WHITE PAPER

Alternative LTE Solutions in Unlicensed Spectrum: Overview of LWA, LTE-LAA and Beyond

Abstract

LTE technologies for unlicensed spectrum are gaining both attention and momentum within various regulatory bodies (European CEPT, US FCC), standards groups (3GPP, ETSI) and industry fora (Wi-Fi Alliance, MulteFire Alliance, Wireless Innovation Forum, CTIA, and GSMA). It is a major area of discussion among the wireless community of operators, OEMs, infrastructure vendors, chipset vendors and operators. It is expected to be a key tool that will enable requisite data capacity required for burgeoning new mobile applications. This white paper provides a detailed and comparative overview of emerging LTE-Wi-Fi Aggregation and Licensed Assisted Access (LAA) technologies.

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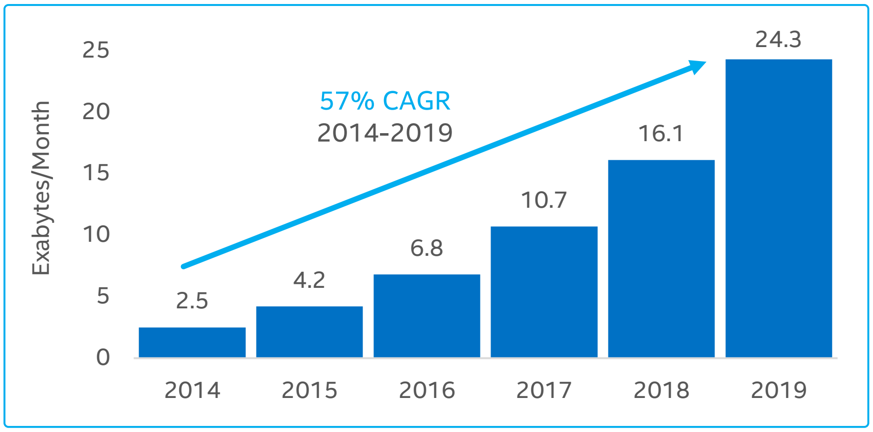
Introduction

Mobile service providers continue to experience a phenomenal increase in mobile data consumption driven by increased adoption of smartphones, emergence of new applications, video, and the younger generation's dependence on always being connected. There are no signs that this growth will slow down any time soon. At the same time, the cellular operators do want to be able to service their customers, while maintaining appropriate levels of CapEx/OpEx spending and still enhance revenues.

Figure 1 provides a projection of mobile data growth from Y2014-2019. Even though advancements in cellular technology have resulted in increased performance and capacity of mobile networks, this alone will not be sufficient to meet the mobile data demand. Mobile data consumption continues to grow rapidly and meeting the demand for high performance, low cost services remains enormously challenging.

FIGURE 1. FUTURE MOBILE DATA TRAFFIC UPDATE



Source: Cisco Visual Networking Index (VNI) Forecast Mobile Data Traffic Update 2014-2019

Several new technology options and innovations are emerging to address the growth in data capacity using cell densification and spectrally efficient methodologies. The need for spectrum is fundamental for wireless cellular communications. The type of spectrum that is in use is either licensed, where most of the cellular operations are conducted, or unlicensed, used by a number of access technologies such as 802.11 (Wi-Fi), 802.15.1 (Bluetooth), and 802.15.4 (Zigbee). Additionally, there are several efforts underway to use spectrum sharing techniques to address data capacity concerns. Essentially, spectrum is shared in different dimensions: time, frequency and geography where the latest 3.5 GHz CBRS spectrum allocation for new technology development by United States FCC is a good example.

Unlicensed spectrum is free and the systems are in general susceptible to unpredictable interference. On the other hand, licensed spectrum, such as used by LTE and other cellular networks, provides exclusive license for a specific band of spectrum to operators, so as to provide superior performance and ensure that operations are protected from other interference.

Due to limited availability and the cost of licensed spectrum, cellular operators have relied on the use of unlicensed spectrum to ease congestion on their networks. The conventional method of data offloading to unlicensed spectrum has been using WLAN networks based on IEEE802.11. 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, the 3rd Generation Partnership Project

(3GPP) has developed several solutions such as nonseamless WLAN offload (NSWO), access network discovery and selection function (ANDSF), and S2b interface, which enable interworking with WLAN and provide data offloading through switching of data bearers to WLAN.

LTE is currently the latest of the various generations of successful and widely used technologies for cellular networks operating over licensed bands. Recent work proposes the direct use of LTE Advanced based networks over unlicensed spectrum to address the challenge of exponential growth of traffic consumption. In principle, the use of the same core radio technology across both licensed and unlicensed spectrum is an important motivating factor in using LTE in unlicensed spectrum, as the data offloading can be enabled in a seamless fashion. LTE usage in both licensed and unlicensed spectrum can enable operators and vendors to leverage the existing LTE/EPC hardware in both the radio and core networks. The basic idea in aggregation of licensed and unlicensed spectrum is that the unlicensed band provides an increment in user data rates and data capacity while ensuring higher reliability of the data connection. This, in effect, is an attractive opportunity for operators in supplementing their licensed spectrum to increase network data capacity.

LTE usage in both licensed and unlicensed spectrum allows operators and vendors to leverage existing LTE/EPC hardware in radio and core networks.

There is a substantial amount of unlicensed spectrum available around the globe allowing unlicensed access to short range radio communications in the 2.4 GHz and 5 GHz range. In North America, the 5 GHz unlicensed band has up to 600 MHz available at no auction cost, providing an attractive opportunity for operators to use the spectrum. Currently, Wi-Fi technology has been widely adopted in these unlicensed bands, and serves as one of the readily available means to access the large amount of unlicensed spectrum. With significant technical advantages and numerous innovations in addition to the implementation of IEEE 802.11ax, ay deployments in a local wireless environment, Wi-Fi today remains a first choice of connectivity for numerous use cases and business segments. Given a strongly established base of deployments and wide acceptance, Wi-Fi adoption only continues to grow.

In addition, a variety of different approaches to converge Wi-Fi and cellular technologies are being considered by various industry groups. In fact, there has been significant work and track record of technical approaches through the 3GPP standards process to provide mobile data traffic offload via WLAN networks by interworking between Wi-Fi and cellular networks.[1 2 3 4 5 6 7] Most recently, new technologies for even tighter integration of Wi-Fi as an integral part of 3GPP radio access network (RAN) has been proposed, which allow for seamless integration of unlicensed spectrum in the RAN while using the widely adopted Wi-Fi technology.

LTE WLAN Aggregation (LWA) and LTE/WLAN radio level integration with IPsec tunnel (LWIP) are one category of techniques that aim to provide seamless aggregation of LTE and WLAN radio links. This technology option links the Wi-Fi traffic to the mobile network operator’s (MNO’s) network, and having the LTE network decide the utilization of Wi-Fi in unlicensed network in conjunction with LTE in licensed spectrum. This technology option allows the operators to leverage existing cellular network deployments and the established base of Wi-Fi deployments in various different forms (carrier-based, enterprise, residential, etc.).

The second category of techniques aim to achieve a similar goal, but by using LTE in unlicensed spectrum in place of Wi-Fi. Two technology solutions have emerged using this principle: Licensed Assisted Access (LAA), a 3GPP standards-based technology mechanism, and LTE in unlicensed spectrum (LTE-U), a proprietary technology solution developed by Qualcomm. LAA and LTE-U essentially require an anchor channel in licensed spectrum to primarily enable mobile operators to use unlicensed spectrum.

There is also another technique emerging called MulteFire planned to be built on LTE-LAA and 3GPP Release 13 standard in unlicensed spectrum, incorporating a full LTE core network supporting voice and data. Unlike LTE-U and LAA, MulteFire is expected to operate solely in unlicensed spectrum without requiring an LTE anchor in licensed spectrum. As this technology is currently under development, the details of this option are beyond the scope of this version of the white paper.

Unlicensed spectrum combined with licensed spectrum is a step toward 5G enabling higher data capacity use.

These technologies, where unlicensed spectrum is combined with licensed spectrum, are a step toward 5G. They enable the higher data capacity use cases needed with 5G. All techniques have their merits and suit different deployment scenarios. Some operators, e.g., ones with a large installed base of Wi-Fi Access Points (APs), might prefer LWA, while others who have a strong dependency on LTE cellular infrastructure may prefer LAA or LTE-U.

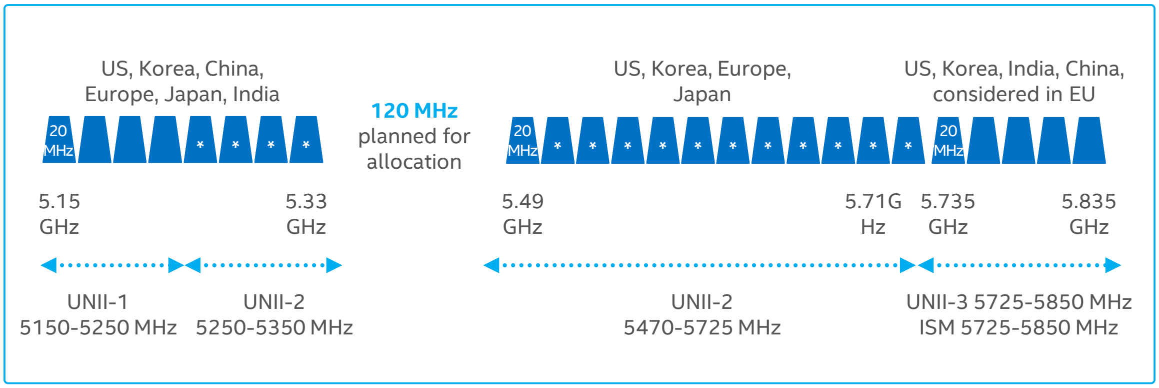
All three technologies (LWA, LWIP, and LAA) essentially share the same advantages, making licensed and unlicensed spectrum usage transparent to the core network, thus reducing the management burden and cost. LWA and LAA defined in Release 13 provide similar performance gains. However, with the introduction of 60 GHz support for eLWA in Release 14, LWA will be able to also utilize substantially larger bandwidth (> 2 GHz).

While LWA and LWIP naturally support coexistence and fair usage of unlicensed spectrum by virtue of the fact that it uses plain Wi-Fi physical layer of the OSI model (PHY) and media access control (MAC), LAA and LTE-U need to add techniques for fair coexistence with other unlicensed technologies in unlicensed spectrum such as Wi-Fi.

Use of LTE in Unlicensed Spectrum

The frequency band of most interest for LTE for unlicensed spectrum is the 5 GHz band where it has an opportunity of several hundred MHz of bandwidth based on the country and region. See Figure 2.

FIGURE 2. 5 GHZ BANDS FOR LTE-U AND LTE-LAA



In addition to the basic frequency limits, the use of the 5 GHz bands for LTE are dictated by regulatory stipulations. Another main requirement for access to these frequencies is to ensure fair coexistence with other users in the band by implementing widely accepted technical mechanisms such as Clear Channel Assessment (CCA) and Listen before Talk (LBT).

This often means that instantaneous access may not always be available for LTE in an unlicensed band. Other requirements relate to different power levels that are allowed based on the country and the frequency band where typically a maximum power limit of 200 mW is imposed in the frequency band 5150 -5350 MHz and operation is restricted to indoor use only and the upper frequencies are often allowed power levels up to 1 W.

Technology Alternatives in Unlicensed Spectrum

LTE Wi-Fi Aggregation (LWA)

LWA as a technical approach to integrate the carriers of LTE and Wi-Fi is gaining increased attention as a key alternative over other interworking options considered by 3GPP as it allows mobile operators to readily roll out this feature with the existing base of established networks and access points. Also, LWA's performance is expected to deliver similar performance as other LTE proposals in unlicensed spectrum while requiring only a software update to handset devices. For the initial introduction, LWA uses LTE for the uplink and both LTE and Wi-Fi for the downlink.

LWA is gaining increased attention because it allows MNOs to readily roll out this feature with established networks and access points.

In LWA, Wi-Fi is scheduled in unlicensed bands and LTE in licensed bands, and the combined two radio technologies offer a compelling user experience. LWA enables LTE and WLAN interworking with data aggregation at the radio access network, using an LTE dual-connectivity like framework. Here an eNB schedules packets to be served on LTE and Wi-Fi radio links. In essence, to achieve enhanced performance, the LTE data payload is split, with some traffic tunneled over Wi-Fi and some transmitted over LTE.

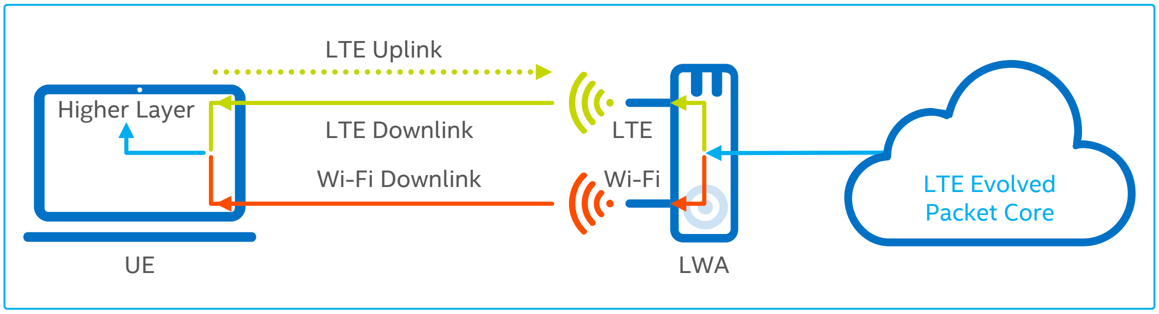
LWA centers on using a Wi-Fi access point to augment the LTE RAN by tunneling LTE in the 802.11 MAC frame for transparent transport of LTE data, without requiring changes to the Wi-Fi air interface. LWA link aggregation applies to existing and new carrier Wi-Fi deployments and utilizes both 2.4 and 5 GHz bands.

LWA has been standardized in Release 13. Release 14 Enhanced LWA (eLWA) adds support for 60 GHz band (802.11ad and 802.11ay aka WiGig) with 2.16 GHz bandwidth, uplink aggregation, mobility improvements, and other enhancements.

The advantage of the LWA 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 improves the total system capacity by better managing the radio resources among users. Because LWA uses plain Wi-Fi PHY and MAC, it guarantees fair coexistence with other technologies operating in the unlicensed band.

Unlike the deployment of LTE in unlicensed spectrum, which requires all new network hardware and all new smartphones, LWA could be enabled with a straightforward software upgrade, allowing smartphones to power up both radios, and split the data plane traffic so some LTE traffic is tunneled over Wi-Fi and the rest runs natively over LTE. In LWA, the traffic that flows over Wi-Fi is routed via the LTE eNB which anchors the session. The flows to and from the evolved packet core (EPC) are routed via the LTE eNB. The advantage of this approach is that all Wi-Fi traffic can benefit from the services provided by the mobile operator's EPC. These services include billing, deep packet inspection, lawful intercept, policy, authentication, and more.

FIGURE 3. LWA CARRIER AGGREGATION (IN A COLLOCATED SCENARIO)



LWA Deployment Scenarios

The deployment scenarios for LTE-WLAN radio level aggregation can be grouped into two categories:

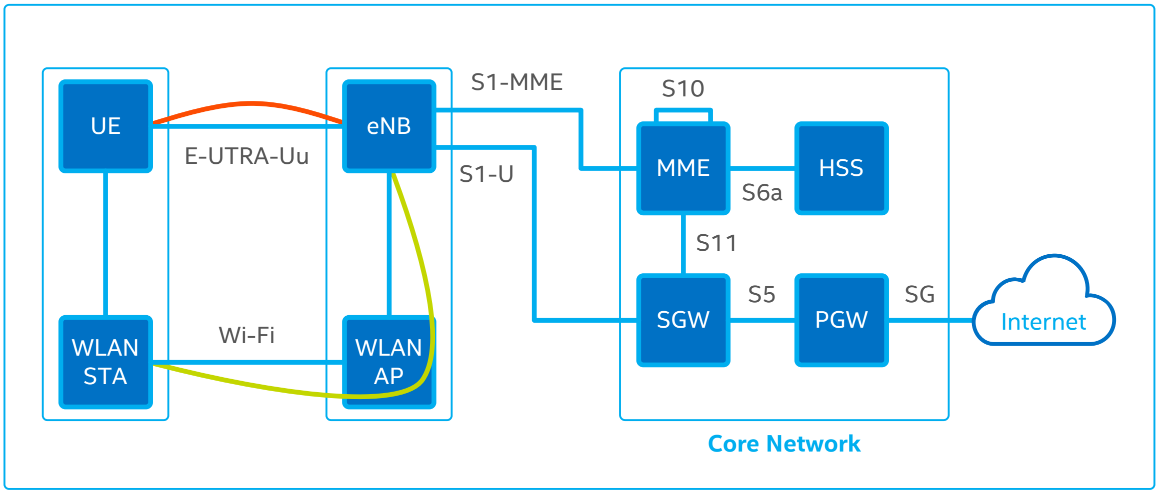
1. Collocated scenarios: An integrated LTE eNB and a WLAN access point (AP) or access controller (AC)
2. Non-collocated scenarios: Situations where there are WLAN APs within a macro or small cell coverage area, but not collocated with the macro or small cell. This refers to scenarios where LTE and Wi-Fi access points are at different physical locations. The non-collocated case has two scenarios:
   - The WLAN APs connect directly into the LTE eNBs
   - A WLAN access controller aggregates a cluster of WLAN APs and then interfaces to the LTE eNBs

LWA Aggregation for Generic Collocated Scenarios

In this scheme, where an LTE eNB and Wi-Fi AP are integrated, scheduling of packets are made at a packet level based on real-time channel conditions and system utilization. Data aggregation at the RAN is implemented without any changes to the core network as the WLAN radio link effectively becomes part of the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN). The collocated scenario—essentially the non-collocated scenario—with an ideal backhaul with little to no latency. In this case, the control plane and user interfaces are internally integrated between the eNB and WLAN AP.

In the case of LTE + Wi-Fi Link Aggregation, LTE eNBs are typically deployed in the same venue, and any Wi-Fi APs in the venue can be software-upgraded to support LWA. The Wi-Fi APs can also continue to support non-LWA traffic on a separate SSID. Therefore, LWA is a compelling technical solution that doesn't impact the unlicensed band while leveraging existing Wi-Fi access points and improving indoor cellular performance.

FIGURE 4. ARCHITECTURAL ASPECTS OF LTE AND WI-FI AGGREGATION



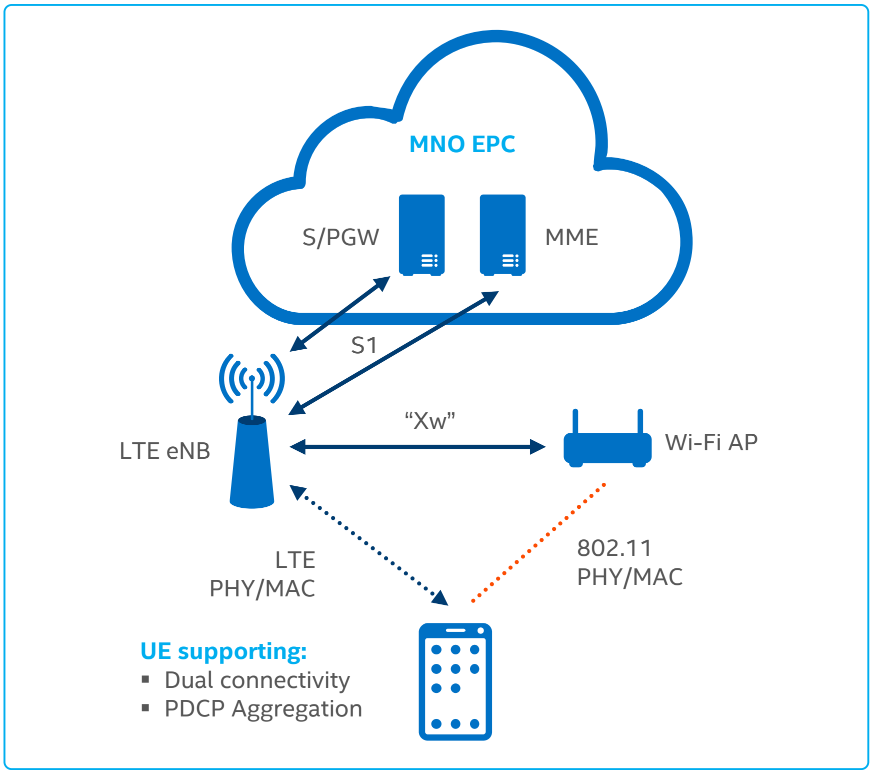
LWA Aggregation for Non-Collocated Scenarios

A non-collocated scenario corresponds to a situation where the Wi-Fi AP is within an LTE macro or a small cell coverage area, but not collocated with the macro or small cell. 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. In the non-collocated case, the eNB connects to Wi-Fi via a new standardized interface Xw, where the end-point of this interface on the Wi-Fi side is a logical entity named WLAN Termination (WT) which can reside at the AP, the AC, or deployed as a standalone network node. This interface has two components:

- Xw-c: Used for control plane between eNB and WLAN Termination Device (WT). WT can be a WLAN AP or WLAN controller. This interface is primarily used for setting up the LWA configuration in the WLAN infrastructure.
- Xw-u: Used for data plane between eNB and WT, which is the LWA path for aggregating user data as well as for flow control.

Figure 5 depicts the LWA configuration for the non-collocated scenario. This configuration builds on today's deployed equipment of both Wi-Fi APs and LTE eNBS.

FIGURE 5. LWA CONFIGURATION DEPICTING THE INTERFACES BETWEEN ENB, WI-FI AP, AND UE WITH THE CORE NW FOR A NON-COLLOCATED SCENARIO



LWA supports real-time packet level scheduling for non-collocated deployments as well, and introduces several features to support this function through the Xw interface. However, in order to allow LWA deployments with limited WLAN infrastructure impact, 3GPP has defined certain optional LWA features that can be enabled according to operator WLAN deployment considerations, e.g., UE-based reporting instead of network-based flow control. This and other features allow LWA deployments with little to no WLAN infrastructure impact, e.g., by deploying standalone WT not integrated into WLAN APs or ACs. Once the operator is ready for software upgrade of WLAN ACs, for example, additional LWA features may be enabled.

LTE Wi-Fi Aggregation Using IPSec Tunnel (LWIP)

The main objective of the LWIP solution is to provide LTE-Wi-Fi aggregation at the RAN to ensure legacy WLAN deployments are utilized without major modifications to existing WLAN nodes or the terminal devices. The LWIP solution defined by 3GPP in Release 13 supports both downlink and uplink transmissions of multiple bearers via an internet protocol security (IPSec) tunnel.

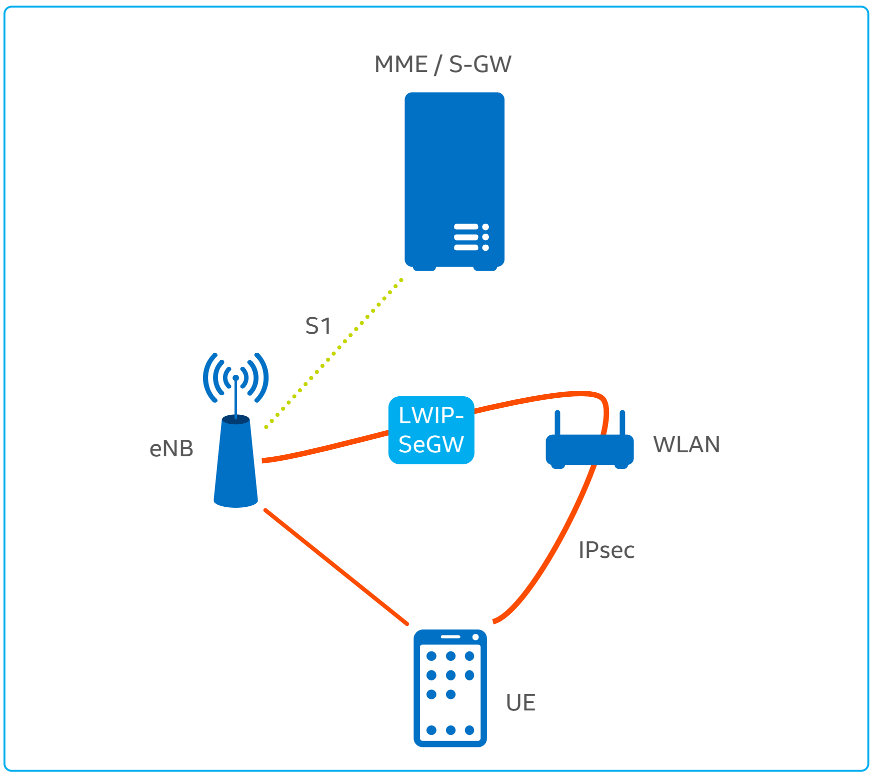
The advantage of LWA is that it utilizes Wi-Fi without any changes to the WLAN infrastructure.

The advantage of this solution is that it allows utilizing Wi-Fi without any changes to the WLAN infrastructure. However, compared to LWA and LAA, it may not be able to achieve the same performance as it does not support split bearer.

In LWIP, the LTE-Wi-Fi aggregation is accomplished by routing user traffic between EUTRAN and WLAN using bearer switching between the eNB and WLAN. Some of the traffic is routed directly between the eNB and the terminal device and the remaining traffic is routed between WLAN infrastructure and terminal device using an IPSec tunnel as shown in Figure 6. The IPSec tunnel is terminated at a security gateway (SeGW), LWIP-integrated with the eNB or connected to the eNB via a proprietary interface. LWIP uses a single IPSec tunnel per device for both uplink and downlink data transportation over the WLAN. Also, in LWIP, multiple bearers can be offloaded via the same IPSec tunnel.

LWIP re-uses some of the functionality defined for LWA, e.g., the WLAN measurement framework.

FIGURE 6. LWIP ARCHITECTURE



LTE Licensed Assisted Access (LTE-LAA)

Licensed Assisted Access LTE (LTE-LAA) is a new alternative for using LTE in unlicensed spectrum to complement mobile networks. LAA is an LTE technology enhancement defined in 3GPP Release 13, where the unlicensed carrier can be used as a secondary component carrier in the LTE carrier aggregation framework with a primary component carrier in licensed spectrum.

The 3GPP completed a Release 13 study item and now has a work item in process on LTE-LAA. LAA aims to help MNOs manage the user experience, from both a wireless air interface perspective using LTE technology with known scheduling, and from the core network perspective.

An important element of LTE-LAA is to ensure fair sharing of unlicensed spectrum.

One of the important elements of LTE-LAA is to ensure fair sharing of unlicensed spectrum with other operators and other systems such as Wi-Fi. LAA incorporates a mechanism where the LAA node searches for a channel in unlicensed spectrum with low load to avoid conflicting with other users and systems. Importantly, LAA includes the Listen BeforeTalk (LBT) feature to meet the regulatory requirements of the Release 13 timeframe, the only fairness coexistence mechanism in unlicensed spectrum around the world. LBT is a technique used in radio communications, where radio transmitters first sense the radio environment before starting a transmission. With LBT, in order to use a network, the device is typically allowed to operate on or find a free radio channel at a certain threshold. The following are some of the key design goals for LAA:

- LAA should not impact Wi-Fi more than any other Wi-Fi network on the same carrier. The determining fair sharing metrics include throughput, latency, and jitter.
- To comply with region-specific regulations, LAA mandates the inclusion of LBT in unlicensed frequency bands.
- To ensure fair coexistence of LAA with incumbent co-channel Wi-Fi deployments, an LAA eNB should perform LBT prior to DL/UL transmission over an unlicensed SCell.
- Adapt an Energy Detection Threshold (EDT) for sensing whether the medium is idle or busy to ensure effective coexistence with Wi-Fi and performance of LAA networks.

Only downlink LAA operation is specified in the Release 13 timeframe, while studies on LAA uplink in 3GPP are slated for Release 14. LAA is built upon the carrier aggregation capability of LTE-Advanced that has been deployed since around 2013. Essentially, carrier aggregation seeks to increase the overall bandwidth available to user equipment by enabling it to use more than one channel, either in the same band or within another band. LAA can be deployed in the following three modes:

Downlink only: This is the most basic form of LTE technology in unlicensed spectrum and it is similar in approach to some of the first LTE carrier aggregation deployments. In this, the primary cell link is always located in the licensed spectrum bands.

When operating in this mode, the LTE eNode B performs most of the necessary operations to ensure reliability is maintained and interference is not caused to other users by ensuring the channel is free.

Uplink and downlink: Full TDD LAA operation with the user equipment having an uplink and downlink connection in unlicensed spectrum requires the inclusion of more features. See Figure 7.

FDD/TDD aggregation: LTE-CA allows the use of carrier aggregation mixes between frequency division duplex (FDD) and time division duplex (TDD). This provides for much greater levels of flexibility when selecting the band to be used with unlicensed spectrum for LTE-LAA operation. See Figure 8.

LTE-LAA relies on the existing core network for the backhaul and other capabilities like security and authentication. Therefore, no changes are needed to the core network. A few modifications to the base station, however, are necessary to accommodate the new frequencies and also incorporate the capabilities required to ensure proper sharing of the unlicensed frequencies. In addition to this, LTE-LAA capability needs to be built into new devices to access LTE on the additional frequencies in the unlicensed spectrum.

FIGURE 7. LTE IN UNLICENSED SPECTRUM TO PROVIDE A SUPPLEMENTAL DOWNLINK CARRIER

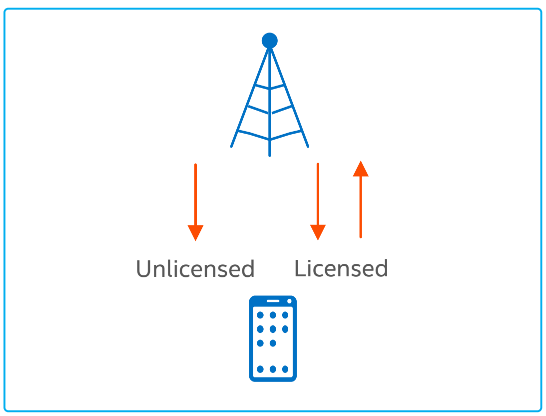
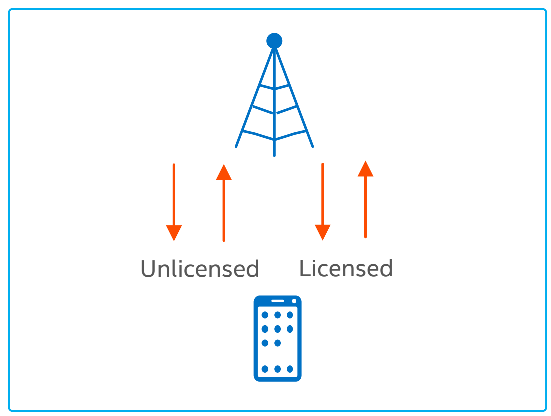


FIGURE 8. LTE IN UNLICENSED SPECTRUM TO PROVIDE FDD AND TDD AGGREGATION



LAA Deployment Scenarios

The deployment scenarios for LTE-WLAN radio level aggregation can be grouped into three categories based on network topology as shown in Table 1: Network assisted LAA, eNB Controlled LAA and Centralized LAA. Table 1 further illustrates the description of the different scenarios and defines the requirements for deployment for each scenario.

TABLE 1. LAA DEPLOYMENT SCENARIOS

	NETWORK BASED LAA	ENB BASED LAA	CENTRALIZED / VIRTUALIZED LAA
NETWORK TYPOLOGY	Network assisted LAA	eNB controlled LAA	Centralized LAA
DEPLOYMENT REQUIREMENTS	• Upgrades existing eNB deployment with 5 GHz RF • Or a new deployment with 5 GHz RF included • Software upgrade eNB G/W to share self-organizing networks (SON) and channel usage with other Wi-Fi gateways	• Upgrades existing eNB deployment with 5 GHz RF • Or a new deployment with 5 GHz RF included • Software upgrade eNB G/W to share SON and channel usage with other Wi-Fi gateways	• Upgrades existing eNB deployment with 5 GHz RF • Or a new deployment with 5 GHz RF included • Software upgrade eNB G/W to share SON and channel usage with other Wi-Fi gateways
DESCRIPTION	• eNB and Wi-Fi AP operate independently • eNB adjusts unlicensed spectrum usage, based on channel loading • Traffic management on unlicensed spectrum supported in LTE controller/gateway	• eNB and Wi-Fi AP operate independently • eNB adjusts unlicensed spectrum usage, based on channel loading • Traffic management on unlicensed spectrum managed on eNB – locally decided	• Multiple eNBs (and possibly APs) can be managed and scheduled across wider footprint • eNB and Wi-Fi AP operate independently • eNB adjusts unlicensed spectrum usage based on channel loading • Traffic management on unlicensed spectrum supported in centralized and virtualized LTE controller/gateway and eNB
SUMMARY	• Enhanced data capacity without additional spectrum cost • S/W and H/W update to eNB for 5 GHz RF • Same LTE core network infrastructure	• Enhanced data capacity without additional spectrum cost • S/W and H/W update to eNB for 5 GHz RF • Same LTE core network infrastructure • Suitable for network in a box configuration	• S/W and H/W update to eNB for 5 GHz RF • Same LTE core network infrastructure • Scalable across multiple eNBs and APs

LTE-U

LTE-U is another option to use LTE in unlicensed spectrum that is developed outside the 3GPP standards as a proprietary technology mainly led by Qualcomm. A controversial aspect of LTE-U is that it doesn't incorporate an LBT mechanism for coexistence and doesn't meet the regulatory requirements for using unlicensed spectrum in a significant part of the world.

LTE-U developed outside the 3GPP standards and doesn't incorporate the LBT mechanism for coexistence nor meet many regulatory requirements.

In several markets, including those in Europe and Japan, LBT is a specific waveform requirement mandated by regulatory restrictions. However, LTE-U can be suitable for some countries such as the United States, Korea, and China, where there are no regulatory requirements for using LBT. To provide the requisite coexistence feature, LTE-U technology modifies the eNode B design outside the 3GPP standards process.

To provide fair coexistence in unlicensed bands, LTE-U adopts the following proprietary mechanisms:

1. **Channel Selection:** This is used for eNBs to choose the cleanest channel based on Wi-Fi and LTE measurements. This is used as an attempt to avoid interference between the eNB and its neighboring Wi-Fi devices and other LTE-U eNBs, provided an unused channel is available. The channel selection algorithm monitors the status of the operating channel on an ongoing basis, and if needed will select a more suitable one and change. The interference level is measured by energy detection, which doesn't guarantee the accurate detection of other occupied users in the channel.
2. **Carrier-Sensing Adaptive Transmission (CSAT):** In the event that no clean channel is available, the CSAT mechanism is used in very dense deployments where LTE-U nodes are allowed to share the channel with the neighboring Wi-Fi APs. In CSAT, the eNB senses the medium for longer (than LBT) duration, around 10s of ms to 200ms. Based on channel occupancy activity, the algorithm gates off LTE transmission proportionally. CSAT defines a time cycle where the eNB transmits in a fraction of the cycle and gates off in the remaining duration. The duty cycle of transmission vs. gating off is dictated by the sensed medium activity of other technologies. CSAT uses a comparatively longer latency and its impact is mitigated only by avoiding channels where Wi-Fi APs are used for discovery signals and QoS traffic.

Supplemental Downlink (SDL) Transmission: The SDL transmissions are conducted based on the traffic demand. If the eNB is lightly loaded, the secondary component carrier in the unlicensed band can be turned off to avoid transmission of overheads such as CRS signals, which further reduces the interference to neighboring Wi-Fi APs. This is possible because the primary carrier is always operating in the licensed band.

System Performance Results

Performance of LTE-Wi-Fi Integration

LTE-Wi-Fi Integration can help improve user quality of service and overall system capacity, through efficient management of radio resources across both links. The LWA approach offers performance enhancements beyond the LWIP approach through its use of dynamic bearer aggregation across both WiF and LTE links. A simulation analysis based on 3GPP Het-Net 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.

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 FTP traffic model. We focus on the downlink performance to be consistent with Release 13 LWA priorities.

TCP performance characterization is based on 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.

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 9. 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.

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 (RCLWI, LWIP): Release 12 RAN-assisted WLAN interworking with optimum thresholds or Release 13 radio interworking enhancements with measurement reporting (RCLWI), or LTE WLAN IP Layer interworking (LWIP). This scheme may be considered reflective of radio interworking schemes that do not employ aggregation with bearer split.
- Release 13 LWA (with bearer split): Two variations are considered. The first is suitable for collocated WLAN and LTE small cells.
  - Joint Queue/Scheduling, 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.

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.

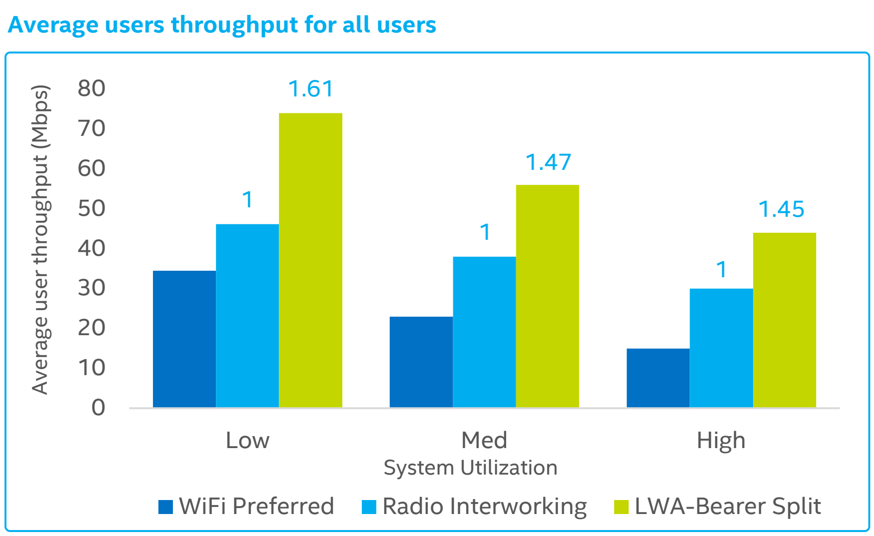
System Performance Results

Figure 9 illustrates 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 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 Release 12/Release 13 radio interworking scheme. When considering medium system load, LWA gains in average user throughput of up to 70% are observed. The cell edge gains for small cell users, which exploit aggregation, also increase substantially.

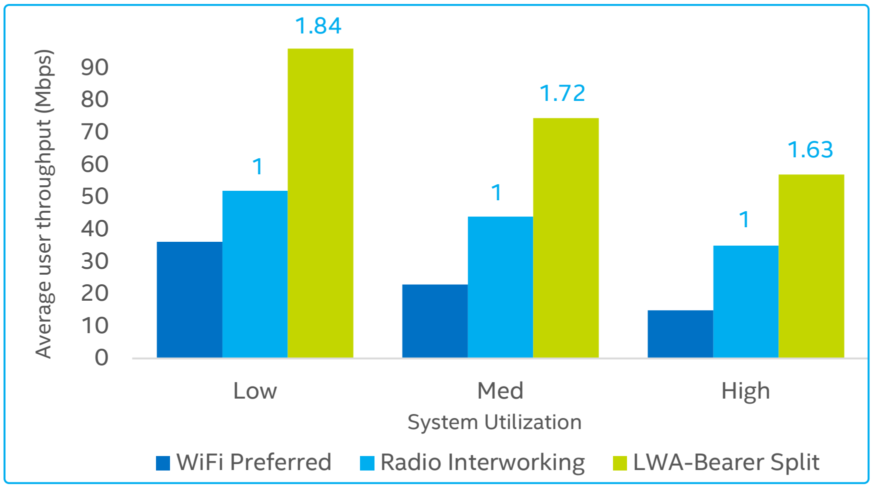
When considering medium system load, LWA gains up to 70% in average user throughput.

FIGURE 9. LWA PERFORMANCE GAINS FOR COLLOCATED HET-NET DEPLOYMENTS

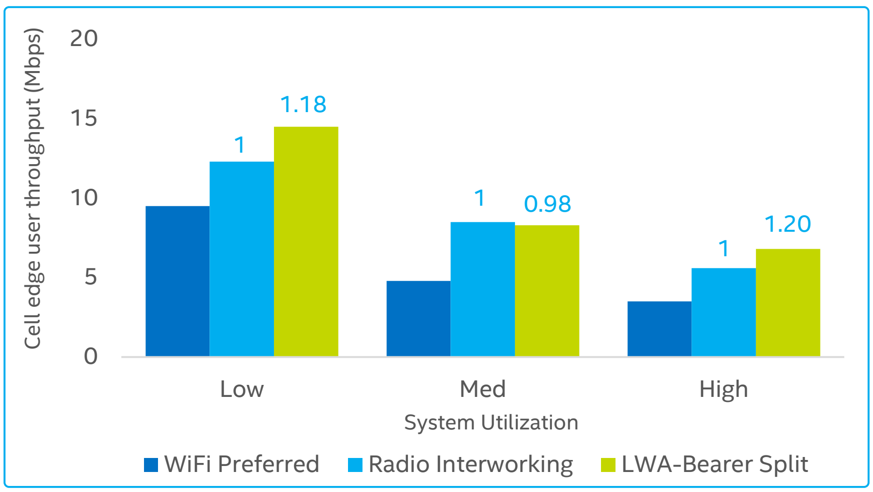
Measured with same licensed carrier being used across macro and small cell tiers. No interference coordination is assumed. 1 AP/9 UEs per macro cell sector are considered. System utilization of Low, Med and High correspond to 20-25%, 40-50% and 60-70% utilization levels, respectively.



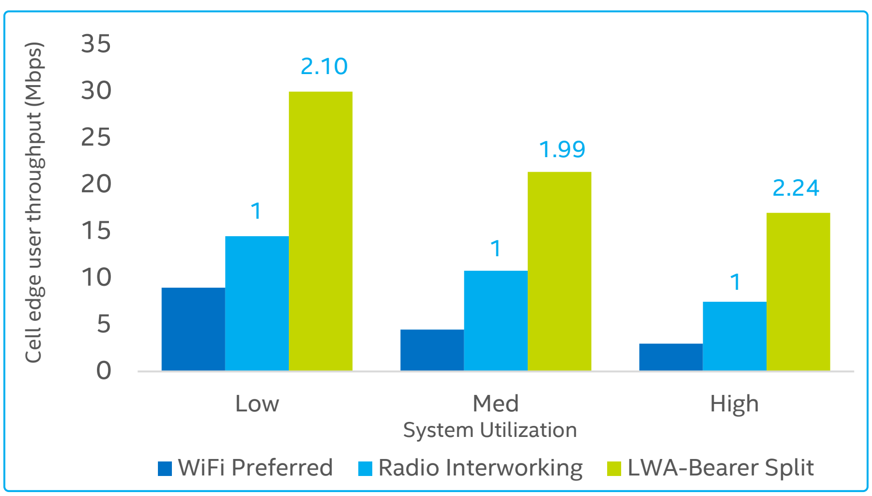
Average user throughput for small cell users



Cell edge user throughput for all users



Cell edge user throughput for small cell users



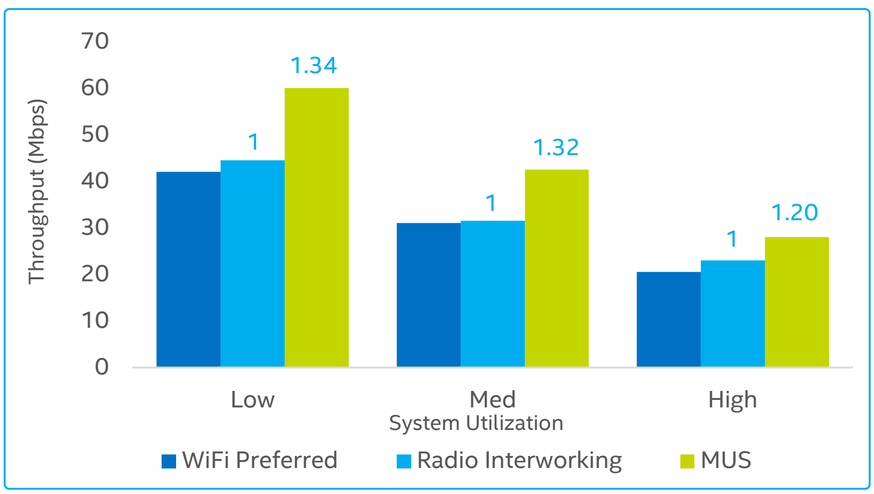
LWA's MUS algorithm outperforms the radio interworking solution with an average gain of 30% and cell edge gain of 85% across all users.

Figure 10 illustrates the LWA performance gains for non-collocated deployments (macro cell and Wi-Fi only small cell) with ideal and 20 millisecond backhaul delay. The LWA bearer split scheme is based on the "multi-user splitting" (MUS) algorithm. Considering the scenario with ideal backhaul, it can be seen that LWA based on the MUS algorithm outperforms the radio interworking solution, with average and cell edge gains across all users, of 30% and 85%, respectively, at medium utilization level. LWA MUS gains are still available (especially for cell-edge users) even when considering non-ideal backhaul with 20 millisecond delay, with gains of 24% and 45% in average user throughput across all users in the system.

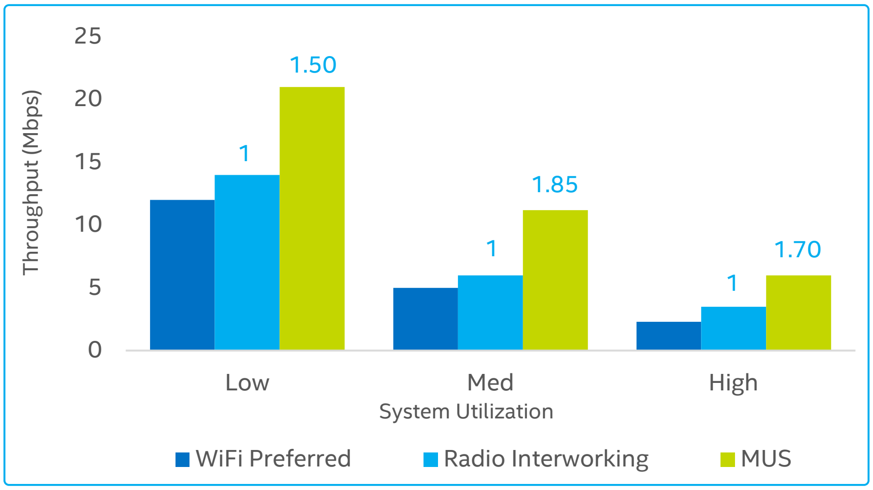
FIGURE 10. LWA PERFORMANCE GAINS FOR NON-COLLOCATED HET-NET DEPLOYEMENTS

Measured by comparing average and cell-edge performance results across all users with ideal backhaul delay (0ms) with a non-ideal delay scenario of 20 milliseconds. 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.

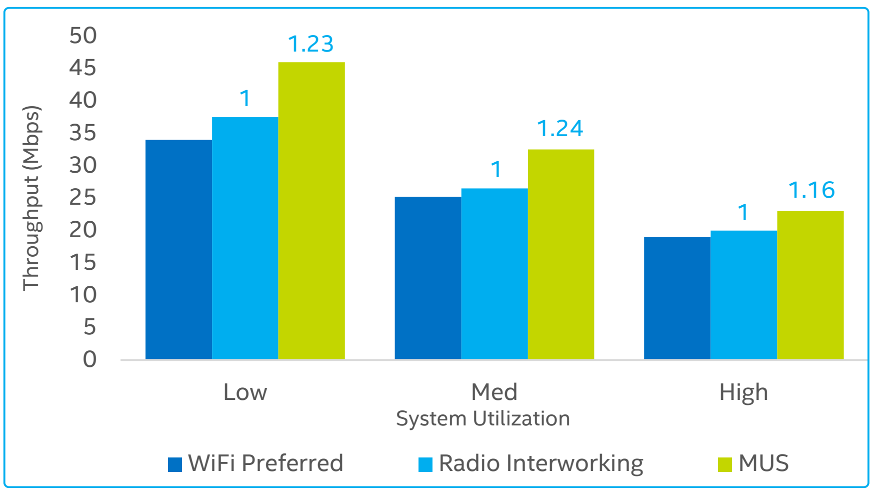
Ideal Backhaul (All-users, average user throughput)



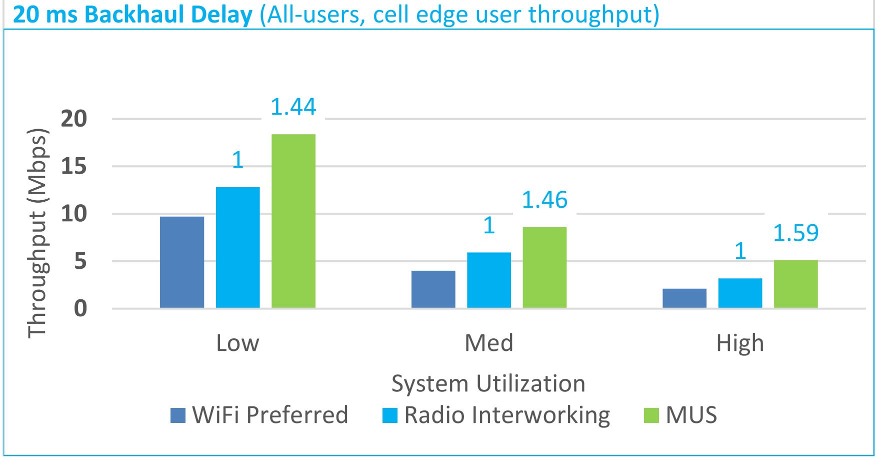
Ideal Backhaul (All-users, cell-edge user throughput)



20 ms Backhaul Delay (All-users, average user throughput)



20 ms Backhaul Delay (All-users, cell edge user throughput)



TCP Performance Results

Table 2 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 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 2. LWA TCP PERFORMANCE GAINS COMPARED TO LAYER 2 THROUGHPUT GAINS

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	Radio Interworking	15	13.3	13
	R13 LWA	26 (1.73x)	22.9 (1.72x)	22.6 (1.74x)
Median User	Radio Interworking	43	38.4	37.4
	R13 LWA	59 (1.37x)	46.8 (1.22x)	46.6 (1.25x)

Summary

The results shown in this section are illustrative of substantial performance benefits for Release 13 LWA solutions with bearer split, when compared to radio interworking solutions. Our results show up to 70% system gains in average user throughput for users associated with a collocated Wi-Fi/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 average cell edge gains of more than 30% and 80%, 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 be shown that gains in user throughput also result in system capacity improvements, in that LWA can support a 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, and show that layer 2 gains translate to TCP layer gains.

LTE-LAA System Performance Results

An important goal for LAA design is to ensure fair coexistence with other incumbent systems operating in the same unlicensed spectrum. This is essentially met by the inclusion of the LBT mechanism where the LAA network limits any impact to Wi-Fi services (data, video, and voice) more than an additional Wi-Fi network on the same carrier. This section presents the extensive performance evaluation effort contributed by numerous sources who participated during the LAA standards study item phase.[8]

3GPP considered both indoor and outdoor deployments with various traffic models such as File Transfer Protocol (FTP) traffic and mixed FTP and Voice over Internet Protocol (VoIP) traffic. The Wi-Fi network with DL-only traffic and both DL and UL traffic were considered as well.

To verify the coexistence, a two-step methodology is used:

- Step 1: The performance of two coexisting Wi-Fi networks is evaluated as a benchmark.
- Step 2: One of the Wi-Fi networks is replaced with an LAA network and performance of the non-replaced Wi-Fi network is compared against Step 1.

The following are two important aspects that need to be considered as the performance of the LAA scheme is evaluated:

- Ensuring coexistence for the indoor scenario is more difficult than that for the outdoor scenario due to close proximity between LAA eNBs and Wi-Fi access points/stations (STAs).
- It is more challenging to prove fair coexistence when LAA eNB transmits data only in the unlicensed carrier versus when LAA eNB transmits data on both licensed and unlicensed carriers. This is because the licensed carrier given to LAA eNB is an additional resource that can be exploited to alleviate the transmission demand on unlicensed spectrum in Step 2, resulting in a more friendly environment for fair coexistence.

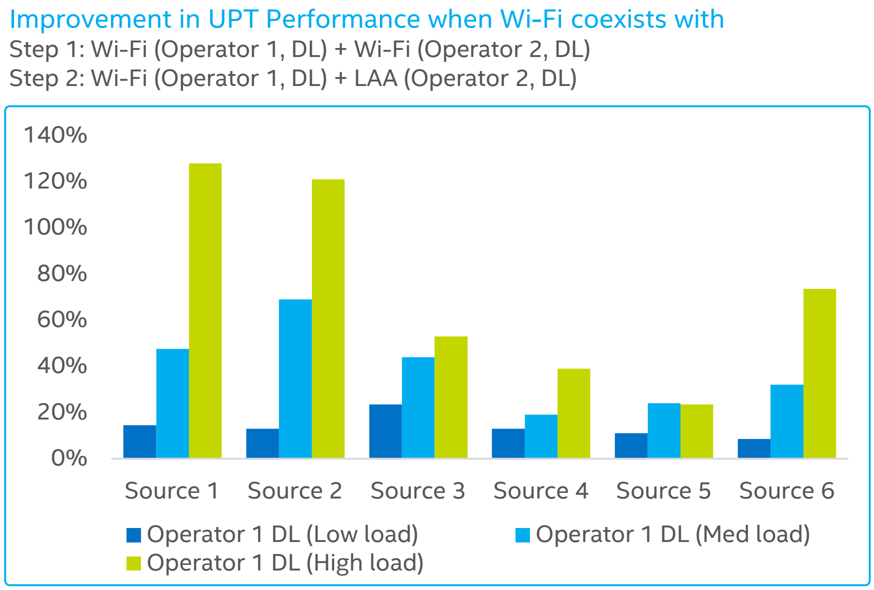
The results captured in this section are thus focused on the most demanding scenarios in which ensuring fair coexistence is most difficult.

The 3GPP-defined indoor scenario consists of four equally spaced LAA eNBs and/or Wi-Fi APs deployed by each operator in a single story building serving 10 uniformly distributed LAA UEs and/or Wi-Fi STAs operating on the same unlicensed carrier. The IEEE 802.11ac technology is assumed for Wi-Fi networks.

The user perceived throughput (UPT) is considered by 3GPP as an important performance measure for network serving non-full-buffer traffic. The UPT is defined as the amount of data over the actual time spent for downloading, excluding the idle time waiting for files to arrive.

Figure 11 shows the improvement in the UPT for the non-replaced DL-only Wi-Fi network in Step 2, compared to Step 1 with different loading conditions.

FIGURE 11. SYSTEM PERFORMANCE RESULTS – 1
USER PERFORMANCE IMPROVEMENT WITH LAA



Improvement in the UPT for the DL only Wi-Fi network (Sources 1-7 are from 3GPP contributions R1-150694, R1-152732, R1-151821, R1-152863, R1-153384, R1-153426, and R1-153629, respectively.)

Buffer occupant time of 15-30%, 35-50%, and 60-80% (averaged over APs of the non-replaced Wi-Fi network in Step 1) is considered as low, medium, and high load, respectively.

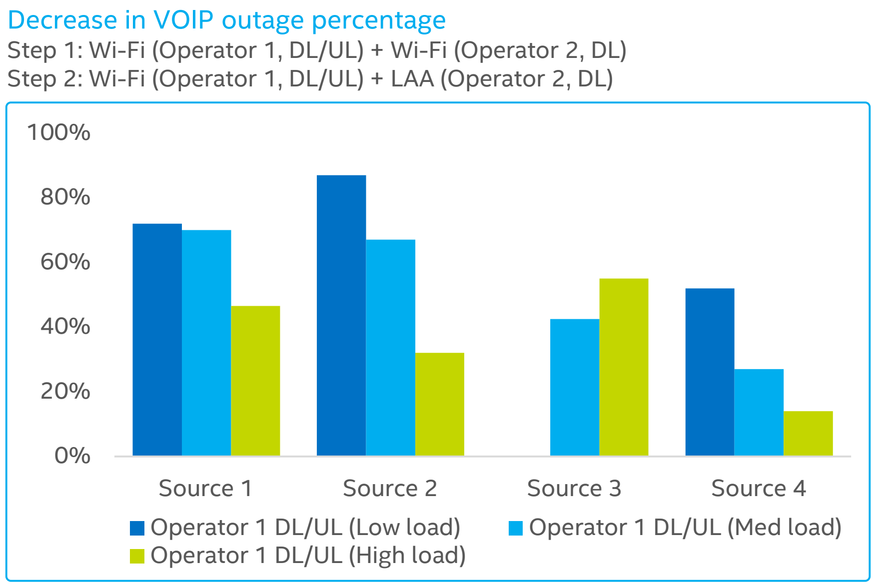
From Figure 11, it can be observed that the Wi-Fi UPT performance is improved when the Wi-Fi network coexists with an LAA network rather than another Wi-Fi network.

This is mainly because LTE has a higher spectral efficiency than Wi-Fi due to better link adaptation based on explicit CSI feedback, while the control messages such as CSI feedback can go through a licensed carrier. Consequently, the interference from Operator 2 to Operator 1 is reduced in Step 2, thereby improving the Wi-Fi performance in Step 2.

The VoIP outage for a non-replaced Wi-Fi network reduces significantly when it coexists with an LAA network.

Figure 12 shows the coexistence performance when Operator 1's Wi-Fi network serves bi-directional, i.e., both DL and UL, mixed FTP and VoIP traffic. It is shown in Figure 12 that VoIP outage for a non-replaced Wi-Fi network can be reduced significantly when it coexists with the LAA network. This draws the conclusion that 3GPP LAA design can indeed ensure the coexistence with incumbent Wi-Fi networks for both non-real-time and real-time traffic.

FIGURE 12. SYSTEM PERFORMANCE RESULTS – 2
VOIP OUTAGE IMPROVEMENT WITH LAA



Decrease in VoIP outage for the DL/UL Wi-Fi network (sources 1-4 are from 3GPP contributions R1-152326, R1-152642, R1-152937, and R1-153343, respectively.)

Conclusions

New innovations are continually being explored to offload mobile data traffic over to unlicensed spectrum. This paper presents a detailed overview and issues concerning the multiple technical solutions (LWA, LWIP, LAA, and LTE-U) proposed by industry proponents to use LTE networks in unlicensed spectrum, tapping a large swath of spectrum opportunistically to meet the challenge of exponential growth of cellular traffic.

The LWA and LWIP mechanisms propose a dual connectivity framework aggregating LTE and Wi-Fi carriers. 3GPP has recently developed the specification to define the interface between the LTE eNB and Wi-Fi AP, wherein packets of a bearer from the LTE network can be split dynamically between LTE and Wi-Fi for downstream transmission. On the other hand, LAA and LTE-U proposes using LTE directly in unlicensed spectrum. The downlink specifications for LAA are completed in Release 13 and the uplink specification is slated for Release 14. LTE-U is proprietary technology and the specification effort is undertaken in the LTE-U Forum.

Each of the different solutions presented in this paper offer distinct advantages and disadvantages in implementing these techniques on the networks and devices. Table 3 summarizes the LWA, LWIP, and LAA solutions in terms of the implementation impact on various elements of the network and devices.

LWA and LWIP are most promising because MNOs can readily roll out these solutions with minimum impact to infrastructure.

The LWA and LWIP solutions seem to be promising for mobile network operators, as these technologies can be readily rolled out with a minimum impact to infrastructure of both LTE and WLAN networks. Also, LWA and LWIP technology solutions allow mobile network operators to leverage existing investments in cellular networks and an extensive established base of Wi-Fi deployments in carrier networks, enterprises, campuses, municipal, residential, and other settings. Further, the performance gains of LWA are expected to be high and comparable to LAA. The LWA uplink functionality is planned to be specified in Release 14 timeframe. On the other hand, the expected performance of LWIP is not as superior as LWA but the mobile network operators can implement downlink and uplink functionality right away with LWIP. It is important to note, there are additional costs expected and minimal changes required on the devices to roll out the LWIP solution. The LAA technologies are expected to be commercialized providing the downlink functionality in the mid-2017 and 2018 timeframe. The performance studies indicate the LAA technical solution show higher performance but require moderate to high level changes to cellular infrastructure and devices.

TABLE 3. COMPARISON OF THREE TECHNOLOGY ALTERNATIVES: LWA, LWIP AND LAA

	SAME EPC	PERFORMANCE GAINS	WLAN INFRASTRUCTURE IMPACE	CELLULAR INFRASTRUCTURE IMPACT	ADDITIONAL UE COST	SAME NETWORK INFRASTRUCTURE FOR LTE & WLAN USERS
LWA	Yes	High[1]	Medium[2]	Medium[3]	Low[4]	Yes
LWIP	Yes	Low	No impact	Low[3]	Low[4]	Yes
LAA	Yes	High	N/A	High[3]	Medium[5]	No

[1] As of Release 13, LWA and LAA performance gains are similar. With Release 14, enhanced LWA is likely to deliver higher gains, as 60 GHz unlicensed spectrum will exploit much larger bandwidths

[2] Impact will vary depending on deployment options. There are ways to minimize it.

[3] LWA – new Xw interface, LWIP – LWIP-SeGW security GW to terminate Ipsec, LAA – new hardware

[4] *Software only*
[5] *New RF for 5 GHz*

Given the extent of the current established base of Wi-Fi systems and business, another important issue that needs to be taken into consideration using unlicensed spectrum is transparent coexistence. The need is to ensure fair and good neighborly use of unlicensed radio resources between LTE and Wi-Fi implementations. The LWA, LWIP, and LAA technical solutions offer a standardized approach to define the specifications for operating LTE in unlicensed spectrum and also a standardized, certifiable approach to coexistence. LWA and LWIP use existing Wi-Fi transmission and therefore ensure coexistence with Wi-Fi and require no hardware changes in the UE transceiver.

LTE-U is another technology alternative sometimes misunderstood as synonymous with LAA. The fact is that LTE-U is a non-standard technology that employs a proprietary coexistence algorithm. The main issue is the methodology LTE-U uses to determine the unoccupied channels and access unlicensed spectrum. Several questions were raised by several technical analysts, the FCC, and the Wi-Fi Alliance on the coexistence procedures used in LTE-U technology. LAA, on the other hand, incorporates the LBT methodology, a well-accepted methodology that ensures coexistence in a clear and a formally specified way.

Ancknowledgements

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[2] 3GPP Digital cellular telecommunications system (Phase 2+); Universal Mobile Telecommunications System (UMTS); LTE; Feasibility study on 3GPP system to Wireless Local Area Network (WLAN) interworking (3GPP TR 22.934 version 11.0.0 Release 11)

[3] Universal Mobile Telecommunications System (UMTS); LTE; Architecture enhancements for non- 3GPP accesses (3GPP TS 23.402 version 10.4.0 Release 10)

[4] Digital cellular telecommunications system (Phase 2+); Universal Mobile Telecommunications System (UMTS); LTE; Mobility between 3GPP-Wireless Local Area Network (WLAN) interworking and 3GPP systems (3GPP TS 23.327 version 10.0.0 Release 10)

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Appendix—LWA performance evaluation: Simulation details

TABLE 4. SIMULATION ASSUMPTIONS FOR SYSTEM LEVEL RESULTS

LTE	
Topology	7 cell wraparound (Het-Net deployment w/collocated Wi-Fi-LTE small cells and Wi-Fi-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 (reference signal received quality) 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.
Receiver type	Interference unaware MMSE
Feedback periodicity	10ms
CQI & PMI feedback granularity in frequency	5 PRBs
PMI feedback	3GPP Release 10 LTE codebook (per sub-band)
Outer loop for target FER control	10% PER for 1st transmission
Link adaptation	MCSs based on LTE transport format
HARQ scheme	CC

WI-FI	
Topology	7 cell wraparound (Het-Net deployment w/collocated Wi-Fi-LTE small cells and Wi-Fi-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 (||-->||)

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

List of Acronyms

3GPP	3rd Generation Partnership Project
BS	Base Station
CBRS	Citizen's Broadband Radio Service
CBSD	Citizens Broadband Radio Service Device
CEPT	Conférence Européenne des Administrations des Postes et des Télécommunications
DL	Downlink
eNB	evolved Node B base station
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDD/TDD	Frequency Division Duplex / Time Division Duplex
HetNet	Heterogeneous network
ISM	Industrial, Scientific and Medical
LTE	Long Term Evolution
LTE-LAA	Licensed Assisted Access LTE
LSA	Licensed Shared Access
LwIP	LTE/WLAN radio level integration with IPsec tunnel
MIMO	Multiple Input Multiple Output
NOI	Notice of Inquiry
NPRM	Notice of Proposed Rulemaking
NRA	National Regulation Administration
QoS	Quality of Service
R&O	Report and Order
RAT	Radio Access Technology
RSRQ	Reference Signal Received Quality
SAS	Spectrum Access System
SON	Self-organizing Networks
TDMA	Time-Division Multiple Access
TVWS	TV White Space
UE	User Equipment
UL	Uplink
U-NII	Unlicensed National Information Infrastructure
Wi-Fi	WLAN based on IEEE 802.11 standard
WLAN	Wireless Local Area Network

Definitions

Licensed LTE[i]: Current LTE technology deployed by operators and used by smartphones and other devices, which works in licensed spectrum. With the increase in data demand on licensed spectrum there is an ongoing study and discussion regarding using LTE in unlicensed spectrum (which is traditionally used by other technologies like Wi-Fi and BT).

Licensed Assisted Access (LAA)[i]: LAA is a radio access technology to enable LTE in unlicensed spectrum. LAA uses the Carrier Aggregation (CA) feature of LTE to aggregate two streams (anchor in licensed LTE spectrum and secondary cell in unlicensed LTE spectrum). The initial version of LAA is standardized in 3GPP Release 13.

LTE Unlicensed (LTE-U): LTE-U is another radio access solution that has been proposed to enable LTE in 5GHz unlicensed band. This solution which is similar to LAA but uses a proprietary coexistence mechanism. This solution is developed outside of 3GPP standards in LTE-U forum.

LTE Wi-Fi Aggregation (LWA)[ii]: LWA uses a dual-connectivity (anchor/booster) based framework to integrate Wi-Fi as an integral part of a 3GPP radio access network. It enables simultaneous transmission of packets belonging to the same stream over LTE and Wi-Fi (bearer-split). LWA introduces a standards based interface between LTE eNB and the WLAN network to optimize traffic aggregation across LTE and Wi-Fi links. LWA has been standardized in 3GPP Release 13 and is being enhanced in Release 14 as part of Enhanced LWA (eLWA) work item, adding uplink and 60 GHz support.

LTE Wi-Fi Aggregation using IPSec Tunnel (LWIP): LWIP, like LWA, uses a dual-connectivity based anchor/booster control framework to integrate Wi-Fi in the 3GPP LTE network, but uses an IP-sec tunnel between the eNB and the terminal device to transparently route a traffic stream over the WLAN network.

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[i] The Definitions are in alignment with ETSI TS 103 154: “Reconfigurable Radio Systems (RRS); System requirements for operation of Mobile Broadband Systems in the 2300 MHz - 2400 MHz band under Licensed Shared Access (LSA) regime”

[ii] The Definition is in alignment with FCC Part 96 – Citizens Broadband Radio Service.

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