA-LTE) where the unlicensed carrier can be used as a Secondary Component Carrier in the LTE Carrier Aggregation framework.² The study took into account different regulatory requirements for the usage of unlicensed spectrum around the world, and in particular, the Listen-Before-Talk (LBT) schemes. Furthermore, fair coexistence with other technologies which use unlicensed spectrum, particularly WiFi, was an important part of the study. A Work Item is now ongoing to include LAA-LTE in the Rel-13 specifications.

LTE-U: Another effort in expanding the usage of LTE to unlicensed spectrum has been occurring outside 3GPP in the LTE-U Forum³ which has published specifications and studies for minimum base station and UE requirements and co-existence with Wi-Fi. The focus of the LTE-U Forum based solution is for deployment options and regions where LBT is not required. For the purpose of this document, LTE-U will refer to the LTE-U Forum defined solution.

Others: In the industry, other options for multi-connectivity/aggregation occurring at the network level such as Multipath Transmission Control Protocol (MP-TCP) and Quick User Datagram Protocol Internet Connections (QUIC) are also emerging. These multi-connectivity approaches can work with any combination of licensed and unlicensed band technologies including future ones (e.g., 5G), but these are not within the scope of this paper.

2 DEPLOYMENT SCENARIOS

2.1 LTE-WLAN RADIO LEVEL AGGREGATION (LWA)

The deployment scenarios for LTE-WLAN radio level aggregation can be grouped into two categories as shown in Figure 2.1; collocated scenarios and non-collocated scenarios. The collocated scenario would be most common for an integrated LTE small cell plus one or multiple WLAN Access Points (AP(s)). The non-collocated case corresponds to when the eNB connects to WLAN via a standardized interface. The end-point of this interface on the WLAN side is a logical entity which can reside at the AP, Access Controller (AC) (as shown in Figure 2.2) or at a new WLAN entity. The non-collocated scenarios would represent situations where there are WLAN APs within a macro or small cell coverage area, but not collocated with the macro or small cell.

¹ "LTE-WLAN Radio Level Integration and Interworking Enhancement", RP-151022.

² "Licensed-Assisted Access using LTE", RP-151045.

³ <http://www.lteforum.org/index.html>.

Collocated Scenario
Aggregation/interworking
between the collocated LTE eNB
and WLAN AP



Non-collocated Scenario

Aggregation/interworking between non-collocated LTE eNB and WLAN APs *directly* connected via the Xw interface

Aggregation/interworking between non-collocated LTE eNB and WLAN APs connected via Xw *through a WLAN AC*

Xw = Standardized LTE-WLAN Interface
AC = WLAN Access Controller

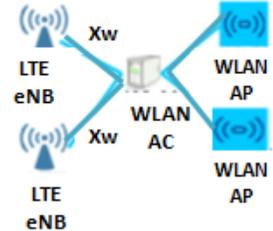
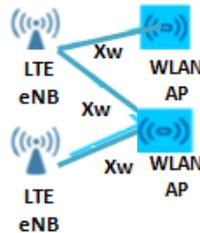


Figure 2.1. Deployment scenarios for LWA-WLAN radio aggregation.

The main deployment scenario for LTE-WLAN Radio Level Aggregation is WLAN networks deployed and controlled by an operator and its partners. The 3GPP Work Item does not consider interworking with other types of WLAN networks.

From a coverage point of view, two basic deployment scenarios are shown in Figure 2.2. The collocated scenario considers the integrated eNB and WLAN AP, such as small cells or when eNB has an ideal backhaul, to a WLAN logical entity which is connected to the APs. The non-collocated scenario is when such backhaul is not ideal.

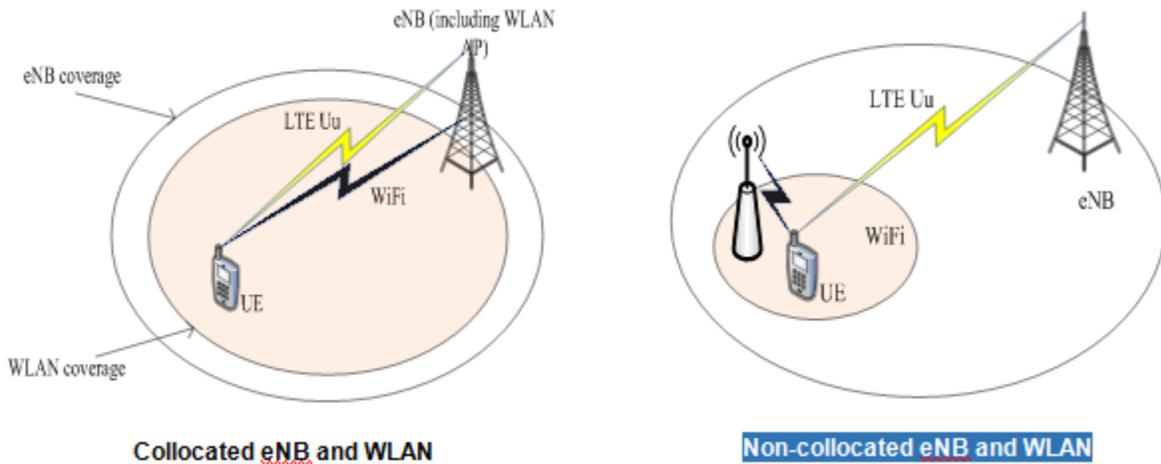


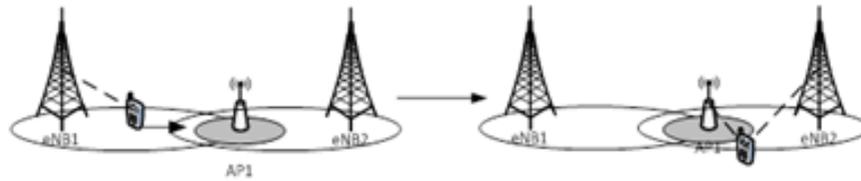
Figure 2.2. Basic Deployment options for LWA.

In LWA, eNB is the anchor node for both data and control planes and connects to the Core Network (CN) via regular S1 interfaces (S1-C and S1-U). Since data packets have to traverse the eNB before being transmitted over WLAN, an interface between eNB and WLAN is needed. This interface is being standardized by 3GPP in Rel-13 and will be used for both control signaling to enable aggregation operation and feedback from WLAN on network, channel and user conditions to help with LWA scheduling operation.

The following use cases are covered by LWA and shown in Figure 2.3:

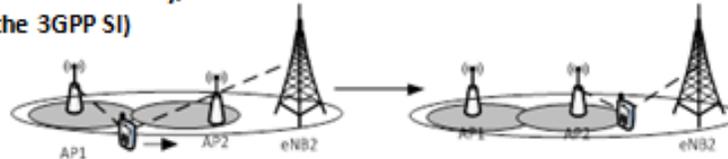
- A. UE is within E-UTRAN coverage, using 3GPP and goes into WLAN AP coverage (scenario 3).
- B. UE is within E-UTRAN and WLAN coverage, using WLAN in aggregation mode and goes out of WLAN AP coverage (scenario 3).
- C. UE is within E-UTRAN and WLAN coverage, using WLAN in aggregation mode and changes association to another WLAN AP (scenario 2).
- D. UE is within E-UTRAN coverage of a first eNB and using 3GPP, then leaves coverage for the first eNB and goes into E-UTRAN coverage from a second eNB and WLAN AP coverage (scenario 1).
- E. UE is within E-UTRAN and WLAN coverage and in aggregation mode and goes out of E-UTRAN coverage and changes association to another WLAN AP.
- F. UE is within E-UTRAN and WLAN coverage, UE using LTE and WLAN in aggregation mode, all, none, or a subset of the traffic of a data bearer for the UE should be routed via E-UTRAN where subset could be empty.

Scenario 1

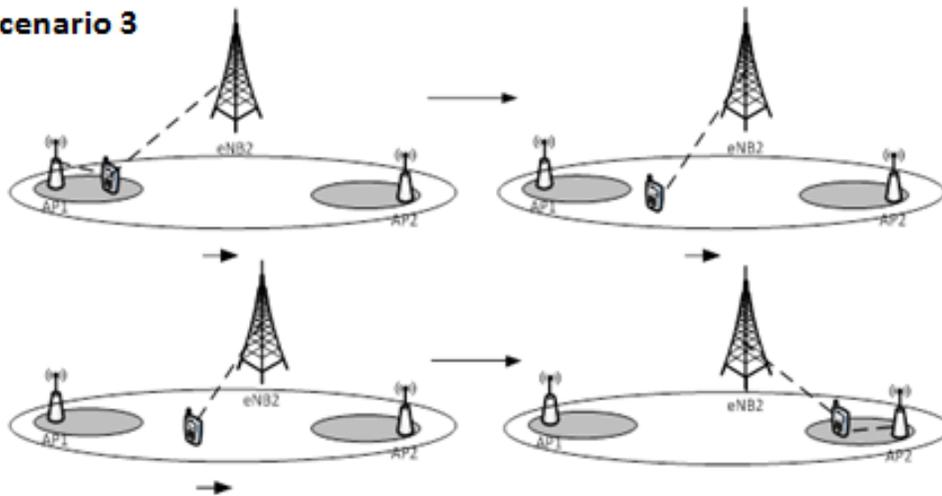


Scenario 2

(covered by WLAN mobility, outside of the 3GPP SI)



Scenario 3



Scenario 4

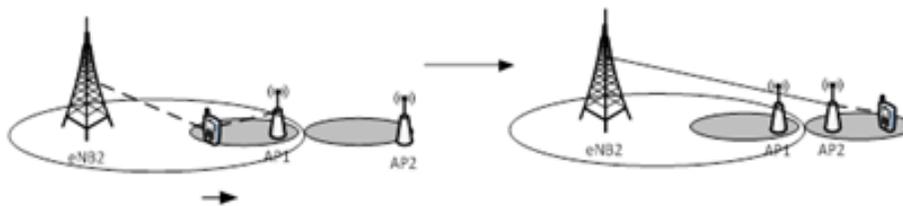


Figure 2.3. Mobility scenarios for LWA.

It should also be noted that alternative architectures to LWA are still being discussed in 3GPP. For instance, a recent proposal has been made using Internet Protocol (IP) tunneling above the Packet Data Convergence Protocol (PDCP) layer packets between the eNB and UE over WLAN as shown in Figure 2.4. The advantage of this approach is that it can be supported by legacy WiFi nodes (no upgrades needed). Some of the challenges of this approach are that the IP tunnel must be re-established for every WiFi AP change and the IP address of the eNB is exposed to the UE.

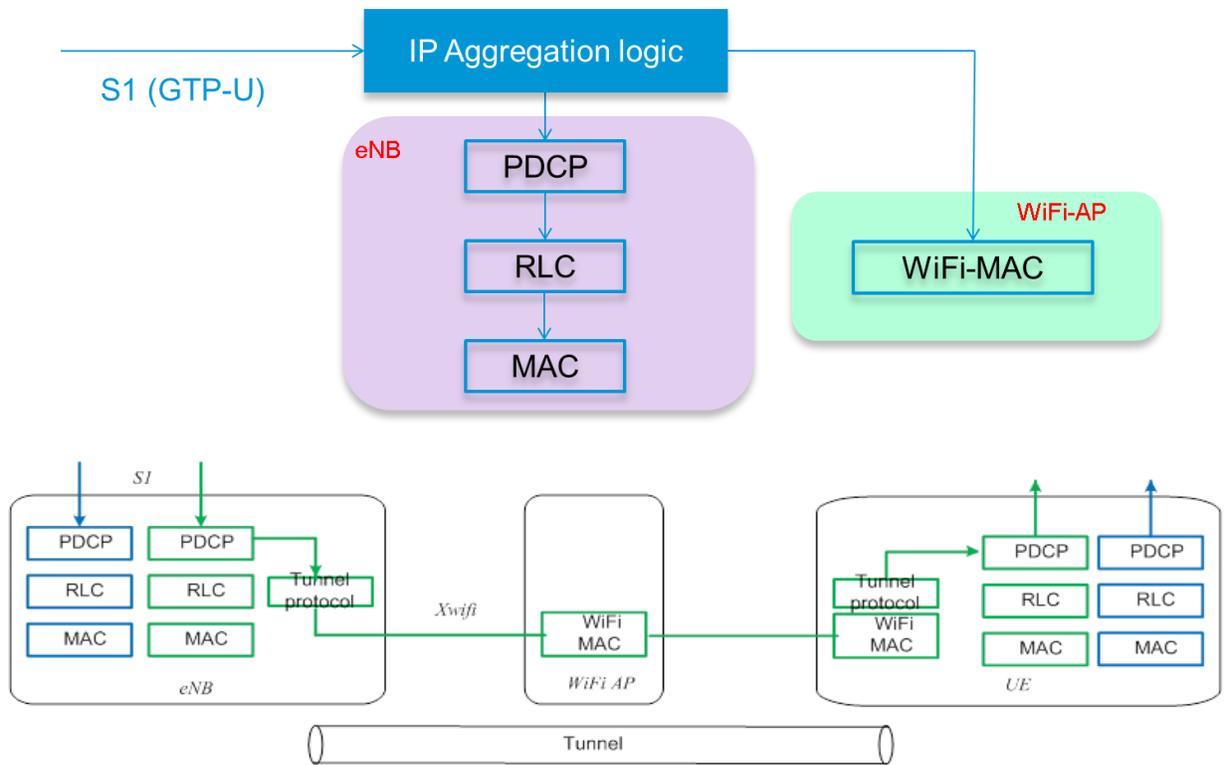
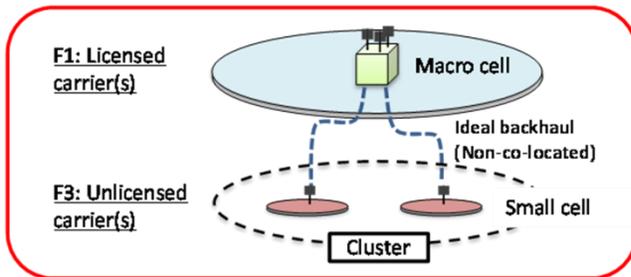


Figure 2.4. IP Tunneling above PDCP layer.

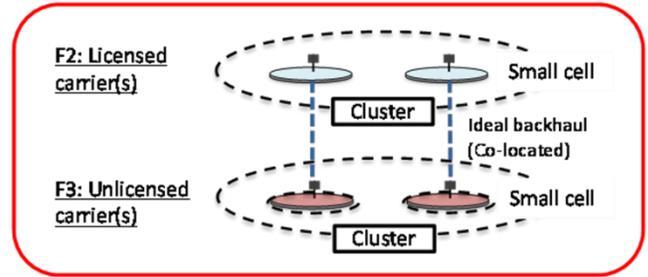
2.2 LTE IN UNLICENSED SPECTRUM

Both LAA and LTE-U use carrier aggregation between a primary LTE component carrier in a licensed band and one or more low power secondary component carriers deployed in the unlicensed spectrum. The deployment scenarios span with and without macro coverage, outdoor and indoor small cell deployments, co-location and non-co-location (with ideal backhaul) between the licensed and unlicensed carriers. Figure 2.5 shows four possible LAA deployment scenarios. Though the backhaul between small cells can be ideal or non-ideal, the unlicensed small cell only operates in the context of the carrier aggregation through ideal backhaul with a licensed cell. In scenarios where carrier aggregation is operated within the small cell with carriers in both the licensed and unlicensed bands, the backhaul between macro cell and small cell can be ideal or non-ideal.

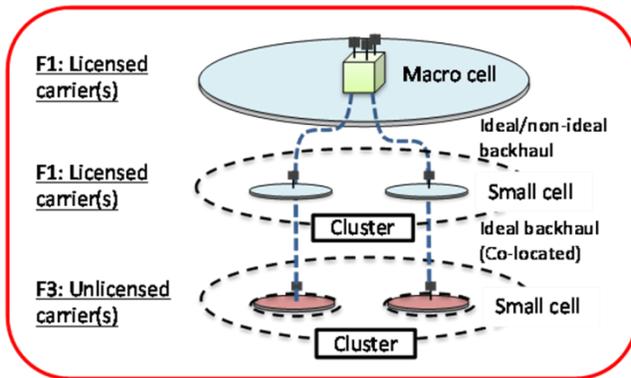
Scenario 1



Scenario 2



Scenario 3



Scenario 4

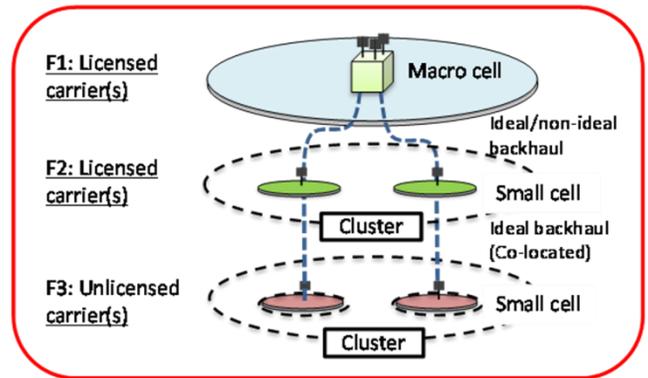


Figure 2.5. LAA deployment scenarios.

Scenario 1

- Carrier aggregation between licensed macro cell (F1) and unlicensed small cell (F3)

Scenario 2

- Carrier aggregation between licensed small cell (F2) and unlicensed small cell (F3) without macro cell coverage

Scenario 3

- Licensed macro cell and small cell (F1), with carrier aggregation between licensed small cell (F1) and unlicensed small cell (F3)

Scenario 4

- Licensed macro cell (F1), licensed small cell (F2) and unlicensed small cell (F3)
 - Carrier aggregation between licensed small cell (F2) and unlicensed small cell (F3)
 - If there is ideal backhaul between macro cell and small cell, there can be carrier aggregation between macro cell (F1), licensed small cell (F2) and unlicensed small cell (F3)
 - If dual connectivity is enabled, there can be dual connectivity between macro cell and small cell.

In the study to support LAA and deployments in unlicensed spectrum for the above scenarios, CA functionalities are used as a baseline to aggregate PCell/PSCell on a licensed carrier and SCell on an unlicensed carrier. When non-ideal backhaul is applied between a macro cell and a small cell cluster in Scenarios 3 and 4, a small cell on an unlicensed carrier has to be aggregated with a small cell on a licensed carrier in the small cell cluster through ideal backhaul. One of the goals of this report is to identify the need of and, if necessary, evaluate needed enhancements to the LTE RAN protocols applicable to carrier aggregation in all of the above scenarios.

Operators can potentially utilize the entire available unlicensed spectrum in addition to licensed spectrum while using the same:

- Core network
- Unified authentication mechanisms
- Unified operations and management systems
- Unified acquisition, access, registration, paging and mobility procedures

At the Physical Layer/Media Access Control PHY/MAC layer, several key functionalities have been identified for an LAA system to operate in unlicensed spectrum. The Listen-Before-Talk (LBT) procedure using energy detection is the primary mechanism by which equipment assesses the availability of the unlicensed channel before transmission. Apart from regulatory requirements, carrier sensing via LBT is one way for fair sharing of the unlicensed spectrum and hence it is considered to be a vital feature for fair and friendly operation in the unlicensed spectrum in a single global solution framework. Discontinuous transmission by limiting the transmission during each channel access opportunity to a few milliseconds (ms) is another vital feature to ensure that all nodes obtain channel both fairly and frequently. A third vital feature for unlicensed operation is carrier selection which enables LAA eNBs to select channels with low interference levels and achieve effective coexistence with other unlicensed networks. Several design enhancements in Discovery Reference Signals (DRS) design, cell selection, Radio Resource Management (RRM) measurements, Channel State Information (CSI) feedback, Hybrid Automatic Retransmission Request (HARQ) enhancements, newer waveforms and flexible multi-carrier transmission have been proposed to be further improve operation in unlicensed spectrum and studied as part of the 3GPP Study Item (SI).

The SI concluded that for Downlink (DL) transmission, a Cat 4 LBT scheme with random backoff and variable contention window sizes would enable fair channel access and good coexistence with WiFi and other LAA networks. The key parameters of such a scheme would be discussed in detail as part of the ongoing Work Item (WI). For UL, it was recommended to support an Uplink (UL) LBT scheme which is different from the DL LBT as the UL access is scheduled and controlled by the eNB.

The two main deployment options that were being considered under the carrier aggregation framework are:

- 1) Indoor Deployments
- 2) Outdoor Deployment

2.2.1 INDOOR DEPLOYMENTS

The indoor deployment is based on a primary component carrier in the licensed band, with LTE in the unlicensed band as the secondary component carrier. While the primary component carrier remains the operator licensed channel, LTE could operate in UNII-1, UNII-2A, UNII-2C or UNII-3 set of channels 17

decibel-milliwatts (dBm) subject to mandatory Dynamic Frequency Selection (DFS) to detect incumbent radar operation and Transmit Power Control (TPC) to protect the Earth Exploration-Satellite services. Since LTE carrier aggregation protocols are used for the small cell operation, seamless interworking and mobility is guaranteed, even if the licensed and unlicensed cell footprints are not similar. The initial attach, authentication and security are performed on the primary carrier, with LTE in the unlicensed spectrum used only for data offloading. All other time/jitter sensitive applications such as Voice over LTE (VoLTE) can be supported on the licensed primary channel that has a more predictable availability and Quality of Service (QoS). The indoor small cell can operate in a dedicated licensed channel (Scenario 4) or in a Heterogeneous Network (HetNet) mode with a common licensed channel (Scenario 3) shared with the macro cell, while the LTE in unlicensed component is used only for offloading data traffic to LTE users nearby or in indoor hotspots. Indoor small cells can be connected directly or most likely through a gateway to the core network.

2.2.2 OUTDOOR DEPLOYMENTS

An LTE Evolved NodeB (eNB or eNodeB) can be augmented to support operating LTE in unlicensed spectrum for outdoor small cell deployments. While the primary component carrier remains the operator licensed channel, LTE in unlicensed spectrum could operate in Unlicensed National Information Infrastructure (UNII)-1 or UNII-3 set of channels that allows a maximum Transmit (Tx) power of 30 dBm, with an additional 6 decibels-isotropic (dBi) antenna gain. Since LTE carrier aggregation protocols are used for the small cell operation, seamless interworking and mobility is guaranteed, even if the licensed and unlicensed cell footprints are not similar. The initial discovery, authentication and security are performed on the primary carrier, with LTE in the unlicensed spectrum used only for data offloading. All other time/jitter sensitive applications such as VoLTE can still be supported on the licensed channel which has a predictable availability and QoS. The Macro and Outdoor Pico cells can operate in separate dedicated licensed channels (Scenario 4) or in a HetNet mode (Scenario 3) with a common licensed channel, while LTE in unlicensed is only used by Pico cells for offloading nearby users or users in a hotspot. LTE in unlicensed enabled Pico cells is connected to the core network directly without the need for any additional network elements.

A key design goal, as defined in the 3GPP Study Item for LAA, was that considering different fair sharing metrics, LAA should not impact Wi-Fi services (data, video and voice services) more than an additional WiFi network on the same carrier; these metrics could include throughput, latency, jitter, etc. 3GPP has identified that in order to comply with region specific regulations mandating LBT in unlicensed frequency bands and ensure fair coexistence of LAA with incumbent co-channel WiFi deployments, an LAA eNB should perform LBT prior to DL/UL transmission over an unlicensed SCell.

To enable a single global solution deployable in all regions and effective coexistence with WiFi and LAA deployments, the SI recommended that LAA will use a variable backoff-based contention window adaptation scheme to access the channel. In the WI phase, several schemes which vary the size the contention window dynamically based on either: (1) Acknowledgement/Negative Acknowledgement (ACK/NACK) reported by the UEs or (2) eNB sensing outcomes have been considered. The exact mechanism to trigger the contention window update is still under discussion and is expected to be finalized soon.

In addition, adapting the Energy Detection Threshold (EDT) for sensing whether the medium is idle or busy has been considered a key variable to ensure effective coexistence with WiFi and performance of LAA networks. 3GPP RAN1 has identified several criteria for adapting the EDT and some detailed rules for triggering such an adaptation are expected to be discussed soon. Finally, there is an ongoing

discussion in 3GPP on how to test whether eNBs are following the expected channel access mechanism and correctly varying the window size and EDT.

Considering the likelihood of discontinuous transmission due to LBT, there has been intent to enable as flexibly as possible resource partitioning between UL and DL traffic. Due to the LBT requirement for both UL and DL LAA operation, there is strong consensus in 3GPP that the existing LTE Time Division Duplex (TDD) UL/DL configurations cannot be utilized in LTE Unlicensed operation as such. Therefore, some new definitions or at least understanding will be needed on the interpretation of UL and DL sub-frames; however, the related discussions in 3GPP are still ongoing.

In the Rel-13 time-frame, only downlink LAA operation will be specified, while studies on LAA uplink in 3GPP would be restricted only to identify (not specify) the principles of channel access for forward compatibility during a later release. Due to discontinuous transmission from LBT in both DL and UL directions, synchronous UL HARQ process retransmission (as in licensed carrier LTE operation) may not be guaranteed. Therefore, 3GPP has proposed to base the UL operation of LTE LAA on asynchronous HARQ (similar as current LTE DL HARQ operation) which may require additional information on HARQ information to be transmitted as part of the UL scheduling grant. All the LAA Physical Uplink Shared Channel (PUSCH) retransmissions will likely be adaptive (i.e., scheduled by separate grants). This also potentially renders usage of the Physical HARQ Indicator Channel (PHICH) to be unnecessary.

The European Telecommunications Standards Institute (ETSI) requires a transmission of a node to occupy at least 80 percent of the nominal bandwidth and that requirement also applies to LTE LAA UL operation. As a single global solution for LAA is envisioned, there is a need to guarantee that the PUSCH waveform should be in compliance with the ETSI channel occupancy requirement. The 3GPP LAA Study Item has identified that for the PUSCH, extending the current single and dual cluster allocation to allow multi-cluster (>2) allocation has been identified as a candidate waveform that satisfies ETSI regulatory requirements and maximizes uplink coverage.

As the amount of unlicensed spectrum aggregated with licensed spectrum increases, there is an increasing need to offload UL control channels to the unlicensed spectrum as well. For example, supporting Physical Uplink Control Channel (PUCCH) operation in the UL might enable significantly more spectrum to be aggregated without increasing the burden on the licensed carriers. In addition, supporting control channel signaling on the unlicensed spectrum provides an opportunity to use the dual-connectivity framework in the future instead of the carrier aggregation framework to ensure that unlicensed spectrum can be integrated into the core network using more flexible deployment models which address several diverse business cases.

3 DATA OFFLOADING WITH LTE-WLAN AGGREGATION

The main use case is WLAN deployments either by a mobile network operator and/or its partners. It is possible to deploy LTE-WLAN Aggregation for enterprise and residential networks; however, 3GPP will not define specific solutions for these use cases.

3.1 ARCHITECTURAL ASPECTS

The user plane architecture aggregation builds upon the 3GPP Rel-12 Dual Connectivity (DC) split-bearer which is illustrated in Figure 3.1 below (taken from 3GPP Technical Report (TR) 36.842):

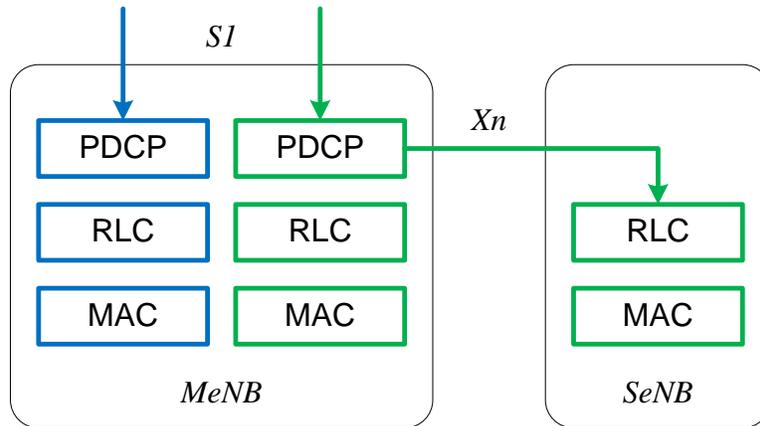


Figure 3.1. Dual connectivity split-bearer architecture.

In the aggregation architecture, WLAN AP will be similar to the Secondary eNB (SeNB) in the user plane. A new interface between eNB and WLAN, called Xw, is defined whose functionality is similar to Xn in the figure for DC but also includes some functionality tailored for the Rel-13 WLAN interworking. (Xn has been standardized as part of X2). The termination point of Xw at WLAN is a logical node, called WT (WLAN Termination), and it can be implemented at an Access Point, Access Controller, or another physical entity.

There are several differences of aggregation from the DC split-bearer architecture:

- The control plane is only at the eNB and not shared with WLAN; therefore, the functionality supported for SeNB RRC is not needed
- Radio Link Control (RLC) is not supported at WLAN and thus PDCP Packet Data Units (PDUs) are delivered by WLAN MAC
- An adaptation layer to deliver PDCP PDUs over WLAN is needed (as discussed in Section 3.2)

Since the eNB is the anchor point for both the user and control plane, aggregation is only feasible when the UE is in LTE coverage and a connected state with LTE eNB. The UE can also use other WLAN offloading schemes defined prior to Rel-13 which do not require LTE connection; however, it is preferable to enable aggregation when available since it provides better performance than other schemes as shown in Section 3.3.

3GPP WLAN offloading solutions always allow the user preferences to have higher priority over standardized mechanisms offered by the network. The same principle continues also on aggregation. When a user, for example, wants to connect to a home WLAN network, aggregation data flow can stop and has to be communicated by the UE to the network.

Figure 3.2 shows the network architecture for aggregation. An important element of aggregation is that it does not require any new CN nodes, interfaces and signaling. In Figure 3.2, the connection of WLAN to the CN is shown to illustrate the fact that the same WLAN network can be used to provide offloading services using such connections (which were standardized by 3GPP before Rel-13).

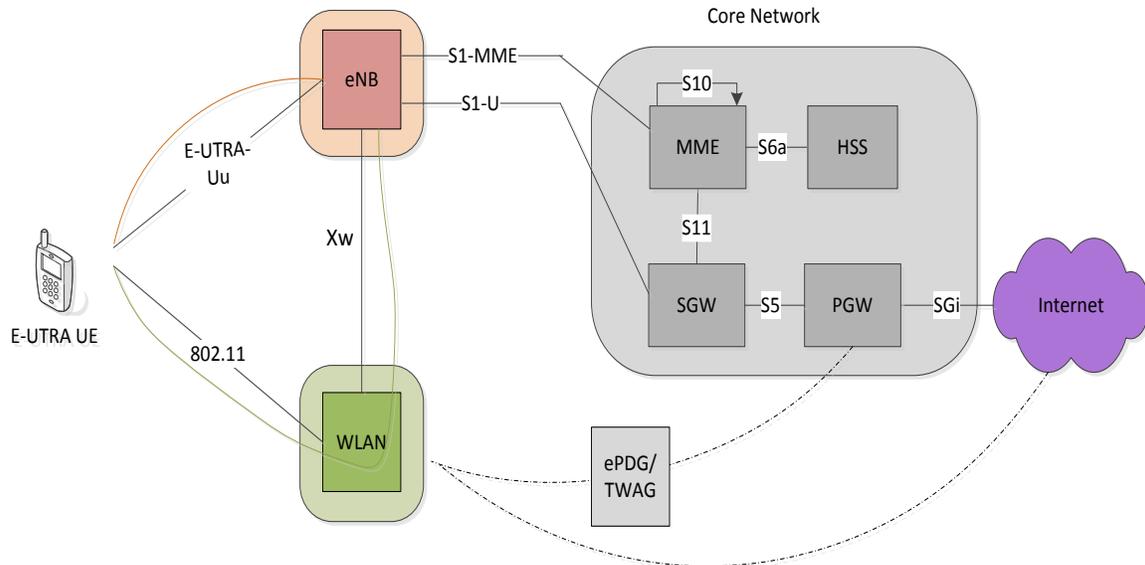


Figure 3.2. Network architecture for LTE/WLAN aggregation.

3.2 USER AND CONTROL PLANE

As described in Section 3.1, the data plane aggregation for LTE and WLAN happens at the PDCP layer located at the eNB and UE. On the downlink, the eNB scheduler decides to send a PDCP PDU on either LTE or WiFi. On the uplink, eNB schedules data transmissions for LTE link per current LTE MAC specifications while the transmissions on WLAN are initiated by the WiFi Station (STA) part of the UE. This can still allow the flexibility for eNB to have control on the total uplink transmissions.

A PDCP PDU transmitted on LTE for either downlink or uplink goes through the same LTE procedures without any modifications to the LTE PHY/MAC/RLC layers. On the WLAN side, the PDCP PDU is encapsulated in a WiFi MAC packet by the AP or STA to be transmitted over WiFi. For downlink, STA will forward the received WiFi packet payload to the UE PDCP layer. For the STA to easily determine that the WiFi packet contains a PDCP PDU, a new identifier will be specified by 3GPP.

LWA will support having multiple bearers per UE to be served over WLAN. For the receiver PDCP layer to determine the correct logical channel a PDCP PDU belongs to, a header containing the logical channel (bearer) information should be attached to the PDCP PDU before transmitting over WiFi. This header will be inserted by the eNB on downlink and UE on uplink and transparent to the WLAN.

Since PDCP PDUs can be transmitted on both LTE and WiFi, they may arrive at different times at the receiver. Therefore, a reordering mechanism is needed in order to deliver the PDCP SDUs to the upper layers. In Rel-12 Dual Connectivity, such mechanism was adopted for the split-bearer option. The same mechanism will also be used for LWA.

When eNB and WLAN are not collocated, the PDCP PDU has to be forwarded between the eNB and WT. A standardized data interface similar to Dual Connectivity MeNB and SeNB interface for data forwarding is also defined between eNB and WLAN Termination (WT). The transport protocol for this interface is General Packet Radio Service Tunneling Protocol (GTP) tunneling over UDP/IP where the data for each bearer is exchanged in a different GTP tunnel. Flow control mechanisms from eNB to WT are also

implemented to minimize buffer underflow and overflow at WLAN side to improve the performance. In addition, the eNB can use UE feedback in controlling the amount of traffic forwarded to WLAN. If LTE/WLAN aggregation is enabled on the uplink, a similar flow control from WT to eNB side may also be useful to prevent buffer overflow at the eNB.

In LTE, the eNB uses UE feedback such as Channel Quality Indication (CQI) and other RRM functionality in deciding which cells to use and how to schedule data packets. A similar functionality is also needed for LWA for the eNB to decide the amount of traffic to forward to WLAN. To this end, feedback for WLAN channel conditions (e.g., signal strength, loading) can be used. The eNB can configure the UE to report such statistics but may also receive them from WT via the Xw interface. Other WLAN statistics such as backhaul conditions and hardware load can also be similarly received at least via the Xw.

The main functionality of the control plane for LWA is the selection of WLAN to configure or de-configure aggregation for data bearers. The signaling between eNB and UE for this is done by Radio Resource Control (RRC) procedures carried on the Signaling Radio Bearers (SRBs). The eNB also communicates with WT for the addition, removal and change of the WT.

The main steps for initial configuration of LWA are: 1) determining UE and network capability for LWA, 2) selection of WLAN AP for aggregation and 3) configuration of aggregation for specific data bearers. These steps can be repeated as needed due to UE mobility and/or changing radio and load conditions.

Since the network should be aware of the UE capability in supporting LWA before initiating any of the procedures, the first step of the eNB-UE signaling for LWA will be the UE reporting such capability (e.g., via conventional RRC messages such as *UECapabilityEnquiry* and *UECapabilityInformation* exchanged during normal UE capability reporting procedure (e.g., during initial attach). The UE can also include WLAN related information such as its MAC address and supported WLAN bands and channels; the MAC address can be used on the eNB-WLAN interface for UE identification in enabling data transfer and exchanging control information.

The second step is WLAN selection to determine a suitable AP which supports aggregation and the radio and channel conditions. In current WLAN implementations, finding WLAN networks (scanning and association) are done by the STA. For LWA, eNB will also be part of this decision by indicating which APs should be targets for scanning so that UE doesn't need to report APs that are not capable for LWA. In many WLAN deployments, using 3GPP-like mobility based on UE measurement and eNB triggers is not optimal for all WLAN mobility. This is especially true when the UE moves between APs controlled by the same AC where current WLAN deployments include many mobility optimizations. In such scenarios, controlling every AP change of the UE by eNB will require signaling exchange between eNB and UE for measurement reporting and eNB actions. This will cause significant overhead and delay and can result in early or late handovers between APs considering the fact that coverage area of single AP is relatively small. For these reasons, 3GPP adopted a UE-based mobility scheme wherein a "WLAN mobility set" is a group of APs (identified via WLAN identifiers) determined by the eNB. The eNB signals to the UE such mobility set where UE is allowed to switch APs without informing the eNB. It is also assumed that all the APs within the mobility set are controlled by the same WT. For APs outside the mobility set or for APs within different WTs, the decision to change AP is made by the eNB based on e.g., UE measurements.

The information of UE moving to another AP can be provided to eNB by either UE or WT. Such information may not always be necessary, e.g., for mobility within the mobility set or when the WT does not change, but in other cases the information is needed for the eNB to direct the backhaul (Xw) data and control plane towards the correct WT. For example, mobility between two WTs requires signaling exchange between eNB and the source and target WT similar to dual connectivity SeNB change.

3.3 PERFORMANCE EVALUATION

LWA can help improve user quality of service and overall system capacity, through efficient management of radio resources across both links. A simulation analysis based on 3GPP HetNet methodology and modeling of WLAN contention based access is used to illustrate these benefits. Accordingly, we evaluate system performance gains in terms of layer 2 throughput enhancements. Additionally, TCP layer performance for a “representative user” is also evaluated to benchmark the impact of reordering delays and protocol overhead on the overall gain from aggregation.

3.3.1 SIMULATION METHODOLOGY AND ASSUMPTIONS

System level simulations to characterize layer 2 throughput enhancements are based on 3GPP methodology as captured in 3GPP TR 36.814, 36.819 and 36.842. The methodology is extended to include the 802.11n interface and the contention based MAC protocol. Application layer performance is modeled assuming the best effort File Transfer Protocol (FTP) traffic model. We focus on the downlink performance to be consistent with Rel-13 LWA priorities.

TCP performance characterization is based on the modeling of full LTE and WLAN protocol stacks. The simulations track the performance of a representative user, whose link throughput is obtained from the system simulation analysis.

Detailed simulation assumptions are described in the Appendix.

3.3.2 DEPLOYMENT SCENARIOS

We focus on outdoor, multi-tier heterogeneous deployments, wherein a 3-sectored LTE macro cell tier is overlaid with a tier of small cells according to the following configurations:

1. *Collocated Deployments* are based on deployments of integrated WLAN-LTE small cells, supporting collocated eNB and WLAN AP as described in Figure 2.2. Small cell LTE operates on the same frequency as the macro-cell.
2. *Non Collocated Deployments* comprise a tier of WLAN only small cells connected to the eNB over a non-ideal backhaul.

3.3.3 WLAN OFFLOADING AND LWA SOLUTIONS COMPARED

We compare the following solutions in our evaluation:

- **WLAN Preferred:** Conventional “WLAN preferred if in coverage” scheme, implemented by most current devices. Here, a device always connects to a WLAN AP if a minimum UE-specific signal quality threshold is satisfied.
- **Radio Interworking:** Rel-12 RAN-assisted WLAN interworking with optimum thresholds or Rel-13 radio interworking enhancements with measurement reporting. This scheme may be considered reflective of radio interworking schemes that do not employ aggregation with bearer split.
- **Rel-13 LWA (with bearer split):** Two variations are considered. The first is suitable for collocated WLAN and LTE small cells.

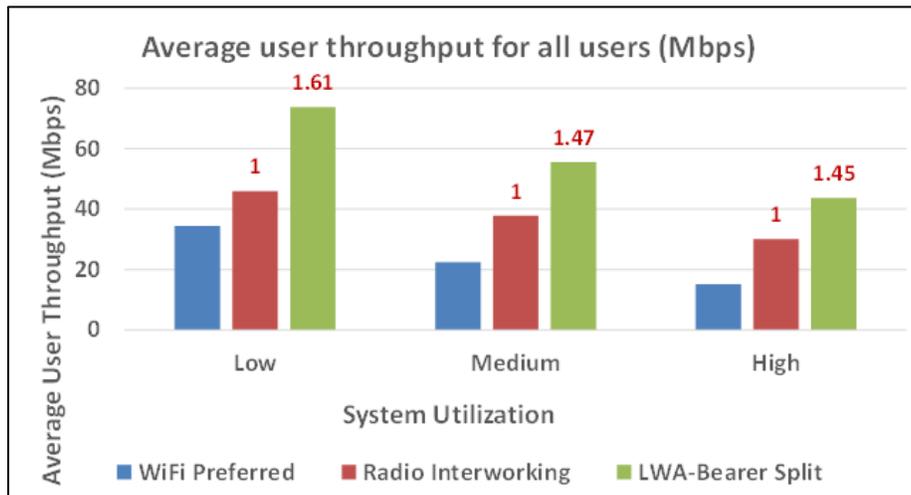
- *Joint Queue/Scheduling* is based on packet level scheduling across LTE and WLAN. The solution assumes a shared transmission queue across independent but cooperative WLAN and LTE schedulers, which are capable of exchanging per bearer throughput history periodically.
- *Multi-user Bearer Splitting (MUS)* is designed to also work with non-collocated deployments with non-ideal backhaul delays. The eNB employs a splitting algorithm based on minimizing the logarithm of sum throughput across all users configured for aggregation. Here, the WLAN/LTE schedulers use independent transmission queues but still cooperate to exchange per bearer throughput history information.

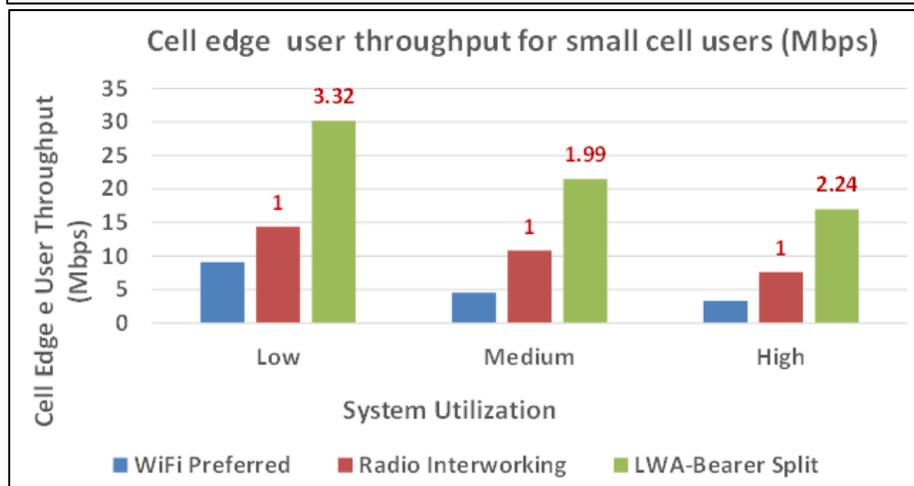
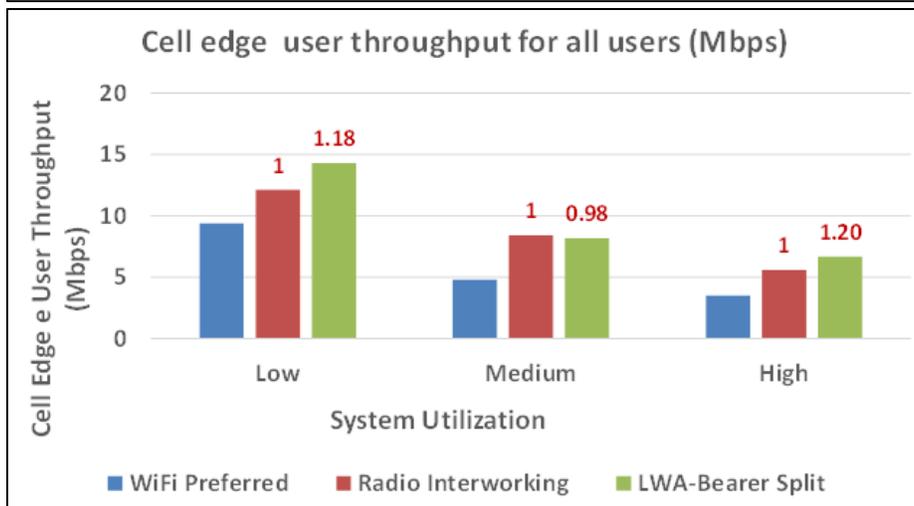
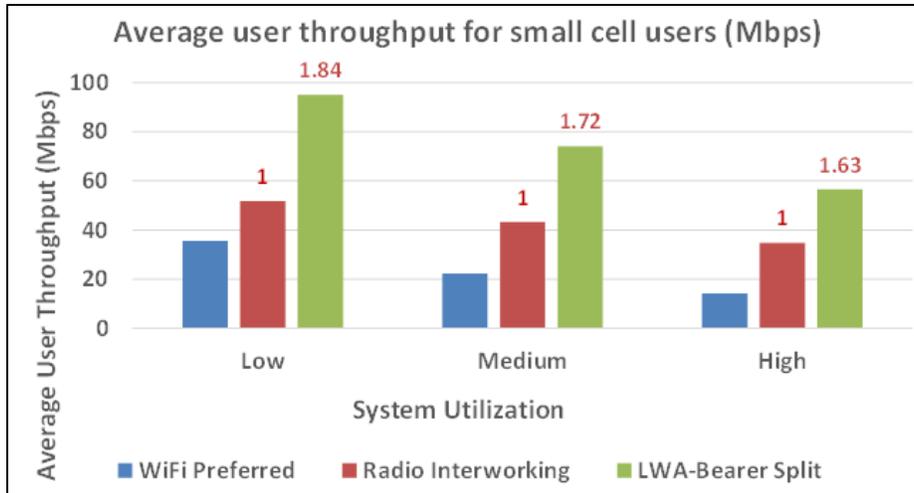
3.3.4 METRICS FOR OPTIMIZATION

User perceived throughput enhancements are used to characterize layer 2 system performance gains. TCP throughput gains are also considered to characterize the application layer performance for a representative user.

3.3.5 SYSTEM PERFORMANCE RESULTS

Figures 3.3 are illustrative of LWA gains for collocated small cell deployments. The LWA bearer split algorithm is based on the joint queue/scheduling algorithm. Results are reported for all users as well as the users that are associated with the small cell. As the macro cell users do not perform aggregation, the performance across users associated with the small cell is of interest. It can be seen that LWA improves the average as well as the cell edge user perceived throughput across all small cell users in the system when compared to the Rel-12/Rel-13 radio interworking scheme. When considering medium system load, LWA gains in average user throughput of up to 70 percent are observed. The cell edge gains for small cell users, which exploits aggregation, also increases substantially.

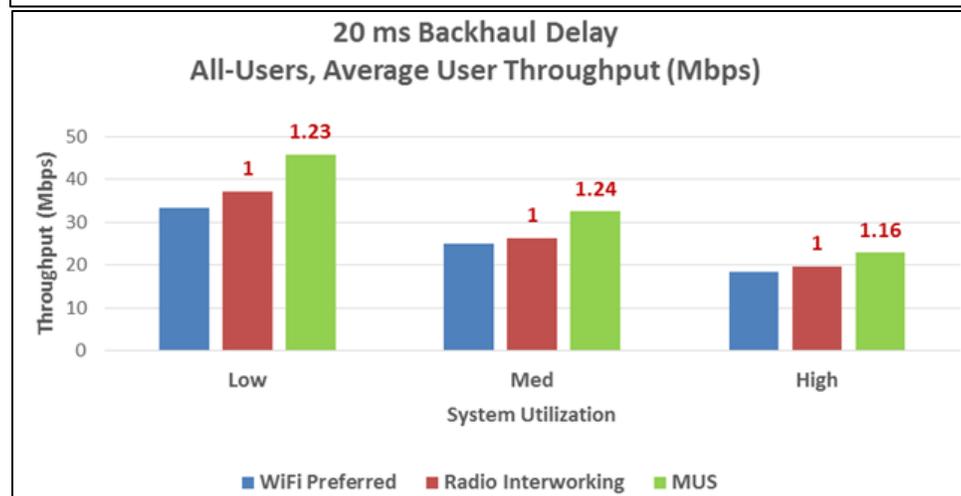
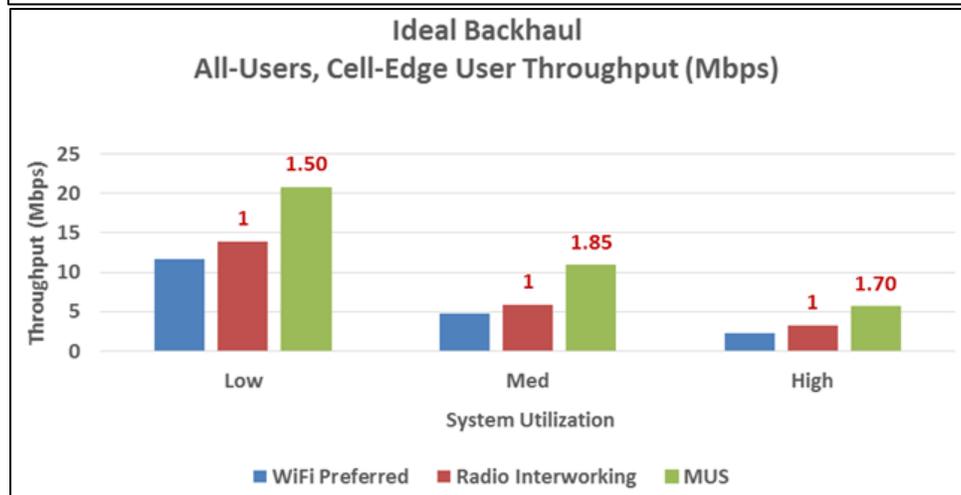
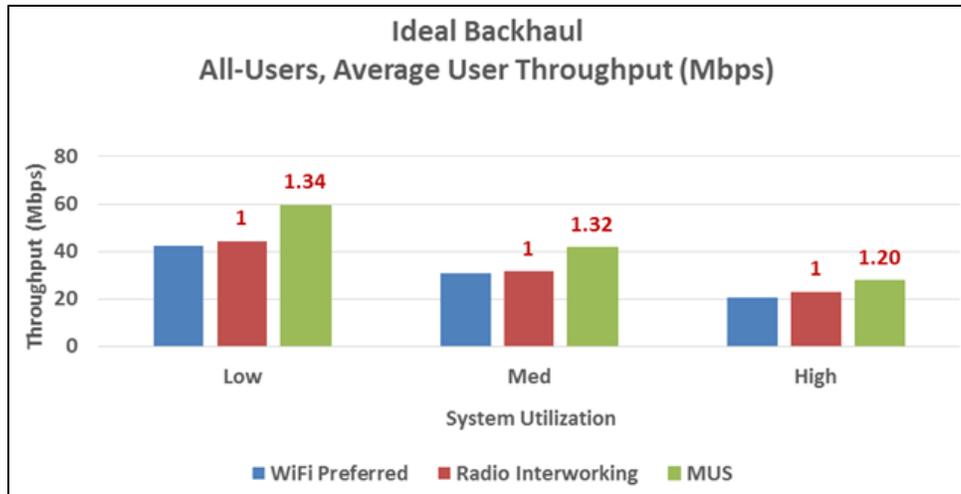


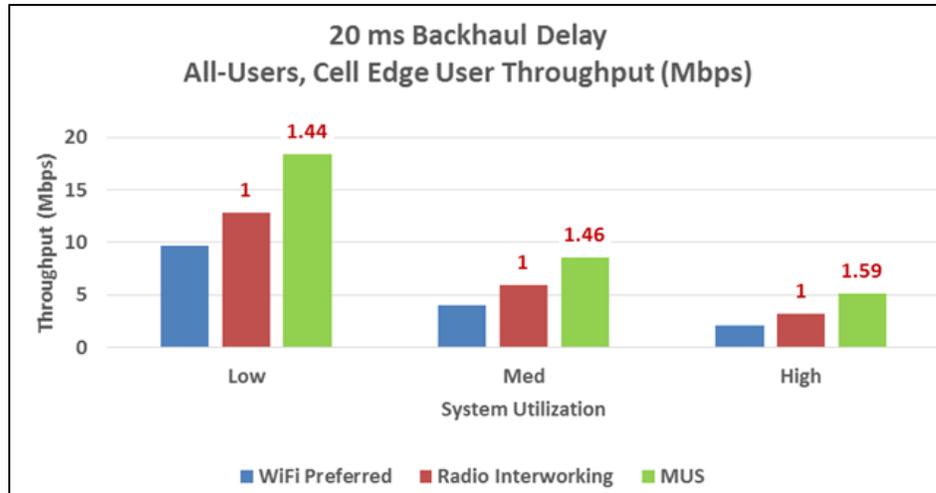


Figures 3.3. LWA performance gains for collocated Het-Net deployments with same licensed carrier being used across macro and small cell tiers. No interference coordination is assumed. 1 AP/9 UEs per macro cell sector are considered. System utilization of Low, Med and High correspond to 20-25%, 40-50% and 60-70% utilization levels, respectively.

Figures 3.4 illustrate the LWA performance gains for non-collocated deployments (macro cell and WiFi only small cell) with ideal and 20 millisecond backhaul delay. The LWA bearer split scheme is based on

the MUS algorithm. Considering the scenario with ideal backhaul, it can be seen that LWA based on MUS algorithm outperforms radio interworking solution, with average and cell edge gains across all users of 30 percent and 85 percent, respectively, at medium utilization level. LWA MUS gains are still available (especially for cell-edge users) even when considering non-ideal backhaul with a 20 millisecond delay, with gains of 24 percent and 45 percent in average user throughput across all users in the system.





Figures 3.4. LWA performance gains for non-collocated Het-Net deployments, comparing average and cell-edge performance results across all users with ideal backhaul delay (0ms) with a non ideal delay scenario of 20 millisecond. Five WLAN APs per macro cell sector are considered. System utilization of Low, Med and High correspond to 20-25%, 40-50% and 60-70% utilization levels, respectively.

3.3.6 TCP PERFORMANCE RESULTS

Table 1 shows LWA performance gains considering TCP throughput. TCP performance is simulated using WLAN and LTE link throughput experienced by representative median and cell edge users to illustrate the characteristic of LWA and radio interworking performance. The scenario shown, corresponds to a non-collocated case with ideal backhaul at low system utilization levels. A simpler algorithm based on per user buffer equalization is used for LWA. TCP performance characterization focuses on whether layer 2 performance gains translate to corresponding gains in TCP throughput, as protocol overhead as well as the impact of reordering delays must be considered for overall application layer TCP performance. Results show that while TCP throughput is reduced to some extent due to the overhead considered, LWA layer 2 gains still translate to gains in overall TCP throughput.

Table 1. LWA TCP performance gains compared to layer 2 throughput gains over radio interworking solution for representative users.

User Perceived Throughput (in Mbps)		SLS: Non-Collocated with Ideal Backhaul	TCP: Non-Collocated with Ideal Backhaul	TCP: Non-Collocated with Backhaul Delay 20ms
Cell Edge User (10th percentile*)	Radio Interworking (Rel-12)	15	13.3	13
	R13 LWA Throughput	26 (1.73x)	22.9 (1.72x)	22.6 (1.74x)
Median User	Radio Interworking (Rel-12)	43	38.4	37.4
	R13 LWA Throughput	59 (1.37x)	46.8 (1.22x)	46.6 (1.25x)

3.3.7 DISCUSSION OF RESULTS

The results shown in this section are illustrative of substantial performance benefits for Rel-13 LWA solutions with bearer split. The results show up to 70 percent system gains in average user throughput for users associated with a collocated WiFi/LTE cell at medium load. The cell edge user experience substantially improved throughput (about 2x gains at medium load levels).

LWA with bearer split also performs well for non-collocated deployments with non-ideal backhaul delays. Our results show an average/cell-edge gains of more than 30 percent and 80 percent, respectively, with LWA multi-user splitting algorithm at medium load. Results also show that LWA gains are preserved for reasonable backhaul delays.

Although not covered here, it can also be shown that gains in user throughput also results in system capacity improvements, in that LWA can support higher number of users for the same target user quality of service when compared to the WLAN/3GPP interworking solution.

We also investigated LWA TCP performance for a representative user accounting for TCP overhead and reordering delays which showed that layer 2 gains translates to TCP layer gains.

3.4 INTERWORKING WITH PREVIOUS OFFLOADING SOLUTIONS

LWA solutions can be deployed by an operator along with its already existing WLAN networks that use a different offloading scheme (e.g., Evolved Packet Data Gateway (ePDG) based). In this case, it is necessary to specify how a UE operates when it has access to both options. Such scenarios can also happen while the user is roaming, for example, in an LWA network while it was configured by home operator Access Network Discovery and Selection Function (ANDSF) policies. 3GPP has not specified solutions to address these coexistence problems. It is envisioned that LWA should have higher priority by default since the UE has to follow LWA traffic steering commands just like any LTE configuration by the network. However, it is possible that the prioritization can be left to the operator choice which can provide the priority list to the user; in this case for example, the network can assign higher priority to a non-LWA WLAN network for certain users depending on their subscription levels.

4 LTE IN UNLICENSED SPECTRUM

4.1 DATA OFFLOADING FOR OPERATORS

4.1.1 OVERVIEW

An alternative technique to WLAN offloading was recently introduced to use LTE-Advanced (LTE-A) in the same unlicensed bands that WiFi traditionally occupied, sharing the spectrum alongside WiFi. Deploying LTE-A in unlicensed bands instead of utilizing WiFi offloading offered a more seamless and spectrally efficient method of offloading data. Deploying both LTE-A and Wi-Fi in the same band presents coexistence issues that are currently under study in 3GPP RAN. Results to date indicate that the two technologies can coexist, thus allowing mobile operators the option to use both LTE-A and WiFi to offload data.

LTE-A can operate in the unlicensed bands in the following configurations:

1. Supplemental Downlink (SDL)
2. Carrier Aggregation (CA)
3. Dual Connectivity (DC)

4.1.1.1 SUPPLEMENTAL DOWNLINK (SDL)

Most of the data demand increase has been in the DL, driving operators to utilize additional download capacity that includes use of unlicensed bands, including both LTE-A (LAA, LTE-U) and WiFi, to offload data traffic in order to supplement DL data capacity. SDL offers the DL capacity for utilization of download-intensive services such as video/music streaming and web browsing. SDL is typically used to refer to an unpaired spectrum band used to supplement download traffic.

4.1.1.2 CARRIER AGGREGATION (CA)

Due in part to the opportunistic nature of unlicensed spectrum, it is not as suitable for control channels, so the initial use of LTE in unlicensed spectrum is as a secondary channel in a carrier aggregation scheme. This allows better management of data traffic between the licensed LTE carrier and an LAA carrier. 3GPP is currently studying coexistence and specification issues for use of unlicensed carriers in LTE CA combinations. CA using unlicensed carriers will allow the offload to be seamless and also accommodate load-balancing between licensed carriers and unlicensed carriers. The current LAA work in 3GPP allows unlicensed carriers to be limited to SCell, or secondary carriers. In addition to LAA, a newly-approved 3GPP work item for CA between LTE and Wi-Fi is also in progress. This will allow tighter integration between LTE and WiFi and give LTE carriers the option to do CA with both LAA and WiFi. The study item for LAA coexistence was completed in June 2015. A work item to incorporate the SI findings into the 3GPP specs was approved in June 2015, with work scheduled for completion as part of Rel-13.

4.1.1.3 DUAL CONNECTIVITY (DC)

Dual Connectivity is a relatively new LTE architecture developed by 3GPP RAN to allow a UE to connect to two distinct eNBs simultaneously, allowing a UE in a HetNet scenario to be simultaneously connected to both the macro eNB and small cell eNB. This architecture allows aggregation of user-plane radio resources to improve UE throughput. In a DC scheme, one eNB, a macro-cell, is defined as the Master eNB, the other, a small cell, is defined as Secondary eNB. The two eNBs are connected via non-ideal backhaul.

4.2 COEXISTENCE WITH WLAN IN ADJACENT CHANNELS

3GPP RAN4 considered adjacent channel coexistence studies between LAA and WLAN. Companies provided results from adjacent channel coexistence studies using scenarios and methodology for evaluating adjacent channel coexistence between different networks in the unlicensed band.

The following scenarios for adjacent channel coexistence were taken into account:

- Indoor scenario
- Outdoor scenario

The coexistence cases for adjacent channel evaluations that have been studied are as follows:

- WLAN to WLAN, which could be the baseline to evaluate case of LAA to WLAN
- WLAN to LAA
- LAA to WLAN

Based on the simulation results provided for 3GPP RAN4, it was concluded that LAA and WLAN can coexist in adjacent channels. According to simulation results, LAA causes less adjacent channel interference to a WLAN system compared to another WLAN system. In other words, LAA is a better neighbor than another WLAN system in terms of adjacent channel coexistence with WLAN system.

4.3 PERFORMANCE EVALUATION FOR CO-CHANNEL LAA AND WIFI

The key focus of the LAA SI in 3GPP was to determine if an LAA network could coexist with a WiFi network and other LAA networks. Extensive evaluations on several DL and UL schemes using various LBT categories were carried out as part of the study.⁴ The following observations have been made in the LAA SI technical report. For a LAA network carrying only DL traffic, it was noted that “a majority of sources that evaluated an LAA network operating a category 4 DL LBT scheme based on ETSI Option B with modifications including at least defer periods and variable (exponential) contention windows showed that it can operate without impacting WiFi more than an equivalent WiFi network”. For networks carrying both DL and UL traffic, it was similarly noted that “a majority of sources showed combinations of LAA DL and UL LBT schemes that do not impact WiFi more than another WiFi network (offering the same traffic to the same users) in any of the measured performance metrics. Category 3 and 4 were tested for the DL and Categories 1 through 4 were tested for the UL. Within each LBT category, the LBT schemes and/or parameters shown by different sources to not impact WiFi more than another WiFi network may be different.” The conclusions in the Technical Report (TR) clearly demonstrate that LAA network supporting both DL and UL traffic can coexist well with a WiFi network.

5 CONCLUSION

Both LTE/WiFi aggregation and LTE in unlicensed spectrum provides distinct advantages for data offloading to alleviate the data capacity constraints in licensed LTE deployments. LWA can be leveraged using the existing WiFi networks while providing better performance and control compared to other WLAN offloading mechanisms. LTE in unlicensed spectrum can provide seamless and efficient offloading by using the same core radio technology across both licensed and unlicensed spectrum. Both LWA and LAA allow mobile operators effective mechanisms in using unlicensed spectrum to satisfy the increasing data demands. The choice among LWA and LAA will depend on many factors, including an operator’s existing infrastructure, technology road map and capital expenditure plans. However, it is expected that it will be an option for consideration by operators worldwide.

⁴ “Feasibility Study on Licensed-Assisted Access to Unlicensed Spectrum”, 36.889.

APPENDIX: LWA PERFORMANCE EVALUATION - SIMULATION DETAILS

Table A1. LTE simulation assumptions for system level results.

LTE	
Topology	7 cell wrap-around (Het-Net deployment w/ collocated WiFi-LTE small cells and WiFi-only small cells. Small cell LTE interface uses same carrier as macro-cell. No ICIC is assumed.
Cell Association	Network controlled cell-association based on optimizing WLAN QoS and RSRQ Thresholds for each deployment
UE dropping	Clustered
LTE Carrier Frequency	2 GHz
Channel/UE speed	[IMT] UMa Macro, UMi Pico, UE speed= 3 km/hr
LTE mode	Downlink FDD; 20 MHz for DL
No. antennas (macro, pico, UE)	(2, 2, 2)
Antenna configuration	macro, small cell: co-polarized, UE: co-polarized (-->)
Max rank per UE	2 (SU-MIMO)
UE channel estimation	Ideal
Feedback/control channel errors	No Error
PHY Abstraction	Mutual Information
Scheduler	Proportional-Fair Scheduler
Scheduling granularity	5 PRBs
Traffic load	Non full buffer with 3GPP FTP traffic model 3. Arrival rate, file sizes and number of users are varied to generate Low = 20-25%, Med= 35-50% and High= 60-70% load levels.

LTE	
Receiver type	Interference unaware MMSE
Feedback periodicity	10ms
CQI & PMI feedback granularity in frequency	5 PRBs
PMI feedback	3GPP Rel.-10 LTE codebook (per sub-band)
Outer loop for target FER control	10% PER for 1 st transmission
Link adaptation	MCSs based on LTE transport Format
HARQ scheme	CC (Chase Combining)

Table A2. WiFi simulation assumptions for system level results.

WiFi	
WiFi Parameters	802.11n
WiFi Frequency, Channelization	2.4 GHz band, 3 frequency bands, 20 MHz channels; least power based channel selection
AP Transmit power	20dBm outdoor, 18 dBm indoor
WiFi mode	Downlink only.
Scheduler	Proportional Fair and Round Robin
TX-OP	1ms
PHY Abstraction	RBIR
MPDU Size	1500 Bytes

Assumptions for TCP Results

- Full LTE and WLAN protocol stack emulation via OPNET
- 20MHz WiFi 802.11n
- Considers performance of a “representative user” from system level results (link throughput from SLS)
- Below PDCP layer bearer split modeled, with the following parameter settings:
 - Buffer equalization algorithm
 - PDCP flow control modeled
 - PDCP RX reordering time: 500ms
 - PDCP Discard Timer: 1s
 - Results computed across multiple FTP sessions of 50MB DL

ACRONYM LIST

3GPP	3rd Generation Partnership Project	HetNet	Heterogeneous Network
AC	Access Controller	IP	Internet Protocol
ACK/NACK	Acknowledgement/Negative Acknowledgement	LAA	License Assisted Access
ANDSF	Access Network Discovery and Selection Function	LBT	Listen-Before-Talk
AP	Access Point	LTE-A	LTE-Advanced
CA	Carrier Aggregation	LTE-U	LTE Unlicensed
CN	Core Network	LWA	LTE-WLAN Aggregation
CQI	Channel Quality Indications	MAC	Media Access Control
CSI	Channel State Information	MP-TCP	Multipath Transmission Control Protocol
dBi	decibels-isotropic	ms	millisecond
dBm	decibel-milliwatt	PDCP	Packet Data Convergence Protocol
DC	Dual Connectivity	PDU	Packet Data Unit
DFS	Dynamic Frequency Selection	PHICH	Physical HARQ Indicator Channel
DL	Downlink	PHY	Physical Layer
DRS	Discovery Reference Signals	PUCCH	Physical Uplink Control Channel
EDT	Energy Detection Threshold	PUSCH	Physical Uplink Shared Channel
eNB/eNodeB	Evolved NodeB	QoS	Quality of Service
EPC	Evolved Packet Core	QUIC	Quick User Datagram Protocol Internet Connections
ePDG	Evolved Packet Data Gateway	RAN	Radio Access Network
ETSI	European Telecommunications Standards Institute	Rel	Release
E-UTRAN	UMTS Terrestrial Radio Access Network	RLC	Radio Link Control
FTP	File Transfer Protocol	RRC	Radio Resource Control
GTP	General Packet Radio Service Tunneling Protocol	RRM	Radio Resource Management
HARQ	Hybrid Automatic Retransmission Request	SDL	Supplemental Downlink
		SeNB	Secondary eNB

SI	Study Item	UL	Uplink
SRB	Signaling Radio Bearers	UMTS	Universal Mobile Telecommunications System
STA	WiFi Station	UNII	Unlicensed National Information Infrastructure
TDD	Time Division Duplex	VoLTE	Voice over LTE
TPC	Transmit Power Control	WI	Work Item
TR	Technical Report	WLAN	Wireless Local Area Network
Tx	Transmit	WT	WLAN Termination
UE	User Equipment		

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