LWA in 5G: State-of-the-Art Architecture, Opportunities, and Research Challenges

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The authors introduce LTE WLAN aggregation (LWA). LWA, capable of leveraging the LTE and WLAN spectra simultaneously, has emerged as a prominent solution to increase network capacity and enhance end users' quality of experience. They present the latest advances in this exciting technology by reviewing the state-of-the-art LWA architecture, and identify several opportunities and open challenges related to LWA design for future research.

Abstract

To cater to the exponential increase in wireless data demands under limited availability of licensed spectrum, the Federal Communications Commission has released extra bandwidth of 295 MHz in the 5 GHz unlicensed national information infrastructure bands for wireless communications. This free, unlicensed band has drawn considerable attention from academia and cellular operators worldwide. Several standards are being developed for flexible integration, aggregation, and interworking of this unlicensed band with licensed networks or spectrum. Of many candidate approaches, in this article, we introduce LTE WLAN aggregation (LWA). LWA, capable of leveraging the LTE and WLAN spectra simultaneously, has emerged as a prominent solution to increase network capacity and enhanced end users' quality of experience. Further, we present latest advances in this exciting technology by reviewing the state-of-the-art LWA architecture, and identify several opportunities and open challenges related to LWA design for future research.

Introduction

The rise of smart devices and the consequential progression in data traffic has greatly increased the demand for high-capacity wireless systems. According to the estimates presented in [1], the cellular network anticipates an increase in network capacity by 1000 times 10 years later. Additionally, the industry sector together with utility companies, manufacturing industries, and health and education sectors are making considerable attempts to exploit the benefits of the internet of Things (IoT). Such evolution in IoT is expected to contribute billions of additional connected devices by 2020 [1]. On the other hand, spectrum resource shortage and licensing requirements for processing in the cellular band have added extra complication to the procedures to support and manage the network. Hence, some primary efforts, such as cell densification, multiple antennas, and relays, have been employed. These efforts, however, lead to interference and mobility control issues, which are costly. Therefore, the cellular industry is in a desperate search for the next set of economical innovations to secure more spectrum availability. These novelties are anticipated to form an upcoming fifth-generation (5G) wireless communications system. The 5G revolution comprises improvements such as increase in system capacity by 100–1000 times, user data rates of gigabits per second everywhere, less than 1 ms latency, 10–100 times higher density of connected devices per region, and 10 times more energy-efficient devices.

Utilizing the unlicensed spectrum efficiently by internetworking cellular and WLAN networks has emerged as a potential candidate to solve the capacity crunch in 5G. Compared to the potentially fragmented allocation of licensed spectra, unlicensed 5 GHz solutions offer mobile operators the ability to use 295 MHz of free, unlicensed spectrum space. In support, the Third Generation Partnership Project (3GPP) has proposed new approaches at the radio link layer that allow seamless integration of the unlicensed spectrum. The first of such efforts was LTE operation in the unlicensed band, which simply extends the LTE carrier aggregation used in licensed bands to the unlicensed bands. Two technology solutions have emerged using this principle: licensed assisted access (LAA) [2] and LTE in unlicensed spectrum (LTE-U) [3]. Both technologies opportunistically operate in the unlicensed band and require a channel that is hooked into the licensed spectrum. However, due to contention asymmetry [4], regulatory requirements, and cost, these technologies are hindered in global adoption [2].

LTE WLAN radio-level integration with IPsec (LWIP) [5] and LTE WLAN aggregation (LWA) [5] have appeared as an alternative to LTE-U/LAA that no longer requires new 5 GHz LTE-enabled devices and small cells for unlicensed band use. Both technologies are specifically designed to aggregate traffic over LTE and WLAN simultaneously. LWIP supports downlink switching of IP packet transmission at the network layer, whereas LWA aggregates the Packet Data Convergence Protocol (PDCP) transmission at the PDCP layer. LWIP provides a more globalized solution, as it exploits any WLAN node, whereas LWA provides greater performance because of its aggregation capabilities, which is critical for 5G. Yet another technology, led by the Internet Engineering Task Force (IETF) on LTE WLAN aggregation, is taken at the transmission control protocol (TCP) level in the case of multipath TCP (MPTCP) solutions.

All the above technologies augments the capacity and performance for cellular networks exploiting different alternatives for utilization of unlicensed spectrum (i.e., LTE operating directly in unlicensed band or through the supplementa-

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Components	Standardization	Working Group (WG)	Protocol layer	Network element	Traffic direction	Deployment eNB/AP	Access network cost	Performance gain	RAT
LTE-U/LAA	LTE-U Forum in Release 12 / 3GPP in release 13	RAN WG1	MAC layer	LTE-U/ LAA small cell	Downlink	Collocated	High	High	LTE LTE
LWA	3GPP in release 13	RAN WG2	PDCP layer	LWA eNB, WT	Downlink	Collocated/ non-collocated	Medium	High	LTE 802.11
LWIP	3GPP in release 13	RAN WG2	IP layer	LWA eNBs, LWIP-SeGW	Uplink + downlink	Non-collocated	None	Medium	LTE 802.11
MPTCP proxy	IETF in RFC6824	MPTCP WG1	Network layer	MPTCP proxy	Uplink + downlink	Non-collocated	None	High	LTE 802.11

* Green: LTE band; pink: 5 GHz; character: medium access control (MAC)/physical (PHY) layer.

Table 1. Comparison of alternative technologies in 5G.

ry channels via Wi-Fi). Thus, the use of different approaches and integration layers has important deployment and performance implications. A set of features and components of LTE-U/LAA, LWIP, LWA, and MPTCP are summarized in Table 1. From the comparison, we observe that LWA, which is capable of leveraging legacy devices and base stations, has emerged as the best alternative with high performance gain from the unlicensed band in both collocated and non-collocated scenarios. Here, we concentrate on a detailed summary of the latest standardization and regulatory efforts on LWA in 3GPP Release 13 [5], and discuss several open research challenges and opportunities related to its design.

The remainder of this article is structured as follows. The following section overviews LWA fundamentals proposed in 3GPP Release 13. Then we describe the opportunities offered by LWA for cellular industries, operators, and users. Following that, we highlight the challenges with possible research directions of LWA. Finally, conclusions are drawn.

LWA Fundamentals

LWA is a technology defined by the 3GPP radio access network (RAN) plenary in March 2016 as the evolutionary path toward 5G [5]. LWA features allow a mobile device that supports LTE and WLAN links to utilize both its links simultaneously for LTE service. For this, evolved NodeB (eNB) with updated software splits/switches the data plane traffic at the PDCP layer so that some LTE traffic is tunneled over WLAN and the rest runs natively over LTE. The traffic that flows over a WLAN is collected at the WLAN access point and then is tunneled back to the LTE user, which anchors the session. In contrast to other LTE/WLAN carrier aggregation technology, LWA has the potential to use an unmodified WLAN air interface in the unlicensed band, that is, LTE no longer needs to operate outside of its norm because WLAN runs in its own unlicensed band, and LTE runs in its own licensed bands [6]. For the initial introduction of Release 13, LWA is limited to downlink aggregation at a 5 GHz link, but there are plans to extend and enhance LWA (eLWA) [5] with additional support for a 60 GHz band with 2.15 GHz of bandwidth, uplink aggregation, mobility improvements, and other enhancements in Release 14.

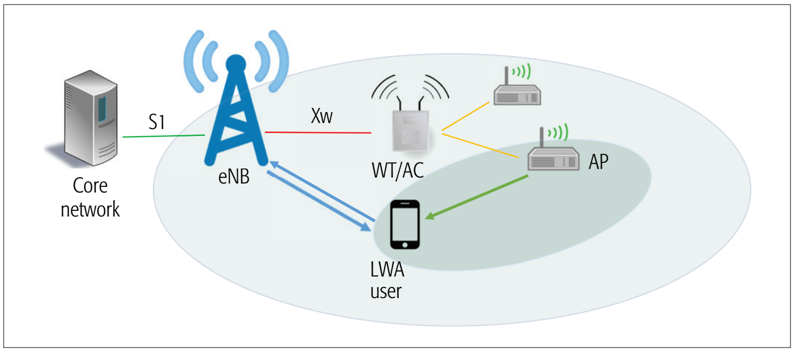

Figure 1. A non-collocated LWA deployment.

Deployment Scenario

The deployment scenarios for LWA are grouped into two categories: collocated scenarios and non-collocated scenarios. In the collocated case [7], the eNB and WLAN entities are assumed to be connected via an ideal link (e.g., unified in a common node), whereas in the non-collocated scenario shown in Fig. 1, the eNB and WLAN entities (WLAN access points, APs, or WLAN controllers, WCs) are connected over a non-ideal backhaul using standardized interfaces referred to as Xw. The collocated option is more suitable for new small cell scenarios with lower user population. The non-collocated deployment option is more appropriate for incorporating present WLAN deployments covering big areas such as universities, hospitals, and enterprise networks [6]. For non-collocated deployments, 3GPP introduces the concept of a wireless terminal (WT) node for logical representation of the WLAN system. These WT nodes control one or more APs/ACs and help carry PDCP packet data units (PDUs), control plane signaling, and flow control feedback between LTE and WLAN interfaces.

Radio Protocol Architecture

A bearer is a path that is used by user traffic while passing an LTE transport network. Based on degree of quality of service (QoS), a user can establish multiple bearer paths concurrently. During the initial authorization process, the default bearer is created. When the user requires service with higher QoS, a dedicated bearer is established. There are two kinds of data bearers supported by LWA radio protocol: switched and split bearers. The switched LWA bearer's packets

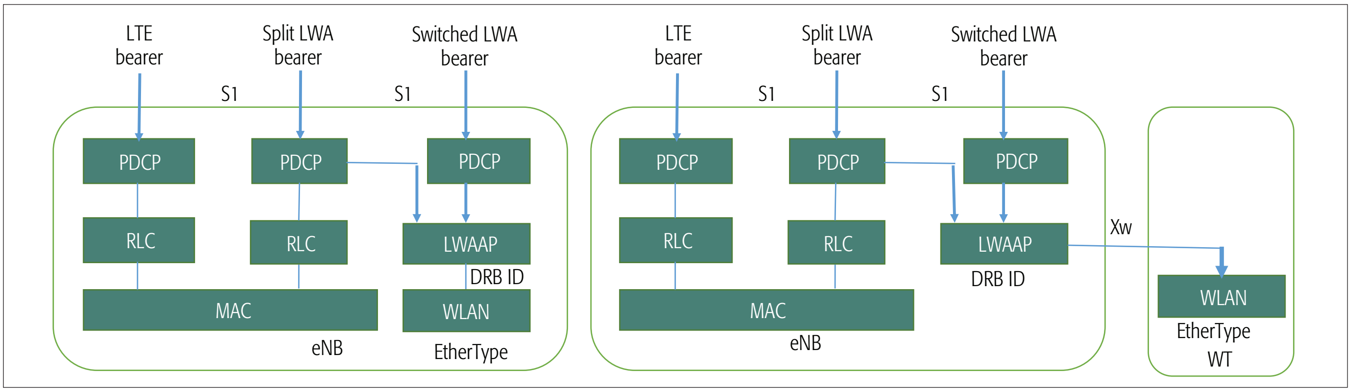

Figure 2. Radio protocol architecture: a) collocated scenario; b) non-collocated scenario.

are always scheduled over WLAN network while split LWA bearer's packets can be scheduled over either WLAN or LTE or both. Both bearers contribute to maximize network utility, however split bearer is more popular for maximizing its end user performance gain (the sum of peak data throughputs via both links), while the switch bearer is popular for removing the device complexity that is required for aggregation. A particular bearer usage depends on the received radio information about both links, including flow control indications. The packets must wait before being transmitted by the WLAN or LTE radio interfaces in the WLAN MAC and radio link control (RLC) layer queues, respectively. The radio protocol architecture for these options is shown in Fig. 2.

In order to avoid changes to the WLAN MAC, 3GPP has defined an LWA adaptation protocol (LWAAP) and a new ethertype (by the IEEE registry authority committee) [5]. For all LWA bearers, there is one LWAAP entity in the eNB and another LWAAP entity at the user. For packets sent over a WLAN, the LWAAP entity (eNB or user) produces an LWAAP PDU comprising a data radio bearer (DRB) identity (one-byte header to each PDCP PDU). The WT uses the LWA ethertype 0x9E65 [8] for transmitting the LWA data packets to the user over WLAN. Subsequently, this information will be used by the user to distinguish the LWA bearer of the received PDUs. The eNB can configure the user to support LWA to transmit a PDCP or an LWA PDCP status report if the feedback from the WT is not accessible.

Network Interface

An interface called the Xw interface [5] is defined for control and data plane connectivity between an eNB and one or more WTs. The Xw interface is an enhanced version of the X2 interface developed in 3GPP Release 12 for dual connectivity. Like other LTE network interfaces (S1), the Xw interface utilizes the general packet radio service (GPRS) tunneling protocol (GTP-U) [8] in the data plane and has optional support for flow control and feedbacks. In the control plane, Xw supports functionality to add, modify, and release WTs, as well as reporting WLAN measurements and user connection status from WT to eNB.

Mobility and WLAN Measurements

LWA deployment constitutes numerous WLAN APs under the control of a WT and numerous WTs under the control of an eNB. LWA defines the user mobility set as one or more WLAN APs, recognized by one or more set identifiers such as service set identifiers (SSIDs) or basic service set identifiers (BSSIDs), within which the LWA users may freely move between WLAN APs belonging to a common WT without informing the eNB. This design reduces the signaling message flows between the eNB and the user equipment (UE). The user, transparent to the eNB, controls mobility within the WLAN mobility set, and the mobility outside of the WLAN mobility set is managed by the eNB. At certain times, a user is linked to at most one mobility set.

The WLAN measurements are used by the eNB to acquire knowledge on the WLAN radio environments. The LWA users perform WLAN measurements to support LWA activation/deactivation and set mobility. The WLAN measurement report comprises received signal strength indication (RSSI), WLAN carrier information, WLAN IDs, channel utilization, number of stations, backhaul rate, admission capacity, and information about the user-connected WLAN.

Feedback and Security

A feedback message is sent between eNB and WT to maintain the optimum WLAN flow control and access utilization. In cases where the WT does not support feedback/flow control, the eNB may trigger status reporting from the user on the air interface (at the PDCP layer) using either a PDCP status report (first missing sequence number, SN, of PDCP, and a bitmap of the collected PDCP service data units, SDUs) or by an LWA status report (first missing SN, number of missing PDUs, and the highest received SN on the WLAN). Moreover, for any packets lost on LTE, the eNB derives information from the RLC layer (RLC acknowledged mode).

In LWA, even though the WLAN payload is encrypted by PDCP, 3GPP decides to use WLAN security, containing authentication, integrity, and encryption security. For this, 3GPP defines an optimized WLAN authentication procedure with or without extensible authentication protocol and key agreement (EAP/AKA) 802.1X authentication. It involves the eNB and the user deriving a common key based on a counter sent by the eNB over LTE radio resource control (RRC) signaling. The eNB communicates the key to the WT over the Xw interface [5], and the WT in turn is supposed to distribute the key to the WLAN APs/ACs to which the user may connect.

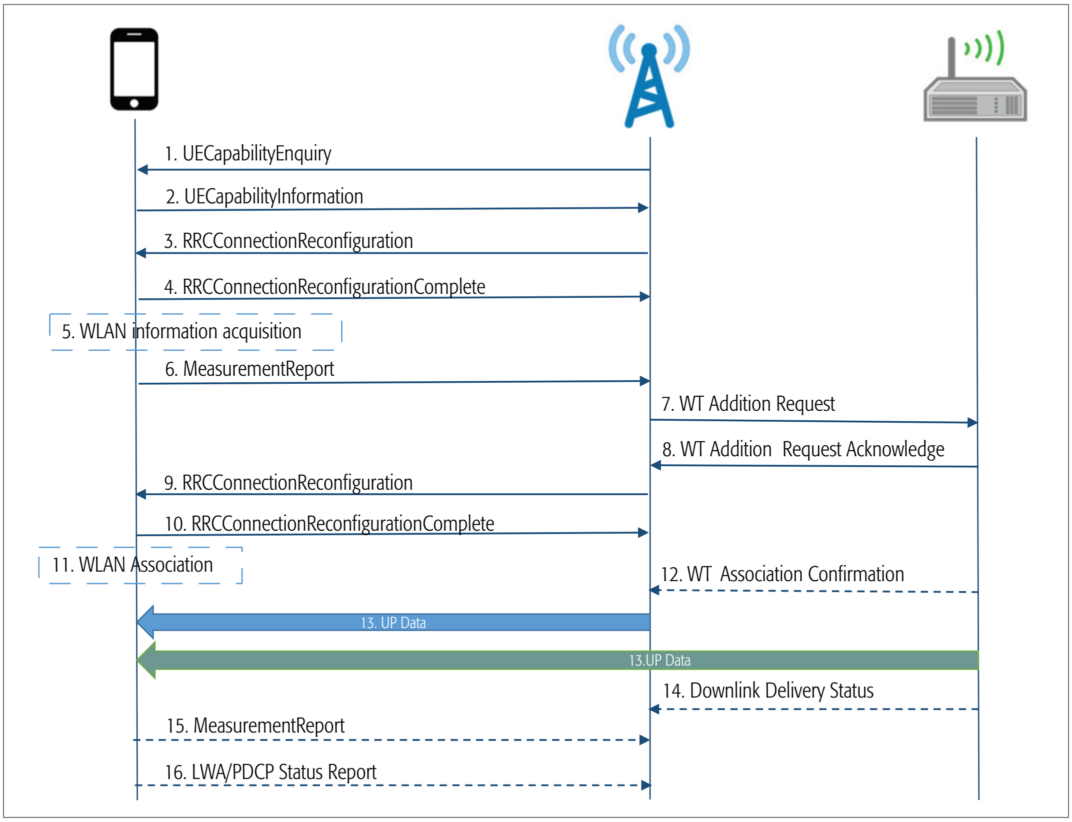

Figure 3. An overview of the LWA procedure.

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The overview of the LWA activation procedure is presented in Fig. 3. The process is categorized into six different parts. They are as follows:
1. User capability inquiry
2. eNB configuration of WLAN measurements
3. Measurement configuration/report
4. User capability information
5. LWA activation
6. Feedback/flow control

LWA Opportunities

On the way to the optimum usage of the unlicensed spectrum, LWA is considered as more established technology for 5G. The LWA approach of aggregating the licensed and unlicensed band spectra offers numerous benefits to mobile operators, service providers, and end users. Table 2 provides a brief summary of the LWA opportunities.

Enhanced network performance: LWA trials conducted by the Industrial Technology Research Institute (ITRI) and MediaTek in Taiwan demonstrated a peak throughput of 400 Mb/s (100 Mb/s for LTE and 300 Mb/s for WLAN) at Mobile World Congress 2016 [9]. In an improved version, the throughput of the eNB has been further pushed to 900 Mb/s. Likewise, Korea Telecom (KT) also claims the highest throughput of 600 Mb/s in their trials of LWA, where 150 Mb/s is for LTE and 450 Mb/s is for WLAN [10]. Thus, access to the unlicensed radio resources to offload traffic appears to be an ideal capacity solution for cellular operators to meet future traffic growth. Moreover, LWA introduces new features for WLAN mobility management (i.e., mobility set), measurement (i.e., LWA status report and Xw feedback), and security (i.e., WLAN security) for an optimized connectivity experience in real time, which results in fast roaming, reduced overhead, load balancing, and a more secure LWA network.

Better coverage: LWA supports the distributed model, which does not need to have both radios in the same device, as LTE-U and LAA do. This non-collocated deployment flexibility helps optimize the coverage and capacity of both the lower-frequency licensed radios and higher-frequency WLAN radios. Additionally, the use of highly available WLAN nodes can also provide better coverage for the users near the edge of a cell or in an indoor environment where cellular coverage is weak. In [7], Intel reports the gain of 80 percent for cell edge users but only 30 percent for average users.

Enhanced end-user experience: High throughput is always in demand for wireless network entities. Due to the simultaneous use of both LTE and WLAN links, high throughput can be achieved by using larger bandwidth. Thus, an end user can experience enhanced data downloads with improved QoS. According to D. Laselva *et al.* in [6], users experience approximately 40 percent higher data rate. Moreover, LWA can be operated in network-assisted or user-assisted mode. In both cases, users can switch to either network (LWA or non-LWA) while the existing LWA session continues, uninterrupted, over the LTE bearer. In addition, while the LWA user moves within the mobility set of WLANs, WT handles smooth handover between APs, and over LTE bearers as well. Hence, LWA provides smooth utilization of both LTE and WLAN networks. In [11], Y. B. Lin *et al.* report a throughput drop of 40 ms with open system authentication of WLAN.

Benefit	Rational
Enhanced network performance	Aggregation of LTE and WLAN links (e.g., on LWA trails peak throughput of eNB): • Chunghwa Telecom Taiwan: 900 Mb/s [9] • KT Telecom Korea: 600 Mb/s [10]
Better coverage	Distributed model is supported: • Non-collocated deployments • 80% gain for cell edge user [7].
Enhanced end-user experience	Aggregation of LTE and WLAN link: • 40 percent higher data rates [14] • Double or triple data rate of user [15] WLAN mobility set supports autonomous mobility • Data throughput drop limited to 40 ms [11]
Spectrum efficiency	Use of best upload and download links: • Wi-Fi has inefficient uplink contention • LTE suffers from bandwidth scarcity in the downlink [12]
Cost efficiency and fast deployment	Needs only software upgrade for network and operating system update in user device [9, 12].
Remedy for WLAN limitations	Use of LTE network for control plane and uplink helps WLAN quality and scalability issue [7, 12]
Best use of unlicensed band	No coexistence challenge and regulatory issue like other parallel technology (LTE-U/LAA) [2, 3] such as discontinuous transmission, carrier sensing, power regulations, etc.

Table 2. Summary of LWA opportunities.

Spectrum efficiency: LWA utilizes LTE access for uplink or downlink, and uses existing WLAN networks for downlink. With LWA, LTE no longer needs to operate outside its normal parameters for accessing the unlicensed band. Both technologies are allowed to do what they do best, as WLAN is well suited to carry downlink traffic, but less suitable for uplink traffic (due to inefficient uplink contention), while LTE uplink is better than WLAN uplink, but LTE experiences bandwidth scarcity during downlink [12]. This means operators and users will obtain the best download and upload performance.

Cost efficiency and fast deployment: The main advantage of LWA is that it offers network providers to utilize huge incumbent WLAN APs to increase LTE capability. This technique runs with only minor intervention in existing networks (requiring only a software upgrade or a new WLAN terminal) and in devices (only requiring an operating system update), saving hardware cost [7, 12]. WLAN APs supporting LWA also have the ability to continue to carry regular WLAN traffic (using different SSIDs), supporting different types of users and making LWA broadly applicable.

Remedy for WLAN limitations: WLAN is deployed everywhere; however, it is not efficient or perfect. There are still some quality and scalability issues such as uplink interference problems, insufficient coverage, biased service quality, and contention on user uplinks. On the other hand, the LTE network does not have any of these issues. An LWA unified network opens the door to allow new partnerships among WLAN service providers and LTE operators toward better WLAN performance [12]. Moreover, in LTE, control signals are granted the highest priority, which means whatever the unlicensed channel conditions are, the control plane messages are always transmitted properly [10]. The effort to use LTE for uplink and control messages helps deliver anticipated performance even in unpredictable environments.

Best use of unlicensed band: Innovations are continually being explored to offload data traffic over the unlicensed band. As discussed earlier, 3GPP has already defined a variety of methods such as LTE-U, LAA, LWIP, and LWA of LTE in unlicensed band. However, due to coexistence challenges and regulatory issues, these technologies are hindered in global adoption [2, 3]. The LWA solution seems to be promising, as it can be readily rolled out with a minimal impact on infrastructure and higher performance gain than LWIP [7]. On top of this, LWA can take further advantage of the future innovations in WLAN (802.11ax, ay).

Challenges for LWA

WLAN users have already congested the unlicensed band. Furthermore, when LWA is added, the band will become more overcrowded. Therefore, LWA activation must improve WLAN utilization when it is available, and not contribute to congestion. In this section, we discuss the challenges of LWA and its possible research directions. To provide a comprehensive view, the discussed set of challenges and research directions are summarized in Table 3 and highlighted with bearer types and deployment scenarios.

Latency: The packets must wait in the queues of the WLAN MAC layer and the LTE RLC layer before being disseminated over WLAN or LTE, respectively. The scheduling delay in LTE and contention delay in WLAN might cause packets to experience different amounts of waiting time in these queues. These delays may increase again as the number of out-of-order packets, which must wait at the PDCP layer for reordering, increases [13]. Furthermore, the delay can become even worse as packets are discarded by WLAN when it reaches the maximum retransmission limit. If the difference between the delays on WLAN and LTE is very big, the throughput might worsen when using both from that using a single interface. Variable delay can influence the peak performance, especially for latency-intolerant applications [14]. Therefore, LWA requires a very powerful traffic steering mechanism to ensure that LWA selects the best route and a good WLAN AP. The appropriate threshold for latency should be determined between LTE eNB and WLAN APs that maintain legitimate throughput. In [14], D. Lopez-Petez *et al.* proposed the UE flow control algorithm to reduce the end-to-end delay over the LTE and WLAN links. Similarly, P. Sharma [13] introduced higher RLC layer integration using a virtual WLAN scheduler, eliminating waiting times at Wi-Fi queues.

In-device coexistence (IDC) interference: To support the simultaneous transmission in LWA, users are enabled with several radio transceivers. Due to the high proximity of several radio transceivers within the same user, working on adjacent frequencies can create IDC interference [5]. This is mainly due to the interference power of the collocated radio being much greater than the actual received power of the desired signal for a receiver. An LWA user can be an IDC victim in two cases: (a) when the user uses regular LTE simultaneously for LWA operations (between LTE and aggregated WLAN links), and (b) when the user configured with LWA is additionally using regular

Challenges	Description	Reasons	Potential Approaches	Bearer Type	Deployment
Latency	Throughput performance is degraded by increase in out-of-order packets in the user PDCP layer.	WLAN and LTE links possess different delays.	Traffic steering mechanism to select the best route and a good WLAN AP.	Split bearer	Non-collocated
In-device coexistence (IDC) interference	Interference is caused by simultaneous operation on adjacent frequencies.	There is extreme proximity of multiple radio transceivers.	Based on user IDC report, eNB could solve the situation by suspending, releasing, and/or reconfiguring LWA.	Split bearer	Collocated/ non-collocated
Performance monitoring	LWA performance affected by various factors in WLAN such as end-to-end connection, WLAN load, etc.	Users' autonomy for mobility and implementations is totally beyond the knowledge and control of the eNB.	A periodical WLAN performance monitoring mechanism at eNB.	Spilt/ switched bearer	Non-collocated
LTE QCI vs WLAN QoS.	QoS control parameters have not been clearly defined for LWA.	3GPP QCI parameters and the WLAN QoS parameters (EDCA or HCCA) are different.	Mapping between 3GPP QCI parameters and the WLAN QoS parameters is needed.	Spilt/ switched bearer	Collocated/ non-collocated
Ping-pong effect	Resources are wasted on signaling when the user bounces between the LWA and WLAN.	In highly dense urban areas, WLAN APs are ubiquitous but often have limited overlapping.	Limiting LWA technology to short-range, lower-mobility indoor and outdoor applications.	Switched bearer	Non-collocated
Power and cost	• LWA operation consumes more power of user equipment than normal operation. • Investment cost is still significant.	• Cellular uplink consumes more power than WLAN uplink. Moreover, WLAN measurement reporting uses additional power. • Less-capable eNB/WLAN APs need replacement.	• Energy-efficient signaling and algorithms. • Aggregation at the higher layer (IP layer).	Switched bearer	Collocated/ non-collocated
Fairness	System resources are sub-optimally utilized.	• LWA service is provided to all aggregation-requesting users. • MAC layer implementations of LTE are highly vendor-specific.	• An algorithm that selects only needy users for LWA service. • A scheduling mechanism that resists distinct MAC implementations.	Spilt/ switched bearer	Collocated/ non-collocated
Policies	LWA lacks polices on authorization, inter AP mobility, charging etc.	LWA is still technologically immature.	More research is needed to deal with the policies.	Spilt/ switched bearer	Collocated/ non-collocated

Table 3. Summary of LWA challenges and research directions.

WLAN (between aggregated WLAN and regular WLAN links). Hence, for detecting and mitigating IDC issues, the eNB can configure a user with an IDC report. The IDC report may include a list of carriers facing IDC problems, the technologies suffering from disturbance, and the direction of the interference. The eNB could attempt to solve the situation by suspending LTE/WLAN transmissions, releasing interfering LTE carriers, and/or reconfiguring the time-division multiplexing pattern of LTE [5].

Performance monitoring: The users are often mandated by the network to automatically camp on LWA when the power received by the WLAN AP is higher than that of the LTE eNB. The problem in this scenario is that the user only monitors the air interface link, neglecting the backhaul capacity of the WT and a WLAN AP. Hence, if the backhaul connection speed is lower than that of the cellular network, offloading toward WLAN is a poor decision [14]. In a similar case, LWA performance could be impacted by various factors in WLAN, which are totally beyond the knowledge and control of the eNB due to the user's autonomy for mobility and other implementations. For example, users might be instructed to select a heavily loaded WLAN AP; in this case, the backhaul may be sufficient or better than that of the cellular network. However, the wireless channel might be heavily loaded. This scenario might occur when many users are using the same AP. Thus, the LWA eNB must have full information of the WLAN domain, as the bearer's data path includes many network elements (eNB, WT, AP, and user) and variable links, and hence is affected by many issues [14]. For this, more frequent periodic transmission of feedback messages such as WLAN measurement reports, LWA status reports, and Xw feedback can be adopted for correct and updated channel information. However, these gains from periodicity come at the price of overhead associated with uplink, which should be kept moderate.

LTE QoS class identifier (QCI) vs. WLAN QoS: WLAN (IEEE 802.11) users are facilitated with MAC enhancements to help applications with QoS requirements. For infrastructure mode, IEEE 802.11 allows two methods. The first, enhanced distributed channel access (EDCA), sends traffic based on differentiating user priorities. Second, hybrid coordination function (HCF)-controlled channel access (HCCA) provides the reservation of transmission opportunities with the hybrid coordinator. Because only the "new AP" has been considered in the LWA report [5], we assume that the WT supports QoS-related functions as defined in the 802.11 standards. Even if the QoS-related functions in WLAN are supported by WT, consideration of the QoS control parameters used by the EDCA and HCCA cannot directly match the QoS control parameters of 3GPP (i.e., QCI). The mapping between 3GPP QCI parameters and

Without any contention asymmetry or major upgrades in the core network, LWA provides operators with a capacity increase and a peak throughput experience for the user. However, there are still some design challenges, such as latency due to out-of-order packets, IDC interference, and signaling issues that need to be considered for final LWA rollout.

WLAN QoS parameters is still needed. Hence, the procedure for the cellular network to configure, manage, and control the QoS levels experienced by data flows that are carried over LWA access needs to be addressed.

Ping-pong effect: In highly dense urban areas, where WLAN APs are ubiquitous but often have limited overlapping, users may end up bouncing between the LWA and WLAN networks, significantly reducing the users' QoS. A great amount of resources are wasted on signaling, increasing the signaling traffic at the network side. An obvious solution to this challenge would be for the cellular network to hold on to the users when high mobility is detected within a highly dense urban area. It will probably work much better in controlled environments, such as in offices or large dwellings, rather than in congested public gatherings. Chunghwa Telecom's first deployment trial in a university environment confirmed that indoor small cell designs are well supported [9]. On top of this, the high frequency spectrum at 5 GHz makes this more suitable for short-range indoor applications.

Power and cost: Recent studies in LWA are mostly concerned with maximizing the throughput and increasing the coverage, while user preferences such as battery drainage are not fully studied. In particular, more transmit power will be depleted when uplink traffic is redirected to cellular networks [7]. Additionally, continuous signaling for WLAN measurement reporting and feedback uses additional power. This is not what energy-limited users expect. Hence, LWA should consider some energy-efficient signaling and algorithms. Again, regarding deployment costs, LWA claims to remove the burden of new hardware requirements as existing eNBs and WLAN APs can become LWA-enabled with a simple software upgrade. However, one drawback to this solution is the investment costs needed in cases where less capable eNBs/WLAN APs need to be replaced, or when native WLAN APs (operator-deployed, user-deployed, municipal WLAN, etc.) cannot be used. The costs may not be as high as in LTE-U/LAA, but can still be significant [12].

Fairness: Unlike LTE-U/LAA [2], LWA eliminates potential fairness and regulation issues on the unlicensed band. However, the intra-bearer unfairness remains, and needs to be considered. This unfairness generally arises when LWA unconditionally provides the aggregation service to all aggregation-requested users, degrading the QoS at the system level and sub-optimally using system resources [15]. Hence, the optimal user selection technique is needed that can smartly allocate the needy users for LWA service instead of just allowing the users' intention of aggregation. Additionally, the vender specifies the data link layer implementations of LTE, including many proposals exist on user scheduling, such as proportional-fair scheduler, MAX-MIN scheduler, MAX-SNR scheduler, and so on, which are not defined in 3GPP standards and hold the power to change with mobile network operators' policies. Therefore, a split-scheduling technique needs to be developed that works without information of MAC layer implementations.

Policies: We believe that LWA only describes how and where LTE and WLAN are integrated, but does not provide the essential algorithmic mechanisms [5], for example:

- How to split the bearer and under what criteria a user is authorized for LWA service
- How and when the eNB activates or deactivates LWA
- How inter-AP/AC mobility is achieved under a WT
- How the eNB knows about users within the WLAN coverage
- How the eNB transfers data to a user via WLAN
- How the WT and AP/ACs communicate
- How LTE charges for LTE traffic delivered over WLAN

Conclusion and Discussion

To support the unrelenting growth in data traffic offered by 5G and IoT RATs, LWA features have been introduced in 3GPP Release 13 as a promising candidate to effectively aggregate LTE and WLAN at the link layer. Without any contention asymmetry or major upgrades in the core network, LWA provides operators with a capacity increase and a peak throughput experience for the user. However, there are still some design challenges, such as latency due to out-of-order packets, IDC interference, and signaling issues that need to be considered for final LWA rollout. Hence, unlicensed band and WLAN internetworking will continue to be more important to operators in the coming 5G era. Although it is hard to forecast which WLAN internetworking scenarios will be standardized and deployed by 5G, LWA provides a solid framework for 5G WLAN internetworking.

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