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Combining the benefits of licensed and unlicensed technologies

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SMALL CELL FORUM

Solving the HetNet puzzle

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We have driven the standardization of key elements of small cell technology including Iuh, FAPI/SCAPI, SON, the small cell services API, TR-069 evolution and the enhancement of the X2 interface.

Today our members are driving solutions that include small cell/Wi-Fi integration, SON evolution, virtualization of the small cell layer, driving mass adoption via multi-operator neutral host, ensuring a common approach to service APIs to drive commercialisation and the integration of small cells into 5G standards evolution.

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Scope

This paper describes the role of LTE-U/LAA, LWA and LWIP, technologies that aggregate LTE in licensed and unlicensed spectrum and Wi-Fi. It considers how, together with their existing licensed spectrum, operators can leverage the abundance of unlicensed spectrum using EUTRAN integration directly into small cells.

Executive summary

Demand for wireless data is growing rapidly and such growth is expected to continue exponentially well into the next decade. Operators need to increase their network capacity to meet such growth. Deployment of small cells and the availability of more spectrum are two solutions to address this challenge.

This paper addresses how, using small cells, operators can leverage the abundance of unlicensed spectrum, together with their existing licensed spectrum, to enable a great user experience well into the future. When small cells were first introduced, they supported only cellular technologies in licensed spectrum. The obvious advantage of licensed spectrum is that only the designated spectrum holder has access to it and hence the nature of any interfering signal is predictable. This said, many cellular operators have also leveraged unlicensed spectrum (2.4 and 5 GHz) by complementing their cellular networks with Wi-Fi. At first, their cellular and Wi-Fi networks operated separately. These days, however, increasing numbers of small cells also support Wi-Fi in the same unit.

In addition to integrating cellular technologies and Wi-Fi in the same box, there are a number of scenarios where it is beneficial to aggregate them functionally so that resources can be allocated more dynamically, holistically and efficiently. This paper considers a number of the technologies that aggregate LTE in licensed spectrum with Wi-Fi.

The cellular industry is also considering technologies that extend the benefits of LTE in licensed spectrum to unlicensed spectrum (initially focused on 5 GHz). Since in this case LTE will be used in both licensed and unlicensed spectrum, the architecture will naturally aggregate the licensed and unlicensed carriers. Furthermore, the benefits of LTE in licensed spectrum – like robust mobility – may also apply to LTE in unlicensed spectrum.

While LTE is now being designed to operate in unlicensed spectrum, it is important to ensure that it can co-exist with Wi-Fi, an incumbent technology in the unlicensed 5 GHz spectrum. This paper will consider the technologies that aggregate LTE in licensed and unlicensed spectrum, along with some notable co-existence capabilities.

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1. Operator decision factors

Mobile operators offer a complex set of services. These service sets directly inform the selection of a particular technology or technology combination. In this document, we explore many technology options, performance benefits, and other considerations that should be factored into any operator's decision-making process.

In any decision, operators will likely be considering factors such as:

1. Spectrum regulation
2. Existing and future service provision and distribution across technologies.
3. Legacy infrastructure or capacity limits of existing infrastructure
4. Spectrum availability
5. Flexibility of deployment
6. Deployment & maintenance cost
7. Existing and projected customer terminal/device capabilities
8. Equipment & upgrade costs

2. Regulations for unlicensed spectrum

2.1 Status and requirements of 5 GHz unlicensed band in different regions

The assignments of frequency bands for unlicensed use of different regions on 5GHz are specified in different regional regulations. Figure 2–1 summarizes parts of available unlicensed bands around the world.

Generally, the sub-bands 5150-5350MHz, 5470-5725MHz, and 5725-5850MHz in most regions are open to wireless access system or radio LAN (WAS/RLAN) for unlicensed use.

The specific frequency spectra within these sub-bands which are available for WAS/RLAN are regional. For example, in Europe, sub-bands 5150-5350MHz and 5470-5725MHz are open to WAS/RLAN deployment, which lead to a total aggregate bandwidth of 455MHz.

In the USA, sub-bands 5150-5350MHz, 5470-5725MHz and 5725-5850MHz contribute to a total aggregate bandwidth of 580MHz.

In China, the aggregate bandwidth is 325MHz including sub-bands 5150-5350MHz and 5725-5850MHz, the sub-bands 5470-5725 MHz has not yet been officially open to RLAN but may become available in the future.

There may be additional restrictions in some regions as to whether certain sub-band can only be used for indoor operation. Some of such restrictions are included in Table 3–1. As 3GPP introduced LAA in Release 13, Band 46 that covers 5150 to 5925 MHz was defined.

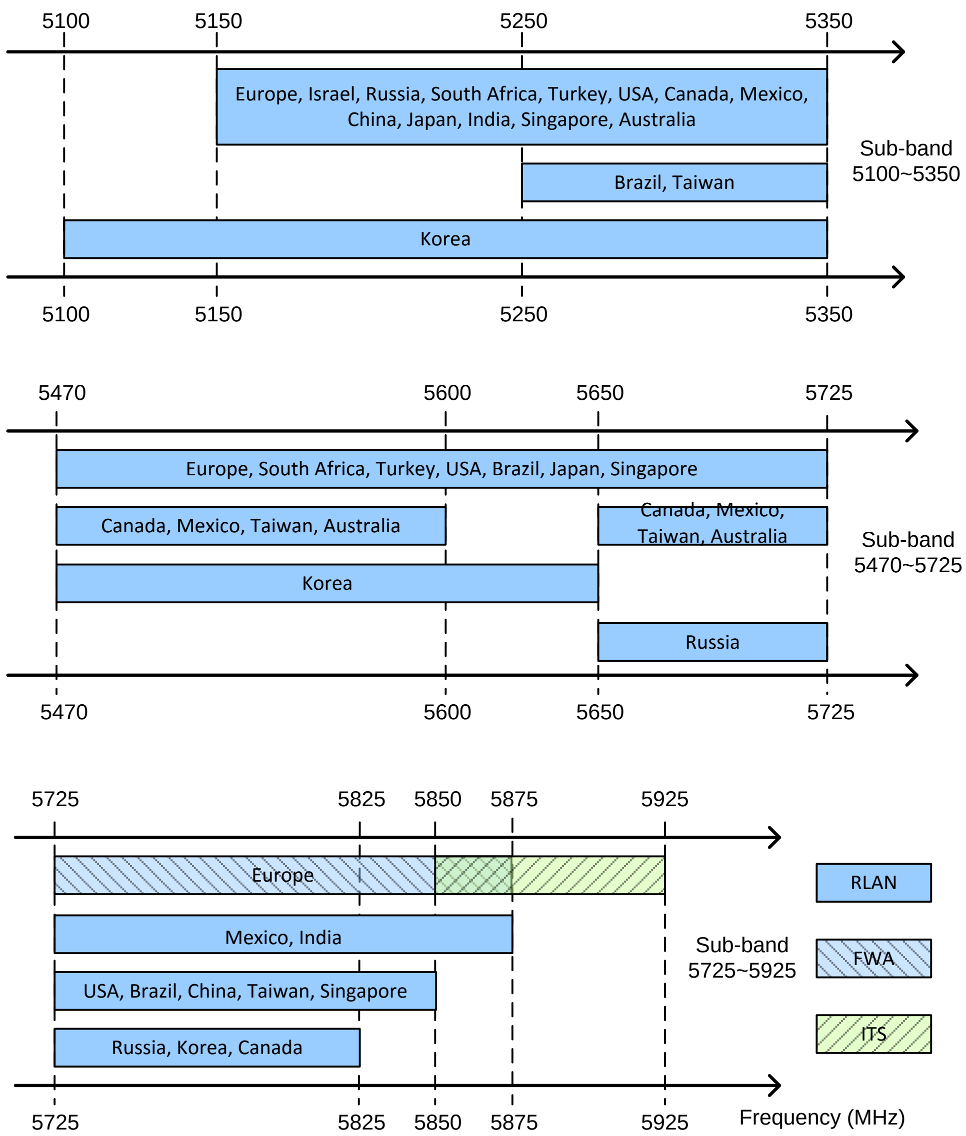

Figure 2–1 Available unlicensed bands around the world

The United States introduced the U-NII band definition for the 5 GHz band and it was also adopted in many other countries. It divided the 5 GHz spectrum into different bands. Operation in some of the bands in some regions may come with requirements to support dynamic frequency selection (DFS) and transmit power control (TPC), as mandated by the local regulators. Such requirements vary in different countries. For example, the FCC in the US mandates DFS and TPC support in UNII-2A and UNII-2C (see Figure 2–2).

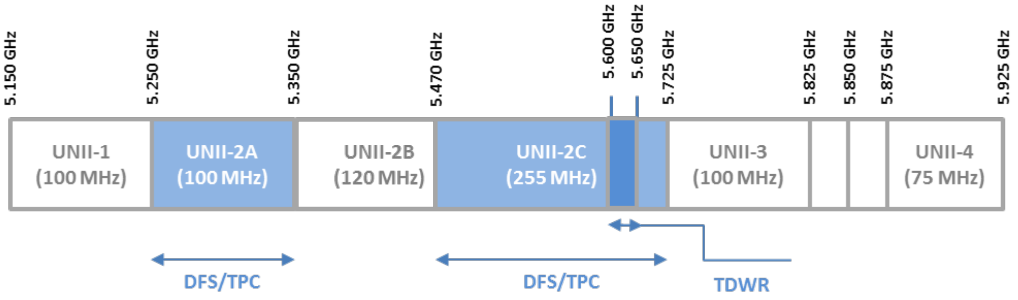

Figure 2–2 UNII bands and DFS/TPC requirements in the US

Furthermore, in order to resolve interference to terminal Doppler weather radar (TDWR), the FCC has defined interim plans to approve UNII devices operating in the 5470-5725 MHz band. In particular, the FCC does not allow any master device to transmit on the channels that overlap with the range 5600-5650 GHz (channels 120, 124 and 128). Channels 116 and 132 may be used, so long as they are separated by more than 30 MHz (center-to-center) from a TDWR located within 35 km of the device.

In the European Union, ETSI mandates DFS on all WAS/RLAN and fixed wireless access (FWA) bands except on sub-bands 5.150-5.250 GHz and 5.850-5.875 GHz, and it mandates TPC on all WAS/RLAN and FWA bands except on the sub-band 5.150-5.250 GHz as shown in Figure 2–3.

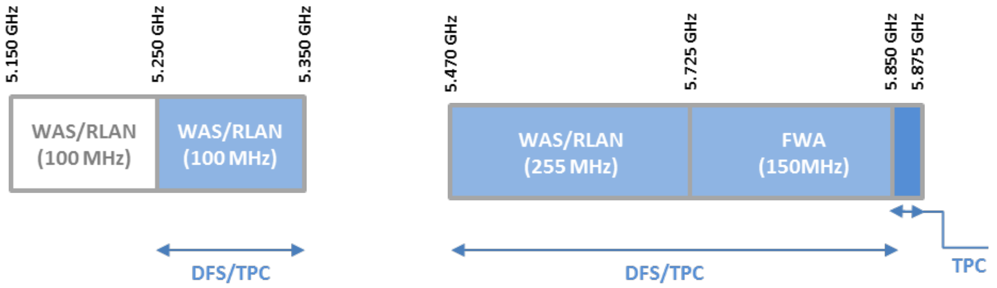

Figure 2–3 DFS/TPC requirements in EU

Although it is a cost effective way to enable LTE evolved node Bs (eNBs) to operate on the unlicensed spectrum, the deployment of any LTE-based technology is still restricted by radio regulations mandated by local governments for 5GHz band to provide friendly co-existence with other radio systems, including maximum transmission power, radar detection and protection, and channel access mechanisms. In Europe and Japan, 'listen before talk' (LBT) is mandated. In other countries such as US, China, India and South Korea, there is no similar requirement for operation in the 5 GHz band.

Details of the how LBT will be supported in some of the technologies that utilize the unlicensed 5 GHz band will be described later in this section.

2.2 Status and requirements of 3.5 GHz unlicensed band in different regions

3.5 GHz band is a loose term used to cover spectrum in the vicinity of 3.5 GHz. WRC-07 identified the spectrum 3400-3600 MHz for use by IMT systems and in many markets, the 3.5 GHz has been or will be licensed for mobile broadband communications. 3GPP had defined Bands 22, 42 and 43 for 3.5 GHz. One of the first LTE deployments in 3.5 GHz will be in Japan in late 2016.

The 3.5 GHz band in US is unique in the sense that it is neither strictly licensed (with a single licensee) nor unlicensed. In April 2015, the FCC adopted Citizen's Broadband Radio Service (CBRS) rules [1] for new commercial service in 2015 between 3.55 and 3.7 GHz, which overlaps partially with 3GPP Bands 42 and 43 (see Figure 2–4).

Provided that incumbents are unaffected, new entrants can be introduced in one of two tiers: priority access license (PAL) and general authorized access (GAA). PALs are allocated through auctions while GAA is free and provides opportunistic access to the whole 150 MHz of spectrum in the absence of incumbents and PAL users. Access to the spectrum will be allocated dynamically by the spectrum access system (SAS) to the deployments in the two tiers based on their respective priority and FCC requirements to protect the incumbents.

FCC also proposes to use a network of sensors known as environmental sensing capability (ESC) in the potential incumbent usage areas to detect the presence of signals from federal systems in 3.5 GHz and communicate that information to the SASs to protect existing federal operations. This cognitive radio approach is taken to ensure that all new licensed (PAL) and unlicensed (GAA) devices do not use the channels in the areas where incumbent systems (e.g. civilian satellite and military radar) are present. Furthermore, the GAA devices should not transmit in a channel and location where PAL devices are active.

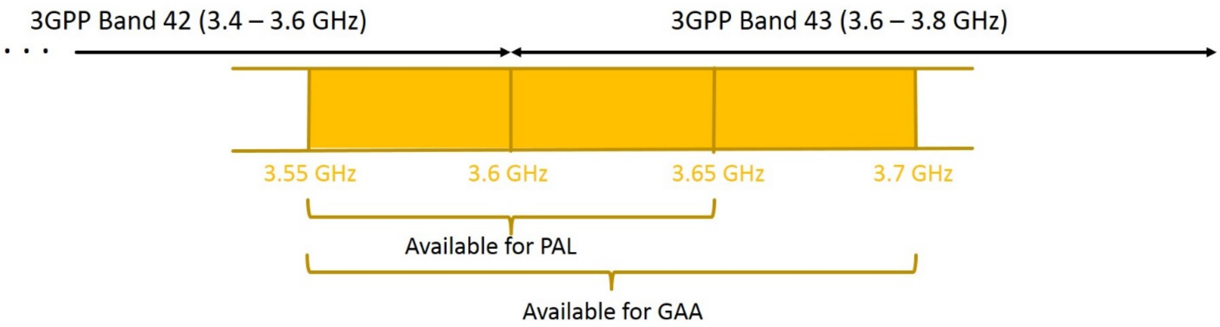

Figure 2–4 US 3.5 GHz CBRS Band

The FCC only defined some fundamental guidelines for this band. More detailed procedures and best practice recommendation will be defined by the WINN Forum.

In addition to standard LTE protocol that can be used in the PAL tier, it is expected that in the US some of the technologies discussed in this paper may be deployed in the GAA tier in the 3.5 GHz CBRS band.

2.3 Status of other higher frequency unlicensed bands

Other unlicensed bands also exist in higher frequencies – e.g., 28 GHz and 60 GHz. Examples of applications that utilize these bands today are satellite, wireless backhaul, wireless docking and multimedia content sharing. Looking ahead, the cellular industry is also considering employing these bands for 5G.

3. General status

In recent years, a number of different technologies have been proposed to leverage both licensed and unlicensed technologies. These include:

- Multi-path TCP (MP-TCP)
- RAN controlled LTE-WLAN interworking (RCLWI)
- LTE WLAN Radio Level Integration with IPsec Tunnel (LW-IP)
- LTE Wi-Fi aggregation (LWA)
- License assisted access (LAA) & LTE in unlicensed spectrum (LTE-U)

Some of these technologies will be discussed in this section. Due to the limited transmit power in unlicensed spectrum, it is expected that these technologies will mainly be deployed on small cells. Figure 3–1 shows how these technologies achieve aggregation at different protocol layers. Note that the eNB shown can also be HeNB or more generally a 'small cell'.

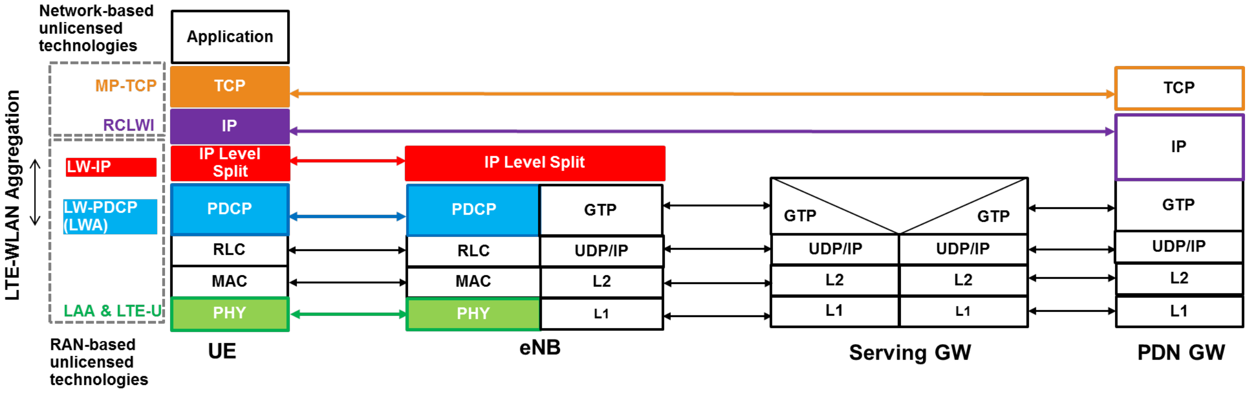

Figure 3–1 **Aggregation of licensed and unlicensed spectrum at different protocol layers by different technologies**

3.1 Unlicensed technologies based in 3GPP

3.1.1 Combining Licensed LTE with Unlicensed Wi-Fi: Overview and Specification Status

Because so many cellular operators have deployed Wi-Fi to complement their LTE networks, it makes sense to integrate the LTE and Wi-Fi networks that belong to the same operator. Prior to Release 13, this was based on integration into the core network, with [SCF178] [2] describing techniques to realize such solutions. Most recently, two 3GPP Release 13 work items – LTE-Wi-Fi aggregation (LWA) and LTE-Wi-Fi IP (LWIP) – have defined how integration can be performed at the EUTRAN access network. The following sections will describe these solutions in detail.

3.1.1.1 LTE-Wi-Fi aggregation

The initial work in 3GPP R-13 regarding LTE/Wi-Fi integration began with LWA. In the context of LWA, tight integration of the eNB and Wi-Fi infrastructure occurs at the PDCP layer. The eNB schedules packets to be served on each link. From a bearer-plane flow-control functionality perspective, the status of data delivery over WLAN is available from the UE. The Wi-Fi access point can provide real-time feedback to the eNB related to the successful delivery of user data over Wi-Fi for optimal performance, but this is not mandatory. No change is needed for the EPC.

The benefit of such tight integration of the two radio access technologies (RATs) is that resource allocation can be dynamic, based on the latest channel and loading conditions on each RAT. For example, if one of the RATs becomes congested, the eNB can route more traffic to the less loaded RAT. Load on LTE and Wi-Fi links are thus balanced.

To support LWA, the eNB and the Wi-Fi access point can be collocated or separated. In the collocated scenario, the eNB and the access point are integrated in the same hardware unit. Fast information sharing between them is simple, due to the proximity as well as the ability to use proprietary interfaces between the two functions. In the non-collocated case, the latency of the link between the eNB and WLAN is critical to the responsiveness of the scheduler – e.g., when the network-based flow control is available from WLAN. This information is shared between the eNB and the AP via the Xw interface. The LWA architecture for the non-collocated case is shown in Figure 3–2.

The Wi-Fi networks of most service providers are deployed with a wireless LAN controller (WLC). For networks with a WLC that support multiple APs, the WLC would be responsible for communication with the eNB via the Xw interface. In this situation, it is possible for changes to support LWA to be made to the WLC while the Wi-Fi APs remain unaffected. The Xw interface terminates in the logical node WLAN Termination (WT), which can be integrated into the WLC or AP or deployed as a separate node.

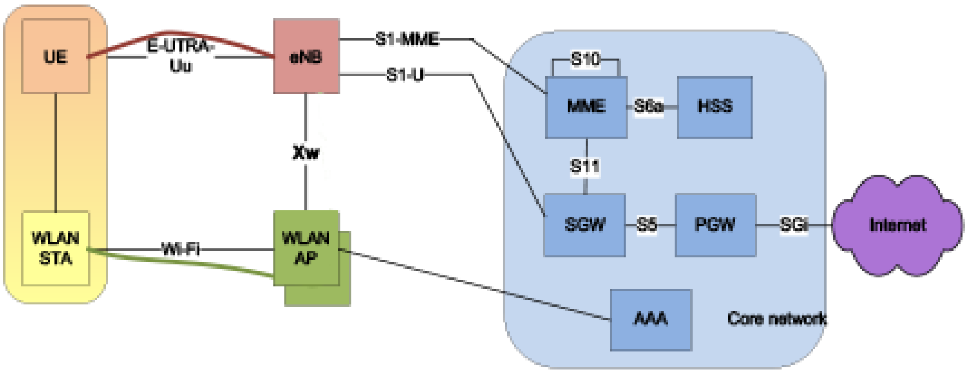

Figure 3–2 LWA architecture for non-collocated LTE eNB and Wi-Fi AP

The aggregation of LTE and Wi-Fi makes use of the dual connectivity (DC) feature that was previously defined in 3GPP R-12 standard. It supports reordering of packets that may arrive out of sequence at the UE through the two links.

While 3GPP R-13 LWA only covers aggregation of LTE and Wi-Fi on downlink, there will be further work in 3GPP R-14 to address similar aggregation on uplink. Furthermore, PDCP aggregation is being considered as a baseline for aggregation with LTE in 5G.

3.1.1.2 LTE-Wi-Fi IP

The challenges of upgrading and supporting tight integration with WLAN in LWA have motivated MNOs like ATT, T-Mobile, Sprint, US Cellular, and others that want to leverage the large capacity of ubiquitous and already established Wi-Fi networks, to support an alternate solution designed for possibly less impact on the WLAN infrastructure – the 3GPP LWIP standard.

Since deploying a LWIP solution does not involve the cost and complexity involved in upgrading the WLAN infrastructure, LWIP is expected to encourage more partnerships between MNOs and WLAN network managers – e.g., enterprise IT, third party, and

Wi-Fi vendor managed. Such collaboration seems especially likely in environments such as large enterprises, where hundreds of Wi-Fi APs are already deployed and where several additional years of service are expected.

It should be noted that LWIP requires a new security gateway and that IPSec needs to be supported by both eNB and UE. It should also be noted that some components of LWA, such as flow control and packet ordering, are not supported in LWIP.

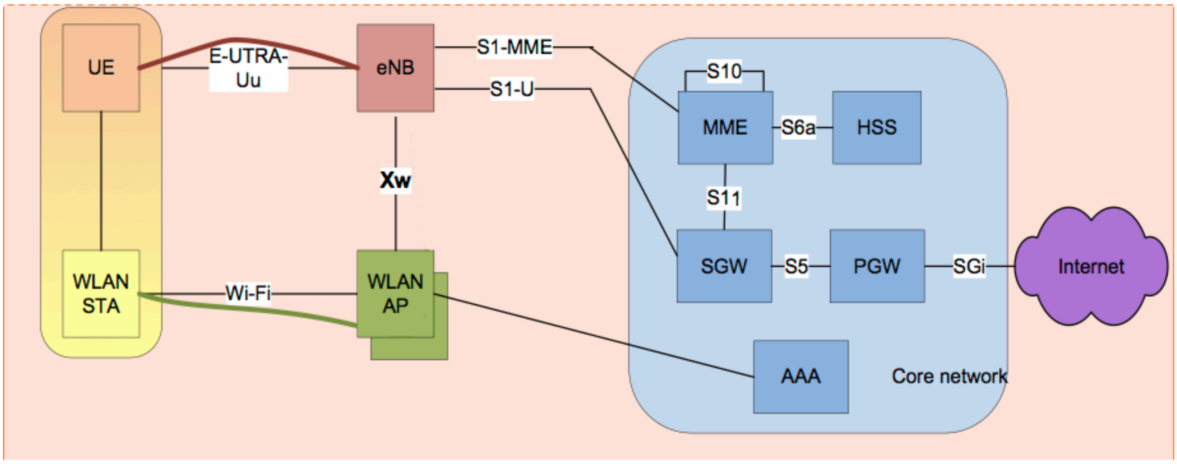

Figure 3–3 LWA architecture - integrating LTE eNB with unmodified WLAN

The LWIP architecture for integrating LTE eNB with unmodified WLAN is illustrated in Figure 3–3. To secure access to the eNB and to transport the user payload over WLAN access, an IPsec tunnel is established between the UE and the LWIP-SeGW. The IPsec tunneling approach leverages many of the concepts used for supporting Wi-Fi Calling (this is also applicable to LWA), and ensures that the solution requires no changes to WLAN infrastructure, other than to ensure users are permitted to establish an IPSec tunnel to the LWIP-SeGW.

Based on Wi-Fi and LTE link measurements that are determined by RRC signaling and operator-determined policy and thresholds, the eNB dynamically configures usage of both LTE and Wi-Fi access for the DL and UL IP packet data bearers at the UE. Typical policies for the combined use of LTE and WLAN capacities for data packets include, but not limited to, selection of LTE or WLAN link for an IP packet based on QCI (per bearer switch), per IP flow (5 tuple based) based intra-bearer split and data volume based distribution.

The determination of the DL and UL paths by the eNB occur independently of each other. For example, in uncongested WLAN environments where there are only few users and WLAN signal strength is good, UL traffic can be transported over the WLAN, the eNB may originally start with DL and UL occurring across the WLAN but as the user moves away from the WLAN AP, switch the UL path to LTE while maintaining DL across Wi-Fi. (Such IP flow-level split at the eNB requires deep packet inspection. This has a major impact on the eNBs.)

By leveraging multiple spatially distributed Wi-Fi APs under the coverage of an eNB, LWIP alleviates the issue of poor and non-uniform per-user LTE throughput in multi-user scenarios, particularly for cell-edge users. The data packets sent and received over the Wi-Fi link bypass the LTE data plane protocol stack. This allows available Wi-Fi capacity to be used regardless of UE's LTE protocol stack capacity.

LWIP offers clear separation of the bearer functions (via IP packet distribution above the PDCP layer) and control functions (i.e., RRC Signaling for configuration) with no impact to data plane inside the LTE and Wi-Fi protocol stacks. Networking at an IP layer inherently supports multiple interfaces. So extending LWIP to include newer and greater than two interfaces at a time is simply a matter of adding an extra rule in the IP routing and ensuring support by the eNB and UE to negotiate the availability of new/multiple interfaces. Most, if not all, of these changes can be accomplished via software changes to the eNB and UE. LWIP is therefore a future-ready solution that can evolve to support multi-connectivity - a key requirement for enabling new, high bandwidth applications.

Further technical details on LWIP can be found in Appendix A .

3.1.2 LAA: Overview and specification status

In 3GPP terminology, License Assisted Access (LAA) describes the standards for supporting LTE operation in unlicensed spectrum. The LAA study phase was kick-started with the 3GPP workshop on LTE unlicensed in June 2014 [3] followed by the 3GPP study item (SI) in September 2014 [4]. After completion of the study item in June 2015 [5], the LAA work item (WI) [6] was established to finalize the detailed specifications in Release 13 that were eventually completed in December 2015.

The SI [4] identified potential LAA solutions needed to support LTE operation in the 5 GHz band, reported existing regulatory requirements for LTE deployment in the 5 GHz band, and provided a performance evaluation of the technology when operating in the 5 GHz band. Moreover, the SI identified coexistence mechanisms that are required to ensure fair coexistence between LAA and Wi-Fi and across multiple LAA networks.

The SI considered that LAA should be supported in the context of carrier aggregation (CA) operation to aggregate a primary cell, using licensed spectrum, and a co-located secondary cell, using unlicensed spectrum. Therefore, the support for dual connectivity and LTE stand-alone access to the unlicensed spectrum are not considered in the SI.

The main aims of the work item [5] were to specify a single global solution framework for LAA in the 5 GHz band, agree an LAA design that enables fair and effective and LAA coexistence with Wi-Fi and other LAA networks (based on recommendations and conclusions from the SI), and define the necessary band/bands combinations that enable LTE operation in the 5 GHz band. Finally, the LAA WI specified support for DL-only LAA operation in Release 13. The support for LAA operation in UL is targeted for completion in Release 14.

LAA was designed in 3GPP Release 13 to co-exist with other systems utilizing the same unlicensed spectrum. Fundamentally, it has to conform to the existing requirements for the unlicensed band it will operate in. These usually include maximum equivalent isotropically radiated power (EIRP) for the respective use cases (indoor or outdoor). Table 3–1 gives the use cases and the maximum EIRP requirements in different regions, where the maximum EIRP includes the potential antenna gain. In Table 3–1, ‘indoor’ represents only indoor deployment is allowed in the sub-band in the region, while ‘NA’ means the sub-band is not available for unlicensed use in the region. Some specific bands which are inconsistent with the declared sub-bands in the headers in the table are also indicated.

Sub-bands	5150-5250MHz		5250-5350MHz		5470-5725MHz		5725-5850MHz	
Region	Deploy	EIRP(dBm)	Deploy	EIRP(dBm)	Deploy	EIRP(dBm)	Deploy	EIRP(dBm)
EU	Indoor	23	Indoor	23	Indoor or Outdoor	30	NA	NA
US	Indoor or Outdoor	eNB: 30 UE: 24	Indoor or Outdoor	30	Indoor or Outdoor	30	Indoor or Outdoor	30
Canada	Indoor or Outdoor	23	Indoor or Outdoor	30	Indoor or Outdoor (5470-5600 and 5650-5725)	30	Indoor or Outdoor (5725-5825)	36
China	Indoor	23	Indoor	23	NA	NA	Indoor or Outdoor	33
Japan	Indoor	23	Indoor	23	Indoor or Outdoor	30	NA	NA
Korea	Indoor (5100-5250)	23	Indoor or Outdoor	30	Indoor or Outdoor (5470-5650)	30	Indoor or Outdoor (5725-5825)	29 or 30
India	Indoor	23	Indoor	23	NA	NA	Indoor (5725-5875) Outdoor (5825-5875)	Indoor: 23 Outdoor: 30
Taiwan	NA	NA	Indoor	23	Indoor or Outdoor	30	Indoor or Outdoor	36

Table 3–1 Maximum EIRP requirements in some regions

In addition to the maximum EIRP, dynamic frequency selection (DFS) and transmission power control (TPC) are also mandated in some specific bands to protect the transmissions of satellites and radar using the same 5 GHz frequency band. The DFS requires the transmission device to persistently check for co-channel interference and switch to another clean carrier when it is detected to avoid occupying the same carrier with the satellite or radar system. According to TPC requirements, the device needs to ensure a mitigation factor on the aggregate power to suppress the interference to radar, where the mitigation factor is at least 3dB for Europe and Korea, and 6dB for USA, Canada and China. The DFS and TPC mechanisms can be achieved by updating the eNB implementation and have little impact on LAA standardization.

Another significant approach to target fair co-existence among transmission nodes of different RATs or belonging to different operators is to specify a moderate and efficient channel access mechanism. As one of the major incumbent RATs operating on 5GHz band, 802.11 a/n/ac make use of the channel by adopting carrier sense multiple access with collision avoidance (CSMA/CA) mechanism in the media access control (MAC) protocol, where the transmitter contends the channel using a distributed coordination function (DCF) manner. In order to avoid causing severe interference and target fair medium sharing with co-existing 802.11 based equipment such as Wi-Fi, 3GPP LAA adopts the 'listen-before-talk' (LBT) mechanism, similar to the approach in Wi-Fi, to achieve a single global framework which complies with the regulations all over the world.

Using LBT, each transmitter has to sense the channel prior to data transmission. If the channel is sensed as idle, the transmitter can occupy the channel, which has to be relinquished after a maximum continuous occupancy time. Otherwise the transmission has to be deferred. The eNB can dynamically occupy the channel based on the detected medium status, which both alleviates the delay issue and effectively balances the channel occupancy among co-existing transmitters.

Detailed design of the LBT mechanism

Listen before talk (LBT) has been adopted by 3GPP as the LAA channel access mechanism because of its ability to support fair channel contention and regulation compliance. The LBT mechanism, together with the maximum continuous channel occupancy duration, are mandated in some regions, e.g. Europe and Japan. The main procedures related to LBT are:

- Clear channel assessment (CCA) procedure for downlink
- Contention window size (CWS) adjustment
- Adaptive configuration of energy detection threshold
- Multicarrier LBT

More details on these procedures can be found in Appendix B .

Other important changes to LAA as a result of R-13 include frame structure for unlicensed spectrum and CSI and RRM measurements. These are also described in detail in Appendix B .

Huawei-DoCoMo trial

An early pre-Cat 4 field trial[1] conducted by NTT DoCoMo and Huawei in July 2015 is described in Figure 3–4.

[1] In this early field trial, the energy detection was -72dB – i.e., the same as in 3GPP. Although the backoff window for CCA was not used, a suitable random number was set manually for CCA in order to guarantee that LAA and Wi-Fi use the almost same time resources (about 50%:50% time).

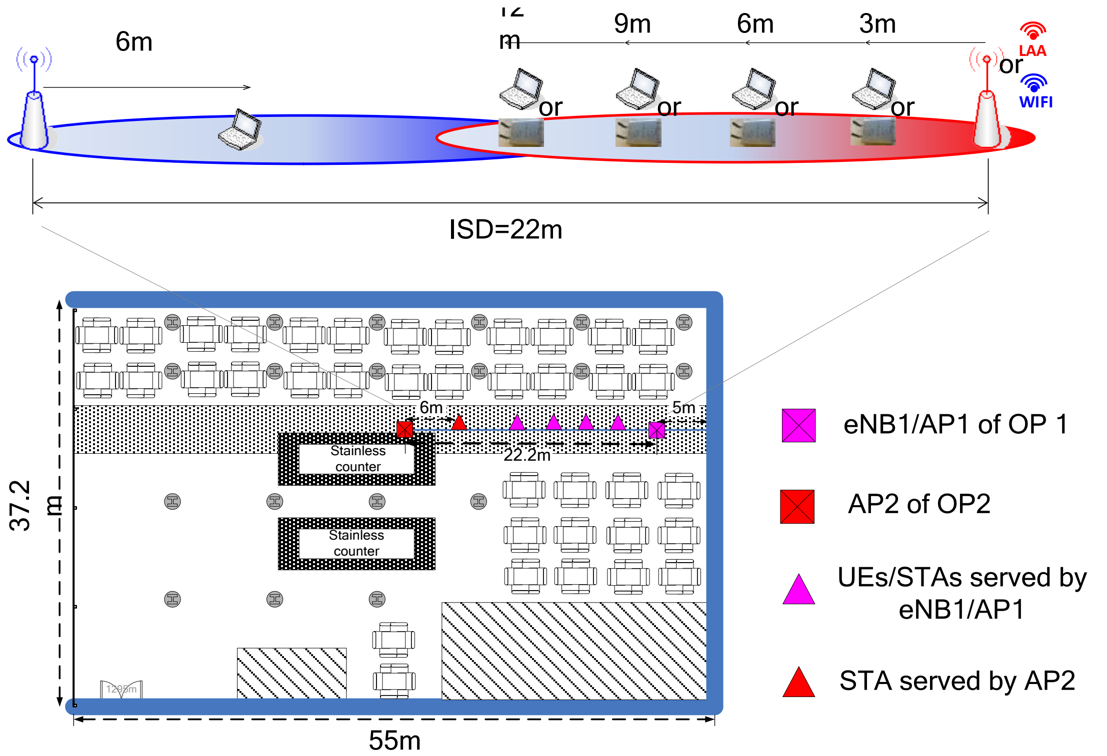

Figure 3–4 Indoor deployment for experimental tests for LAA and Wi-Fi co-existence

Single cell coverage

In this example, LAA or Wi-Fi cell are deployed, UE/STA moving radial from cell center to cell edge, record average user throughput of each test points, average user throughput determined over a several minutes.

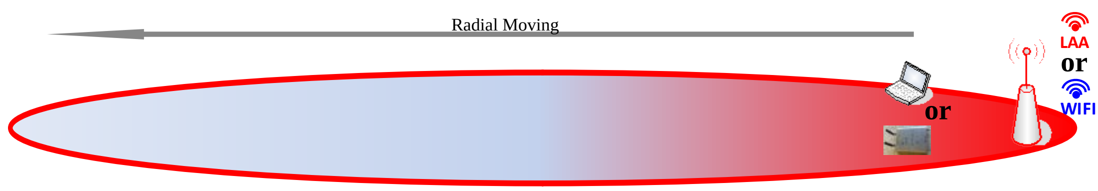

Figure 3–5 Indoor deployment for LAA and Wi-Fi coverage

According to the results described in Figure 3–6, it can be seen that at the cell-edge throughput requirement (10Mbps), LAA coverage can achieve more than 1.5 times that achievable with Wi-Fi.

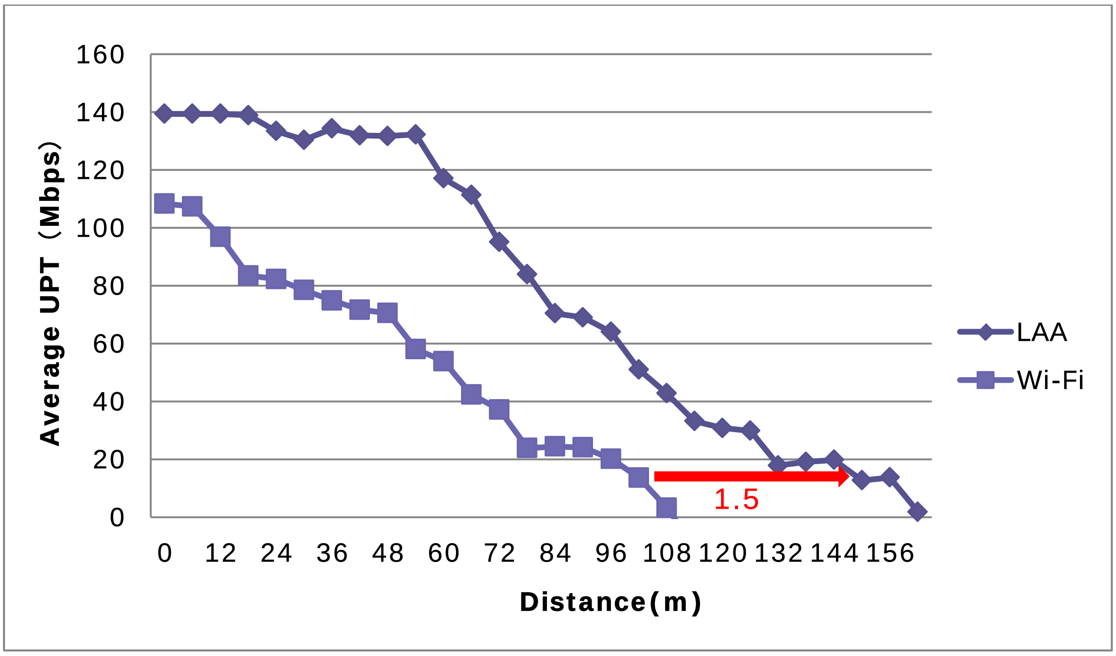

Figure 3–6 Experimental test results for LAA and Wi-Fi coverage

Single cell capacity

In this case, LAA or Wi-Fi cell are deployed, four UEs/STAs are distributed from cell center to cell edge, record average user throughput of each UEs/STAs.

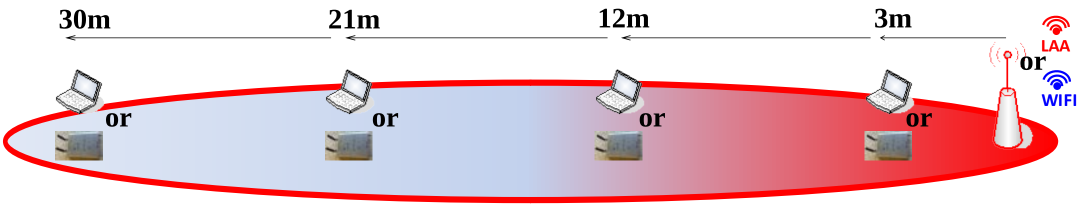

Figure 3–7 Indoor deployment for LAA and Wi-Fi capacity

According to the results described in Figure 3–8, it can be seen that LAA average cell throughput can achieve 1.67 times compared with Wi-Fi.

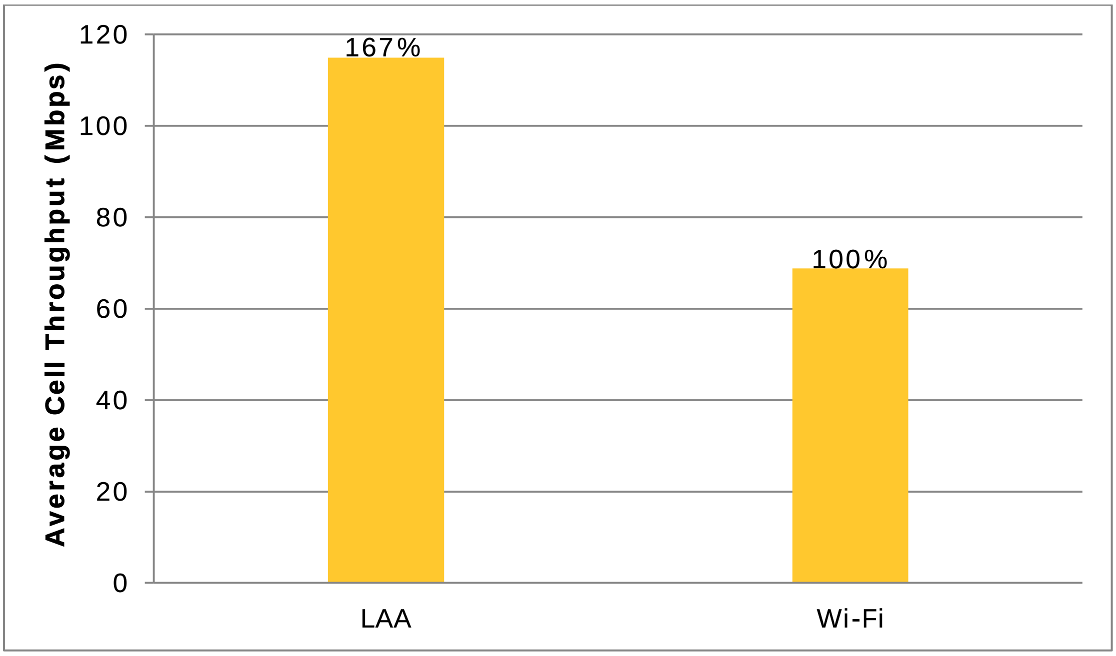

Figure 3–8 **Experimental test results for LAA and Wi-Fi capacity**

LAA co-existence with Wi-Fi

In this case, two available sites with 22.2 meters distance between each other are deployed within an indoor room. The reference network is a Wi-Fi AP with one STA. The performance of the reference system was observed in the case of a neighbor Wi-Fi AP or LAA eNB being present respectively. All Wi-Fi APs and LAA eNB are operated on 5.8G Hz band and 3GPP standardization compatible LBT scheme is adopted by LAA. It can be shown from the test results described in Figure 3–9 that LAA outperforms co-existing Wi-Fi system in terms of both cell center and cell edge throughput. Moreover, the reference Wi-Fi network also benefits with around 10% throughput gain when the co-existing site is replaced with a LAA network.

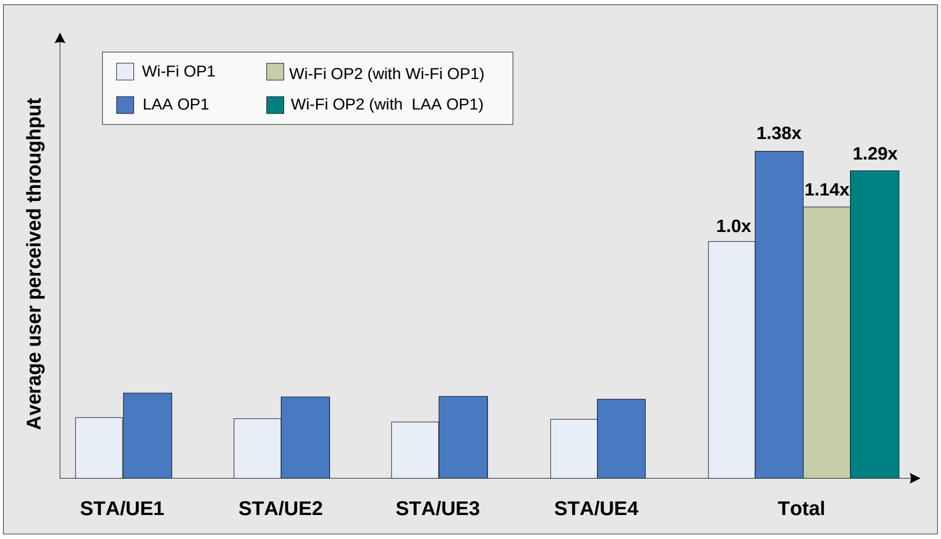

Figure 3–9 **Experimental test results for LAA and Wi-Fi co-existence**

Qualcomm-Deutsche Telekom LAA trial

Another LAA trial was performed by Qualcomm and Deutsche Telekom in Nuremburg in November 2015 [7]. Part of the trial involves two LAA eNBs and collocated Wi-Fi APs being set up on the roof of an office building (as shown in Figure 3–10). In the course of the trial, a van was driven around the building to measure the coverage of the respective technologies. Figure 3–11 shows much better coverage is achieved with LAA than Wi-Fi. It is possible to achieve 10 Mbps or higher throughput with LAA in more than double the locations along the drive route than with Wi-Fi.

Figure 3–10 Nuremburg trial topology

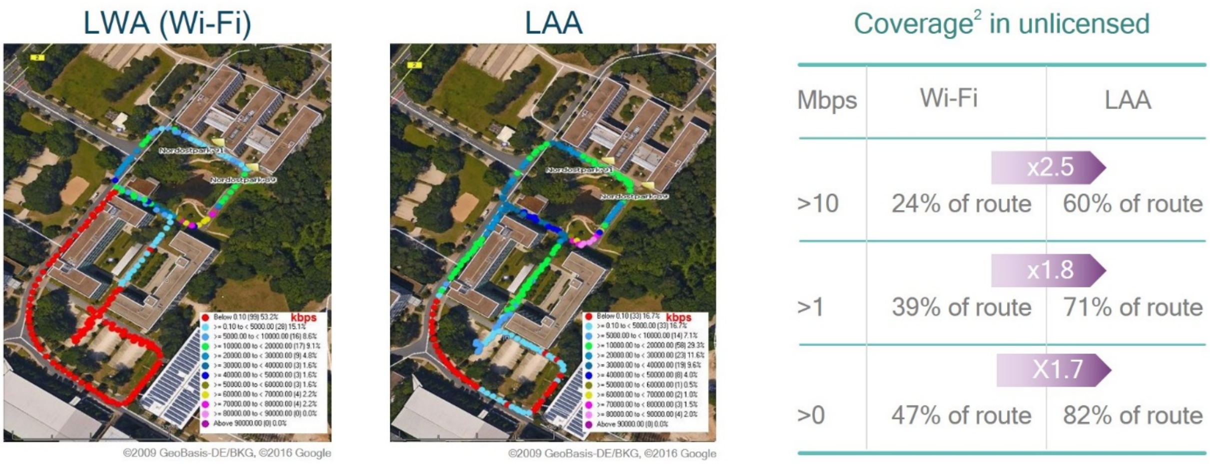

Figure 3–11 LAA has much larger coverage than Wi-Fi

3.2 Additional technologies with a licensed anchor defined outside of 3GPP

3.2.1 LTE-U: Overview and status

In markets such as US, South Korea, China and India, where listen before talk (LBT) is not mandated in unlicensed spectrum, some operators interested in early deployment may consider aggregating their existing licensed LTE network with additional LTE-based carriers in the unlicensed spectrum. For such carriers, one possible option is LTE-U. The LTE-U Forum was formed in 2014 by Verizon in cooperation with Alcatel-Lucent, Ericsson, Qualcomm, and Samsung. LG Electronics also joined the Forum at a later date. This collaboration generated technical specifications for LTE-U operation in the 5 GHz UNII-1 and UNII-3 bands as supplemental downlink (SDL) carriers [8].

Without LBT, legacy LTE (Release 10/11/12) can attempt to co-exist with Wi-Fi (and other technologies) by employing other coexistence mechanisms. In LTE-U, there are three features for coexistence with Wi-Fi: channel selection, carrier-sensing adaptive transmission (CSAT) and opportunistic SDL.

LTE-U eNBs will scan the unlicensed band and identify the least loaded channel(s) for SDL transmission. Such measurements are performed at the initial power-up stage and periodically during operation. If a chosen channel becomes loaded later due to other users being introduced, the LTE-U eNB will switch to another channel with less interference.

As more nodes are deployed in the unlicensed band, there will be periods during which no channel in the band is unoccupied. Under these circumstances, the LTE-U node will share the channel with neighboring users. The CSAT algorithm is designed in a similar philosophy as LBT or carrier sensing multiple access (CSMA) by pursuing fair co-existence with other users in a TDM fashion. The LTE-U eNB will sense the channel's utilization periodically and gate off its transmission accordingly. The duty cycle of the LTE-U eNB varies with the load of the channel. As the channel load increases, the LTE-U duty cycle decreases and vice versa.

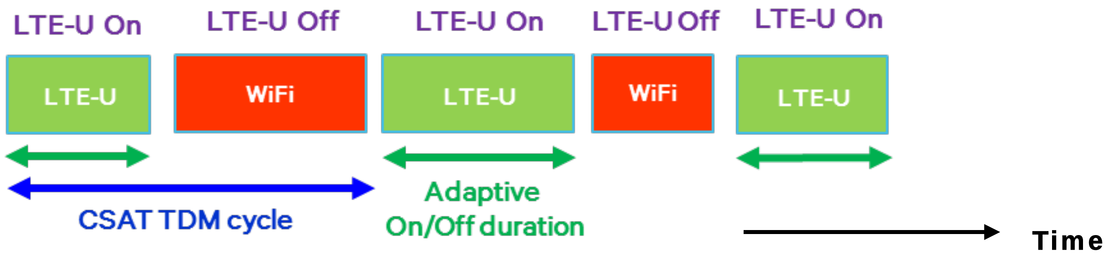

Figure 3–12 Co-existence of LTE and Wi-Fi using CSAT

In order to further reduce interference to other users in the unlicensed band, the LTE-U eNB will only opportunistically transmit in the unlicensed band in SDL mode. The criteria for the LTE-U eNB to enable the SDL carrier is when its downlink traffic exceeds a threshold and when there are active users within its unlicensed band coverage. When these conditions are not met, the LTE-U eNB will turn off its unlicensed transmission and use only its anchor carrier in the licensed band.

MWC 2015 offered a large number of LTE-U demonstrations, including those of Alcatel-Lucent, Ericsson, Huawei, Korea Telecom, Nokia, Qualcomm, Rhode & Schwartz, Samsung, and Vodafone.

Laboratory tests of LTE-U coexistence with Wi-Fi have been conducted by several organizations.

Qualcomm-ETRI LTE-U trial

In November 2015, the Electronics and Telecommunications Research Institute (ETRI) collaborated with Qualcomm on a trial of LTE-U in ETRI's facilities in Korea [9] [9]. Up to 30 Wi-Fi connections (using commercially available APs and STAs) share a 20 MHz channel in 5 GHz with LTE-U neighbors. Results from the trial reveal that when in a dense Wi-Fi deployment where Wi-Fi users are located relatively close to their serving APs, Wi-Fi is not negatively impacted if a Wi-Fi neighbor is replaced with LTE-U. As more Wi-Fi nodes are replaced by LTE-U, the throughput of the remaining Wi-Fi users remains unaffected. At the same time, the total network throughput increases, due to the higher throughput achieved by the LTE-U nodes.

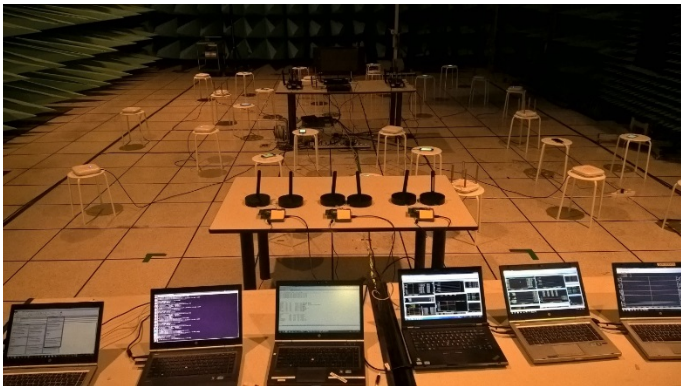

Figure 3–13 LTE-U trial setup in ETRI's lab

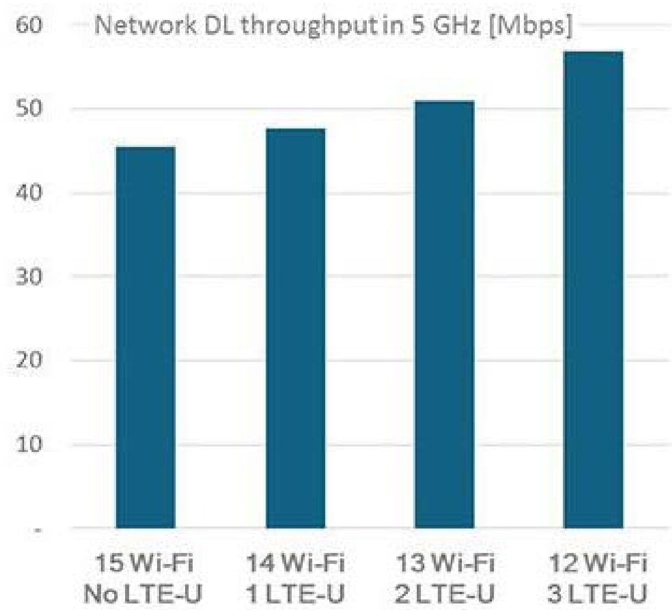

Figure 3–14 Increasing network throughput as Wi-Fi nodes are being replaced by LTE-U nodes

Other trials

In late 2015, CableLabs conducted its own tests on LTE-U coexistence with Wi-Fi [10]. Wi-Fi throughput was measured both in the case of two Wi-Fi networks coexisting and the case of one Wi-Fi and one LTE-U network coexisting. In both cases, the two networks shared the airtime equally. The results (see Figure 3–15) show that a coexisting LTE-U network causes the Wi-Fi throughput to degrade by 43% compared to a coexisting Wi-Fi network.

Similar results have been found in coexistence tests reported by multiple companies, e.g. [11], [12]. In particular, poor coexistence is seen to occur in scenarios where the interference levels are sufficient to negatively impact SINR but the networks cannot hear each other's' transmissions (since LTE-U nodes do not understand Wi-Fi signals). In addition, even in cases where airtime is shared fairly evenly, Wi-Fi throughput is still negatively impacted because the unexpected interference bursts from LTE-U nodes affect Wi-Fi rate adaptation algorithms and give rise to high retransmission rates.

A Coexistence Task Group has been setup in the Wi-Fi Alliance, with strong participation across the LTE-U and Wi-Fi ecosystems, to investigate coexistence issues further. In particular, it is developing a test plan for LTE-U devices designed to ensure that they meet an agreed set of requirements for good coexistence with Wi-Fi.

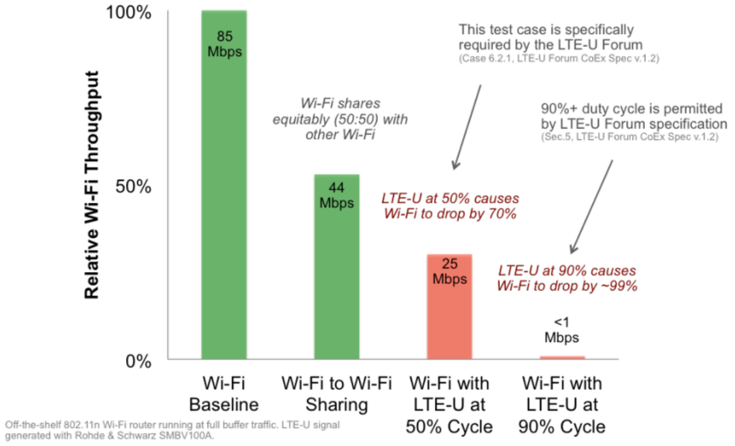

Figure 3–15 LTE-U causes Wi-Fi performance to degrade

4. High-level benefits

With aggregation of licensed and unlicensed spectrum, a user has simultaneous access to both spectrum as opposed to having to choose one. (Such a decision may be made automatically by the connection manager on the phone today.) One common and undesirable situation today is when multiple users compete for resources on the unlicensed spectrum (using Wi-Fi) while the licensed network (LTE) in the same area is lightly loaded. Aggregating the spectrum will avoid such problems. In addition, the user has the possibility of achieving a higher peak data rate (similar to carrier aggregation). For LAA AND LTE-U, since the same technology is used in licensed and unlicensed spectrum in one network, this may make it simpler for the operators from a network management point of view since there is only a single network to deal with.

5. Combining licensed LTE with unlicensed Wi-Fi: Use cases and deployment scenarios

Operators with existing Wi-Fi networks and those that plan to invest in Wi-Fi infrastructure may want to deploy technologies that aggregate LTE with Wi-Fi. Operators may choose between LWA and LWIP depending on whether their existing Wi-Fi infrastructure can be upgraded to support LWA or not.

For both options, the Wi-Fi network supporting LWA or LWIP can be deployed in the same way as Wi-Fi networks are currently deployed – i.e., via indoor or outdoor hotspots, as required.

Operators with upgradeable Wi-Fi APs or controllers can look at LWA as a means of integrating their LTE and Wi-Fi networks.

Operators deploying small cells in enterprise locations may want to partner enterprise IT teams to enable the business's WLAN to be integrated into the small cell infrastructure. In this instance, LWIP may be more applicable to enable the service to be deployed over the legacy enterprise WLAN. With an enterprise small cell deployment, the LWIP-SeGW may be available locally, avoiding any re-configuration requirements associated with IPSec traversal across the enterprise firewall.

6. Extending benefits of LTE to unlicensed spectrum: Use cases and deployment scenarios

Due to the limited transmit power in unlicensed spectrum, it is expected that LAA or LTE-U will mainly be deployed by way of small cells. The regulation for unlicensed spectrum means that LTE-U deployments can only take place in markets where LBT is not mandated. On the other hand, LAA can be deployed whether or not LBT is required.

Given that operators are likely to employ LAA or LTE-U for capacity enhancement, it seems certain to be deployed strategically in hotspots.

It should be noted that LAA/LTE-U and LWA/LWIP are not mutually exclusive. It is possible for an operator to deploy some of these technologies simultaneously to serve different users or in different locations.

7. Operator considerations

A number of technologies that aggregate licensed and unlicensed spectrum were described in this paper. Different operators may have different preferences among these technologies according to their needs and current network configuration. The goal of this paper is not to provide a universal recommendation for all operators but rather to present the various technologies and point out their respective merits.

For operators intending to retain their existing Wi-Fi infrastructure, they may choose to deploy LWA and/or LWIP for tighter integration of their existing LTE and Wi-Fi networks. In particular, the choice between these technologies will depend in part on the Wi-Fi network architecture and upgradability of the Wi-Fi APs and/or Wi-Fi controllers. On the other hand, an operator with plans to upgrade or expand its Wi-Fi network may come to a different conclusion. Alternatively, operators can consider collaborating with third parties to provide the WLAN infrastructure to support LWIP integration.

For operators with little or no Wi-Fi infrastructure, LAA or LTE-U (applicable only to markets where LBT is not mandated) are options. These technologies also offer the best value if the operator wants to maximize the spectral efficiency of its network with a given amount of unlicensed spectrum. LAA or LTE-U would also appeal to operators wanting a more consistent user experience in licensed and unlicensed spectrum (for example, robust mobility already supported in licensed LTE will apply to unlicensed LTE).

Other considerations between the different technologies may relate to achievable throughputs. This will depend on the spectral efficiency of the different approaches, as well as the aggregate channel bandwidths used; with the former leading to a preference to LAA or LTE-U and the latter being a function of what bandwidths are configured for LWA/LWIP (20, 40, 80 or 160 MHz) versus the number of 20 MHz LTE-U carriers being aggregated.

Given that all of the above technologies involve unlicensed spectrum, which comes with a lower limit on transmit power than in licensed spectrum, it is expected that these technologies will mainly be deployed on small cells for indoor use cases. These include scenarios ranging from homes, offices, enterprises, venues, shopping malls, airports and any other indoor hotspots. With a dense deployment, however, these technologies can also be deployed to cover outdoor hotspots such as parks.

It should be pointed out that an operator may deploy one or more of the above technologies to cater to the needs of different scenarios. For example, an operator may use Wi-Fi and LTE on separate unlicensed carriers and aggregate these carriers with its licensed LTE network using different technologies.

8. Miscellaneous considerations

Support of 5 GHz unlicensed spectrum is not new to UEs today given the popularity of Wi-Fi. However, since licensed and unlicensed carriers will be simultaneously enabled, care needs to be taken about possible intermodulation. In addition, if a device needs to concurrently support LTE and Wi-Fi in 5 GHz, it will need to consider how close in frequency LTE and Wi-Fi can be to avoid interference between the 2 technologies.

Other than procedures defined in the standards, additional traffic management policies could be introduced in a network that aggregates both licensed and unlicensed carriers. For example, different applications or users can be preferentially put on licensed or unlicensed carriers based on their performance requirements or service plan. More specifically, service-level co-existence issues may depend on existing use of the Wi-Fi infrastructure. In particular, if an operator has already deployed Wi-Fi Calling service with the service being configured as preferring IMS service over Wi-Fi versus LTE, the interaction between this existing service and LWA and LWIP configurations need to be considered.

As the technologies discussed in this paper will mainly be deployed in areas with high data demand, they are not expected to have ubiquitous coverage. As users move away from the hotspots, they should seamlessly hand over to the licensed LTE network.

In general, unlicensed or shared spectrum lends itself to the neutral host model, where the same network can serve users from different operators on a common channel (not operator-specific) supported by terminals used by most, if not all, subscribers. However, since this paper focuses on technologies with a primary carrier in licensed (operator-specific) spectrum, neutral host is not applicable.

9. Conclusions

The technologies discussed in this paper allow resources from licensed and unlicensed spectrum to be pooled together by the network to serve the users. Operators can leverage these technologies to meet the growing data demand from their users. LWA and LWIP caters to operators that still want to keep a Wi-Fi network to complement their LTE networks, or to leverage third-party Wi-Fi installations.

LAA and LTE-U combine the licensed and unlicensed spectrum under a unified network, while delivering higher efficiency and better coverage than Wi-Fi. At the same time, they preserve the benefits of LTE such as robust mobility.

It is expected that small cells will be the main platform on which these technologies will be commercialized.

Definitions/glossary of terms

LTE-U: The use of LTE in unlicensed spectrum while still having an LTE carrier in licensed spectrum as anchor. This technology is based on LTE R10/11/12 standard with added 5 GHz RF support and co-existence features. It is targeted for markets where Listen Before Talk (LBT) is not mandated in unlicensed spectrum, such as US, South Korea, China, India etc. The LTE-U Forum has published a technical report and various specifications on LTE-U.

Licensed Assisted Access (LAA): The use of LTE in unlicensed spectrum with an LTE carrier in licensed spectrum as anchor with LBT as one of the co-existence features. LAA will be standardized by 3GPP in the Release 13 specification for unlicensed SDL. Extensions to uplink traffic in unlicensed band are anticipated in Release 14. In markets such as Europe, operating in unlicensed spectrum requires support of LBT.

LTE Wi-Fi Aggregation (LWA): The aggregation of LTE in licensed spectrum and Wi-Fi in unlicensed spectrum above the MAC layer. 3GPP is standardizing this feature for Release 13.

Listen Before Talk (LBT): A technique defined by ETSI (ETSI EN 301 891 v1.7.1) that allows multiple nodes to share the same radio channel without coordination. A node that plans to transmit on a channel has to "listen" to a channel to estimate its loading and determine whether it can transmit without causing interference to other users.

ETSI BRAN: European Telecommunications Standards Institute (ETSI) develops a number of standards on various areas in telecommunications. The Broadband Radio Access Networks (BRAN) project was established by ETSI in 1997 focusing on standards for various Broadband Wireless Access (BWA) technologies.

LTE-U Forum: The LTE-U Forum (http://lteuforum.org/) was formed by Verizon together with a number of companies in 2014. The forum prepared several technical documents for equipment that supports LTE-U in 5 GHz and defined performance and co-existence requirements. After the publication of these documents, the forum held a workshop in May 2015 to share the results with the industry.

Supplemental Downlink (SDL): A special case of Carrier Aggregation (CA) in which the secondary carrier only supports downlink (DL) traffic. All uplink traffic and control channels have to go through the primary carrier.

Channel Selection: A co-existence feature in which the eNB chooses a clean channel to operate in order to avoid or minimize interference to other users of the unlicensed band.

Carrier-sensing Adaptive Transmission (CSAT): A co-existence feature in which the LTE-U eNB adaptively changes its duty cycle in the unlicensed band based on the channel utilization.

Unlicensed National Information Infrastructure (U-NII): U-NII-1/2/3 are 3 unlicensed frequency bands in 5 GHz designated by the FCC for high-speed wireless communication.

Appendix A Further technical background on LWIP

LWIP Network Architecture

Figure A–1 illustrates the 3GPP LWIP architecture [3GPP TS 36.300].

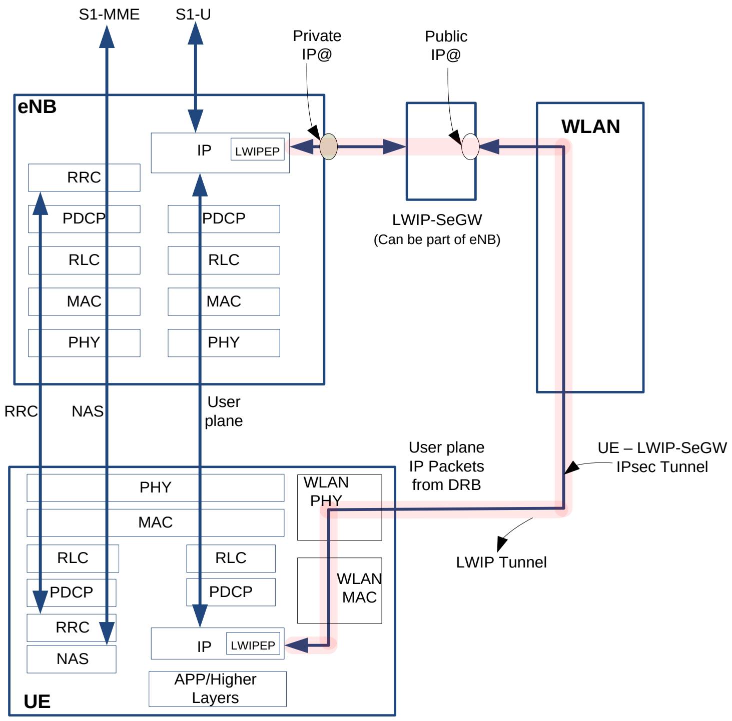

Figure A–1 Detailed LWIP architecture

An IPsec tunnel is established between the UE and terminating at LWIP-SeGW, for securing access to eNB and transport of user payload over WLAN access. IPsec tunneling also ensures that the solution requires no changes to WLAN infrastructure. LWIP-SeGW functionality also ensures protection of the operator's network from external access via the WLAN. It also provides security for the data sent over the WLAN network by using an IPsec tunnel connecting the eNB and the UE. Since the LWIP-SeGW and eNB interface is not specified, LWIP-SeGW can be considered as a function placed between the eNB and WLAN. The LWIP-SeGW functionality can be incorporated in to the eNB via a software only modification to the eNB. The end to end path between the UE and eNB, composed of the interface between the eNB and LWIP-SeGW and the IPsec tunnel between the LWIP-SeGW and UE, is termed the LWIP Tunnel. IP Packets between the eNB and the UE are transported over this secure LWIP Tunnel path. Since the transport of IP packets via the WLAN network is over an IPsec tunnel, LWIP does not impose any requirements, including security, to be fulfilled by the WLAN network beyond basic IP layer connectivity between the WLAN and eNB, which may require adjusting enterprise firewall rules appropriately.

From a control plane perspective, the eNB provides necessary IPsec tunnel establishment parameters to the UE (which is connected and authenticated via LTE) using Radio Resource Control (RRC) messages over the LTE access. The RRC signaling between the UE and eNB also includes UE reporting of WLAN link measurements, e.g. WLAN Received Signal Strength Indicator (RSSI). Based on UE WLAN condition measurements, the eNB makes real-time determinations on which DL and UL paths (e.g., WLAN or LTE) are optimal for the user. The eNB then informs the UE which DL and UL IP packet data bearers can be transported over the LWIP tunnel and the LTE access based on the provisioning policy and operator determined thresholds.

From the bearer plane traffic perspective at the eNB, IP packets are routed at a layer above the PDCP layer and sent to the UE via the LWIP Tunnel over the WLAN and/or via the LTE access. The IP packets are received from the LWIP Tunnel and/or LTE access at the IP layer before forwarding to upper layers.

Aspects of Packet routing performed above the PDCP layer:
Similar to LWA, LWIP places user data routing functions and the selection of data delivery path (i.e., LTE and/or WLAN Wi-Fi) at the eNB. Unlike LWA, which performs the routing at the PDCP layer of the protocol stack, LWIP performs the routing above the PDCP layer. The user's IP packets, as determined through signaling between the UE and eNB, are either transmitted via the LTE access and/or via the WLAN path. The UE category is a factor to be considered in estimating the maximum throughput that can be handled by the UE's LTE protocol stack implementation (e.g. DL PDCP PDU processing limits based on UE category [3GPP TS 36.306]). Some lower category UE LTE implementations may not be sized to handle the large data rates even if their Wi-Fi firmware and higher layers support those data rates. Therefore, UE's LTE category should also be considered in LWA for effectively leveraging high data rates provided by Wi-Fi. The LWIP method of IP layer integration bypasses the LTE RAN data plane protocol stack when transporting packets over the WLAN path. And therefore, unlike LWA, LWIP allows available Wi-Fi capacity to be used regardless of UEs LTE protocol stack capacity.

Unlike LWA in R-13, which covers only downlink aggregation, LWIP in R-13 allows optimal use of resources in dynamic conditions by supporting UL data traffic over the WLAN. UL data traffic on the WLAN is particularly useful for applications like video conferencing where large UL capacity is required. However, it is to be noted that UL aggregation of LTE and WLAN will be addressed by 3GPP in R-14. For supporting transfer of UL data on the WLAN path, LWIP Encapsulation Protocol (LWIPEP) is introduced to specify an encapsulation header for conveying LTE Data Radio Bearer (DRB) Information associated with the UL IP packets for the eNB to select the correct S1-U tunnel in routing towards the LTE core network.

Appendix B Further technical background on LAA

Detailed procedures and parameters for downlink and uplink transmissions are described below:

Clear Channel Assessment (CCA) procedure for downlink
A generic downlink CCA procedure is backoff based LBT with variable contention window size (CWS). In detail, an extended CCA (ECCA) check should be performed before a downlink transmission can occur. At the start of an ECCA check, a backoff counter N is randomly generated in the range 1 to q, where q denotes the CWS with the range from CWS_min to CWS_max. The counter N is decremented by 1 every time the medium is considered to be idle during an ECCA slot of e.g., 9us, and held on if the medium is sensed as busy. When N reaches zero the transmitter may immediately occupy the channel. In addition, given that Wi-Fi ACK feedback is transmitted immediately after receiving the data transmission in several tens of \mu s, the LAA eNB should freeze for a defer period before continuing counting down the backoff counter whenever the busy channel status ends to avoid collision with Wi-Fi ACK feedback. This defer period is comparable to the Wi-Fi arbitration inter frame space (AIFS).

CWS adjustment
To achieve balanced channel access opportunities with Wi-Fi, it is also preferable to adopt variable CWS as Wi-Fi does, where the CWS is exponentially increased if the Wi-Fi transmission burst, namely Transmit Opportunity (TXOP) is not successfully received, and the CWS is reset to the minimum value otherwise. However, different from Wi-Fi where there is only one ACK/NACK for each TXOP, one transmission burst of LAA may include multiple subframes, on each one of which multiple UEs can be scheduled, thus multiple ACK/NACKs are expected from one transmission burst. The eNB needs to record the number of ACKs (N_ACK) and NACKs (N_ NACK) fed back by all UEs which were scheduled in the first subframe of the latest transmission burst. If the ratio of N_NACK to (N_ACK + N_NACK) exceeds a threshold (80%), then the CWS is doubled for the next ECCA check; otherwise the CWS is reset to the minimum value of CWS_min. In addition, when the CWS reaches the maximum value of CWS_max , the CWS can also be reset to the minimum value of CWS_min.

Energy detection threshold
For the LBT mechanism, the medium is considered to be busy if the total sensed power during the ECCA slot exceeds the CCA-energy detection (ED) threshold and idle otherwise. Specifying appropriate CCA-ED threshold for LAA is essential to target fair channel contention with Wi-Fi and achieve trade-off between frequency reuse and interference avoidance. E.g., high CCA-ED threshold may increase the channel access opportunity for LAA but introduce more interference and thereby harm Wi-Fi performances, and vice versa for low CCA-ED threshold. The CCA-ED threshold should be adaptively configured based on three principles:

- Firstly, to provide friendly channel access with co-existing Wi-Fi networks which are vulnerable to interference, a low CCA-ED threshold should be configured if the same unlicensed carrier is known to be shared with a neighboring Wi-Fi.
- Secondly, to make good use of channel in case of LAA only deployment, a higher CCA-ED threshold may be adopted by LAA if the absence of Wi-Fi on the same carrier can be ensured.
- Thirdly, given that lowering transmission power leads to decreased interference to co-existing systems, the CCA-ED threshold should be tied to the expected transmission power, by configuring higher transmission power

with lowering the CCA-ED threshold. Based on the rules, the energy detection threshold is defined as

$$X_{\text{Thresh\_max}} = \min(T_{\max} + 10\text{ dB}, Y), \quad (1)$$

if the absence of any other technology, e.g., Wi-Fi can be ensured over a long time scale, and

$$X_{\text{Thresh\_max}} = \max\left(-72\,\text{dBm (for 20MHz)}, \min\left(T_{\max}, (T_{\max} - T_A + (P_H - P_{TX}))\right)\right), \quad (2)$$

Otherwise, where $T_{\max}$ is denoted as

$$T_{\max}(\text{dBm}) = -75\text{ dBm/MHz} + 10\log 10(BW), \quad (3)$$

Y is the maximum energy detection threshold defined by regulatory requirements, BW denotes the single carrier bandwidth, T_A = 10dB for data transmission, $P_H = 23\text{ dBm}$ denotes the maximum reference power, and P_{TX} denotes the transmission power in dBm.

Multicarrier LBT

In order to fully exploit the advantage of the abundant unlicensed carriers to satisfy bandwidth-greedy data demands, simultaneous transmissions over more than one unlicensed carriers should be supported by LAA. When eNB starts transmitting on one carrier, severe self-interference will be received by other carriers in the same band due to RF leakage, which may probably prevent them from capturing the channel if they are still performing LBT. This implies that the eNB can simultaneously transmit over intra-band, especially contiguous carriers only if it achieves successful LBT over these carriers at the same time. However, it is difficult to achieve simultaneous channel contention success if the eCCA checks are individually performed over carriers. To enable LAA eNB to align the start of transmission over multi-carriers, two alternatives are presented. For alternative 1, the eNB performs backoff based LBT on one unlicensed carrier, and performs a one-shot LBT with single CCA slot on other unlicensed carriers immediately preceding the expiration of the backoff counter. The eNB is allowed to occupy the backoff based carrier if the last ECCA slot is sensed idle or the other carriers if the one-shot CCA slot is sensed idle. By alternative 2, LAA eNB can independently perform backoff based LBT on more than one unlicensed carriers. Then the eNB can defer the transmission on the carriers which have earlier finished the backoff countdown to wait for the countdown of other carriers. After the defer time, an additional one-shot CCA slot is performed over these carriers to align the start of transmissions.

Frame structure on unlicensed spectrum

For DL transmission, the eNB may capture the channel whenever it is sensed as idle due to the DL LBT mechanism. Therefore, different from legacy LTE, the DL transmission of LAA may start at middle of a subframe, and the partial subframe with less than 14 orthogonal frequency division multiplexing (OFDM) symbols could be transmitted. In addition, the eNB should relinquish the channel after a maximum channel occupancy time (MCOT) of e.g. 10 ms according to the regulation restrictions. Therefore, the last subframe of a DL transmission may also be a partial subframe. To reduce the eNB implementation complexity, the candidate starting positions of a transmission can be OFDM symbol #0 or #7, and the number of OFDM symbols in the end partial subframe while ending subframe can consist of any possible DL pilot time slot (DwPTS) configurations as in legacy LTE. Furthermore for the initial partial subframe, when the starting position is symbol #7, the control/data channels resource mapping is as the same as the first half-subframe of LAA regular subframe.

In case of eNB operating DL+UL LAA over the same carrier in unlicensed spectrum, a new framestructure (FS 3) is introduced to ensure a flexible UL/DL configuration, by which the DL transmission burst(s) and UL transmission burst(s) on LAA can be scheduled in a TDD manner while any instant in time can be part of a DL transmission burst or an UL transmission burst, different from conventional LTE TDD configuration. One example to support DL+UL LAA over the same carrier is depicted in Figure B–1, where the starting position for DL is symbol 7. UL LBT is performed by UEs prior to the scheduled UL subframes.

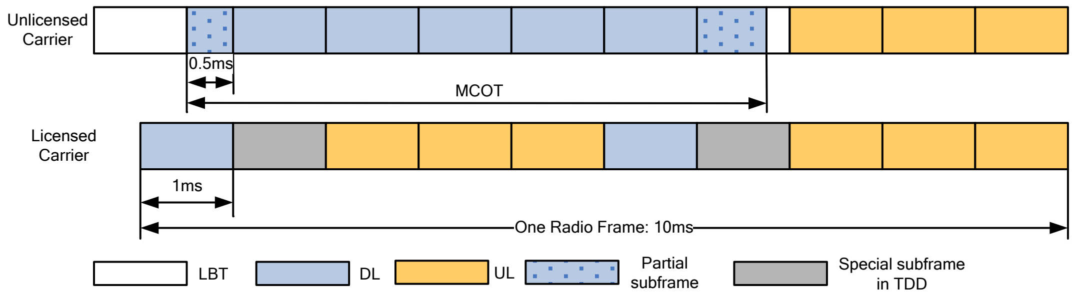

Figure B–1 LAA frame structure

CSI and RRM measurement

The discontinuous transmission incurred by the LBT mechanism also results in the challenges on the measurement of LAA, including CSI measurement, discovery reference signal (DRS) design, and received signal strength indicator (RSSI) measurement.

CSI measurement

CSI-RS measurements including channel and interference measurements are essential for the dynamic scheduling. Due to LBT, LAA eNB may not access to the channel to transmit the CRS or CSI-RS for CSI measurements. Therefore, UE should first determine that LAA eNB has transmitted the CRS or CSI-RS, e.g., by detecting the existence of the CRS or DRS, and then performs the CSI measurement. CSI measurements should be performed during the transmission duration of the measured LAA cell. In addition, the transmit power among different transmission bursts may be different considering that the number of simultaneous transmitted carriers could be different for different bursts, but the maximum transmit power should be the same for the LAA eNB. Therefore, the CSI measurements should be restricted within a transmission burst, and UE cannot average the CSI measurements across different transmission bursts.

RRM measurement

Cell identification and radio resource management (RRM) measurements including reference signal received power (RSRP), reference signal received quality (RSRQ) and received signal strength indicator (RSSI) measurements are essential functionalities for LAA cell management. Due to discontinuous transmission on an LAA cell, the Rel-12 discovery reference signal (DRS) that is transmitted within a 6 ms time window called discovery measurement timing configuration (DMTC) that appears with a periodicity of 40, 80 or 160 ms could be used as a starting point for the cell identification and RRM measurements for LAA. For the LAA DRS transmission, a prioritized LBT mechanism is used, where multiple CCA attempts can be performed within a short time window right before the starting time instant of a candidate DRS transmission, and any one successful CCA permits the DRS transmission. To further increase the transmission probability, multiple candidate time positions are introduced in the DMTC, each of which can be used for the DRS transmission. In addition, LAA DRS transmission occupies time contiguous OFDM symbols when no PDSCH is transmitted in the same subframe as the DRS, possibly with the empty OFDM symbols filled with some reservation signals. Similarly as the CSI measurement, it is desirable that the cell identification and RRM measurements can be achieved in one DRS occasion.

Received Signal Strength Indicator (RSSI) measurement

RSSI measurement and reporting can reflect the load condition around UE and furthermore help detecting hidden node in carrier selection. The hidden node issue can be illustrated in Figure B–2. Assuming that node 1 of operator A and node 2 of operator B cannot sense the transmission of each other so that the two nodes may simultaneously transmit on the same carrier. Hence the edge UE associated with node 1 may be geographically closer to node 2, which becomes a hidden node and may cause severe interference to the UE.

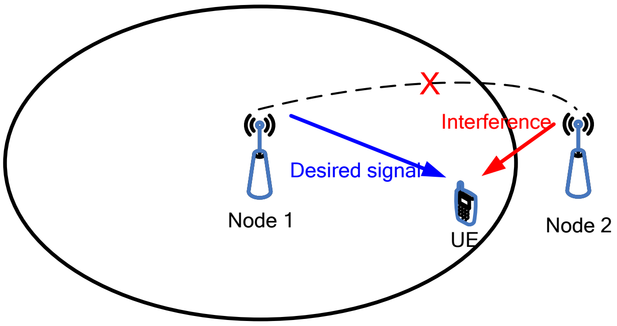

Figure B–2 Illustration of the hidden node problem

In the legacy LTE framework, RSSI measurement has already been supported but it does not require a report from the UE. Enabling the eNB to find the hidden nodes is preferable to resolve the hidden node problem by implementing carrier selection or scheduling. This can be achieved by informing the UE to additionally report the RSSI measurement to the eNB. Specifically, eNB can indicate the timing when UE should perform RSSI measurement. Therefore the eNB and UE could measure RSSI at the same time so that the hidden node can be indentified if eNB detection no or small interference while UE senses large energy over the measured carrier.

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