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# On Convergence and Coexistence of LTE and Wi-Fi Networks

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**Abstract** The proliferation and penetration of smart phones and IoT devices is having profound impact on world economy. In order to support billions of wirelessly connected devices, and tackle exponentially increasing traffic demands and ever-increasing Quality of Experience (QoE) and energy efficiency requirements of diverse services and applications being carried over communication network infrastructure, convergence and coexistence of various radio access technologies (RATs) is required. In this work, we present various architectures and traffic steering mechanisms for efficient interworking of LTE and Wi-Fi networks and evaluate their performance for carrying TCP traffic which is sensitive to Out-Of-Order delivery of packets at the receiver. Unlike interworking which requires simultaneous usage of both LTE and Wi-Fi radios at User Equipment (UE), mobile operators are considering deployment of LTE-U/LAA in Unlicensed bands so that only one radio is used at UE. However, to use unlicensed bands LTE-U/LAA needs to fairly co-exist with Wi-Fi. To address this inter-RAT hidden terminal problem, we present novel solutions that either rely on a central inter-RAT controller or work without any such controller in a distributed manner.

**Keywords** LTE · Wi-Fi · Interworking · Coexistence

## 1 Introduction

The huge growth in the number of smartphones sold and the traffic generated by them have become a major challenge to the telecom industry. Mobile operators are constantly scouting for new technologies and strategies to meet this exponential demand for *data*. The operators are opting for ultra-dense deployment of network elements (*e.g.,* base stations and access points) to boost network coverage and capacity. Densification of the base stations to offer higher data rates by the deployment of various types of small cells (Micro, Pico, Femto, etc) is one of the key components of 4G/5G. Convergence and coexistence of various radio access technologies (RATs), especially various generations of cellular (*e.g.,* 4G/ 5G) and Wi-Fi (*e.g.,* IEEE 802.11n/ac/ax), could play a major role in tackling the data crunch.

Our research work involves carrying out R&D work on various research issues related to interworking and coexistence of LTE and Wi-Fi networks like tighter interworking architectures, dynamic traffic steering, seamless mobility, load-balancing, interference management, coexistence of LTE-U/LAA and Wi-Fi in Unlicensed bands, and optimal resource allocation to realize energy-efficient and spectrally-efficient mobile networks. We build prototype testbeds to assess benefits of technology pilots in real-world settings. In the following, we highlight some of our notable research contributions w.r.t. interworking and coexistence of LTE and Wi-Fi networks, and then present future research directions.

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## 2 Interworking of LTE and Wi-Fi Networks

3GPP defined various LTE and Wi-Fi interworking architectures from Rel-8. Because of limitations in classical cellular and Wi-Fi interworking solutions, in Rel-12 Radio Level Integration (RLI) of LTE and Wi-Fi has been introduced, which enhances the interworking capability between LTE and Wi-Fi by closely integrating them at protocol stack level. Fig. 1 shows a high level view of RLI architecture, with RLI node which encompasses link level connection between LTE Small cell evolved Node B (SeNB) and Wi-Fi AP. RLI architectures allow a user (a.k.a. device/UE) to simultaneously make use of 4G LTE/LTE-A and Wi-Fi links for data transfer depending on reliability, bandwidth, and QoS requirements of applications. As Wi-Fi which operates on unlicensed bands has the ability to boost the capacity for indoor environments, mobile operators are taking advantage of this for offloading of mobile data onto Wi-Fi networks opportunistically. Such radio level integration, can be realized at IP, PDCP, RLC, and MAC layers. 3GPP developed specs for realizing the integration at IP layer and PDCP layer. 3GPP has coined the terms LTE Wi-Fi Aggregation (LWA) and LTE Wi-Fi interworking with IPSec tunnel (LWIP) for realizing integration at PDCP and IP [2], respectively. These RLI architectures have the following advantages:

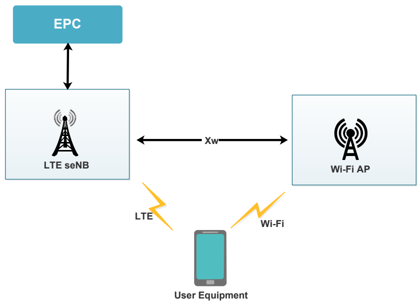


Fig. 1: RLI architecture showing interworking of LTE and Wi-Fi.

- Wi-Fi operations are controlled directly via SeNB inside the RLI node. LTE core network (i.e., Evolved Packet Core (EPC)) need not manage Wi-Fi separately.
- Radio level integration allows effective radio resource management across Wi-Fi and LTE links.
- LTE acts as the licensed-anchor point for any UE thereby providing unified connection management with the network.

We have proposed various RLI architectures which are contemporary with 3GPP architectures. The proposed integration architectures are slightly different from 3GPP architectures in which the integration across LTE and Wi-Fi links has been realized by introducing a link aggregation layer (LAL) at both RLI node and UE. The LAL supports collecting various network parameters and actively participates in intelligent decision making for steering traffic across LTE and Wi-Fi interfaces. The LAL can perform steering of packets/ flows/ bytes across LTE and Wi-Fi links. Our proposed integration architectures include (i) LWIP, (ii) LWA, and (iii) LWIR [6]. Fig. 2 captures all the proposed integration architectures with LAL. LWIP is leveraged by its ease of implementation at IP layer to achieve aggregation benefits. Here LAL does not add any new header to the IP data packets received and packets going through LTE and Wi-Fi interfaces follow regular packet forwarding procedures at their protocol stacks and get delivered to IP layer. The LAL implemented below PDCP layer of LTE does the steering across LTE and Wi-Fi links in LWA architecture. PDCP layer at UE employs reordering function to minimize the out-of-order packet delivery to higher layers. Unlike LWIP, split bearers functionality is enabled in LWA due to its ability to deliver packets of a bearer/flow in-order to higher layers. In-order-delivery is achieved by employing Dual Connectivity (DC) procedure. In order to perform traffic steering at LWIR node, a Virtual Wi-Fi Scheduler (VWS) is introduced inside LAL. This VWS is above the Logical Link Control (LLC) layer of Wi-Fi AP device at LWIR node and it takes data at the granularity of bytes from RLC queue for sending over Wi-Fi link. The VWS picks bytes from different RLC queues based on their QoS requirements and the observed CQI of all the associated users. The VWS retrieves data from RLC queue only when the Wi-Fi back-off counter is about to expire. This notification of Wi-Fi queue status and monitoring the back-off counter are done by the VWS. The VWS periodically queries the Wi-Fi driver to get these parameters and chooses one of the RLC queues from which data has to be steered through Wi-Fi link. LWIR architecture supports high reliability for the packets sent through LTE and Wi-Fi links. When a packet is lost in transmission over LTE or Wi-Fi link, RLC retransmission procedure is invoked to retransmit the lost packet. Table 1 compares the RLI architectures in a nutshell.

LWIP supports traffic steering across LTE and Wi-Fi links at different granularity such as (a) flow level, (b) packet level, and (c) bearer level. In case of flow/ bearer level steering, a flow/bearer is sent either through LTE link or through Wi-Fi link. Out-of-sequence delivery of packets does not arise in case of flow/bearer level steering. The maximum benefit of integration is archivable only if it does steering at the packet level. But, in case of packet level steering, individual packets of a flow that are dynamically sent across LTE and Wi-Fi links might end up arriving Out-Of-Order (OOO) at the receiver. This OOO delivery could be quite problematic for reliable transport protocols like TCP. When the packets are received OOO at the TCP receiver, it leads to the generation of DUPlicate ACKnowledgements (DUP-ACKs). These unnecessary DUP-ACKs adversely affect the growth of TCP congestion window and thereby lead to poor TCP performance. We addressed this problem by proposing a virtual congestion control mechanism (VISIBLE - VIrtual congeStion control wIth Boost acknowLedgEment) [8]. The proposed mechanism not only improves the throughput of a flow by reducing the number of unnecessary DUP-ACKs delivered to the TCP sender but also sends Boost ACKs in order to rapidly grow the congestion window to reap in aggregation benefits of heterogeneous links. These Boost ACKs are pseudo ACKs for the actual TCP packets which are already in the queue of LWIP node. The VISIBLE mechanism has been implemented at the LWIP node in such a way that it does not disturb the semantics of TCP.

### 2.1 Performance Results of RLI Architectures

The performance of LWIP + VISIBLE system has been compared with basic LWIP system by creating a file download scenario from a remote sever to UE using NS-3. The growth of congestion window in case of basic

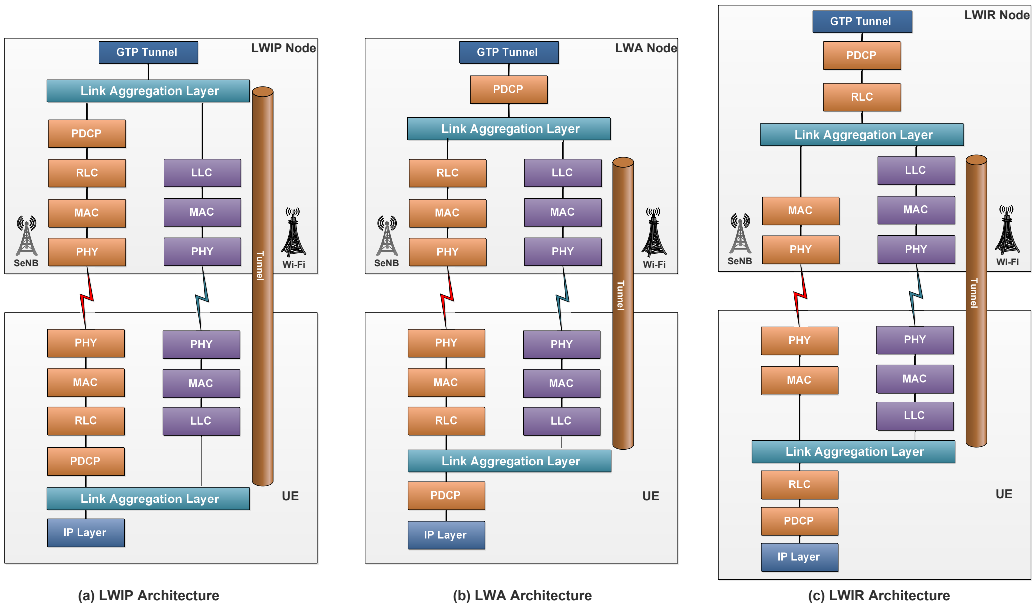


Fig. 2: Proposed LWIP, LWA, and LWIR architectures.

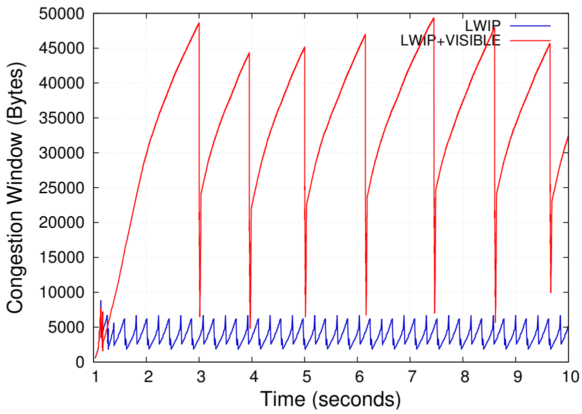


Fig. 3: Congestion window growth of LWIP and LWIP+VISIBLE architectures.

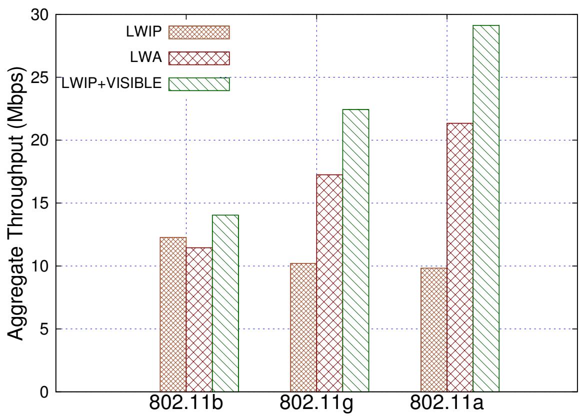


Fig. 4: Throughputs of basic LWA, basic LWIP, and LWIP+VISIBLE.

Table 1: Comparison of proposed RLI architectures

| Feature | LWIP | LWA | LWIR |
|---|---|---|---|
| Operating Layer | Above LTE PDCP | At LTE PDCP | At LTE RLC |
| Compatibility with UEs | Works readily | Requires changes | Requires changes |
| Steering Granularity | Packet, Flow Level | Packet, Flow Level | Byte, Flow, Packet Level |
| WLAN Measurement | Yes | Yes | Yes |
| Feedback | No | Yes | Yes |
| WLAN Changes | No | Yes | Yes |
| Reordering | No | Yes | Yes |
| Retx | No | No | Yes |

LWIP (*i.e.,* LWIP without employing VISIBLE mechanism at LWIP node) is heavily degraded by DUP-ACKs received which could be observed from Fig. 3. In LWIP + VISIBLE, the congestion window grows faster which is not only due to avoiding DUP-ACKs but also due to boosting ACKs which helps the congestion window of the sender to grow faster. Fig. 4 shows the throughputs achieved when different RLI architectures are used for file downloads. Basic LWA has achieved 50% cumulative throughput improvement (with 802.11b, 802.11g, and 802.11a) when compared to basic LWIP because of PDCP reordering procedure which it implements. But LWIP+VISIBLE has outperformed LWA by 30% due to boosting of ACKs which leads to better growth in congestion window and thereby improves the overall network throughput. The proposed VISIBLE mechanism (VISIBLE + LWIP) has almost doubled the throughput of basic LWIP.

## 3 LTE and Wi-Fi Coexistence in Unlicensed Bands

LTE in unlicensed spectrum (LTE-U) [7,1] is considered as one of the latest ground-breaking innovations to provide high performance and seamless user experience under a unified radio technology by extending LTE to the readily available unlicensed spectrum. However, to use unlicensed spectrum LTE-U needs to fairly co-exist with other technologies in unlicensed spectrum, mainly IEEE 802.11 (a.k.a. Wi-Fi). Hence, the main challenge here for LTE-U/LAA is to make better use of unlicensed spectrum without affecting widely deployed Wi-Fi networks. Towards this, LTE-U follows discontinuous and duty cycled transmission approach where eNodeB follows an ON-OFF cycle pattern, with ON and OFF durations corresponding to LTE transmissions and muting duration, respectively. In [7,1], the efficacy of such ON-OFF cycle is shown to have fair coexistence with Wi-Fi. But, inter-RAT (LTE-U and Wi-Fi) hidden terminal problem has not received much attention. Hence in [5], we demonstrated its effects on Wi-Fi network by considering the scenario shown in Fig. 5.

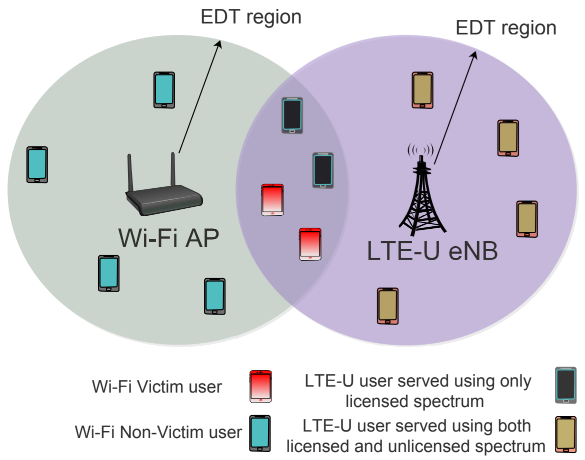


Fig. 5: Considered partially overlapping scenario to demonstrate hidden terminal problem between LTE-U and Wi-Fi operating on the same channel. As Wi-Fi operates only on the unlicensed band, its users are classified as victim and non-victim users. Because of availability of licensed band, LTE-U users who are in overlapping region are exclusively served using licensed band.

To address this inter-RAT hidden terminal problem, a central inter-RAT controller has been advocated in [3]. The controller employs Point Coordination Function (PCF) of Wi-Fi to intelligently serve victim and non-victim users and hence achieves fairness and improves performance of Wi-Fi. With the use of PCF being optional in IEEE 802.11 standards and the centralized mechanism necessitating synchronization between LTE-U and Wi-Fi, it could be difficult to deploy it practically. Hence a simple mechanism named LAW, both in its functionality and the ease of adaptability, is introduced in [4].

The proposed LAW mechanism makes efficient use of the existing Self-CTS frame of Wi-Fi to address hidden terminal problem. The Self-CTS consists of Duration/ID field which informs neighbouring Wi-Fi devices to defer their channel access for a duration by setting Network Allocation Vector (NAV) value. The Duration field is 16-bit and has many reserved values. We used two values from these reserved values to enable inter-RAT coordination. LTE-U eNB informs one of its users (also called as an agent) through the licensed spectrum to send Self-CTS through its Wi-Fi interface. The value 32769 is sent by LTE-U when it is about to use unlicensed band for its transmission (*i.e.,* LTE-U is ON) and the value 32770 is sent by LTE-U when it stops using unlicensed band (*i.e.,* LTE-U is OFF). Once Wi-Fi AP receives the Self-CTS of the LTE-U agent, it behaves as follows: if it is LTE-U ON period, then Wi-Fi will serve only the non-victim users. Whereas, if it is LTE-U OFF period, then Wi-Fi will first serve only the victim users for a specified duration (called $V_{time}$) and then continues serving all of the users. $V_{time}$ is calculated in such a way that average throughput of victim and non-victim users should be same and the maximum value of $V_{time}$ is restricted by LTE-U OFF period.

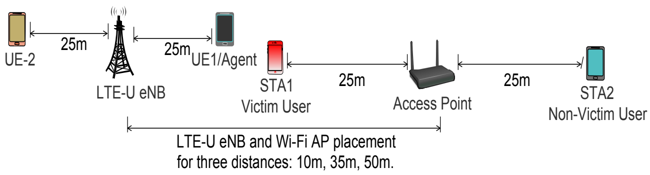


Fig. 6: Experimental setup to study hidden terminal problem between LTE-U and Wi-Fi.

### 3.1 Performance Results of Coexistence Schemes

We consider three scenarios to study the performance of Wi-Fi users in the presence of LTE-U for various coexistence schemes. An LTE-U eNB and a Wi-Fi AP are deployed 50m (outside Carrier Sense Threshold (CST)), 35m (in-between Energy Detection Threshold (EDT) and CST), and 10m (inside EDT) apart as shown in Fig. 6. The proposed LAW scheme is compared with three other schemes: (1) Standard Wi-Fi (SW) (*i.e.,* without any change in LTE-U and Wi-Fi), (2) LTE-U eNB sending regular Self-CTS (LCTS), and (3) LTE-U

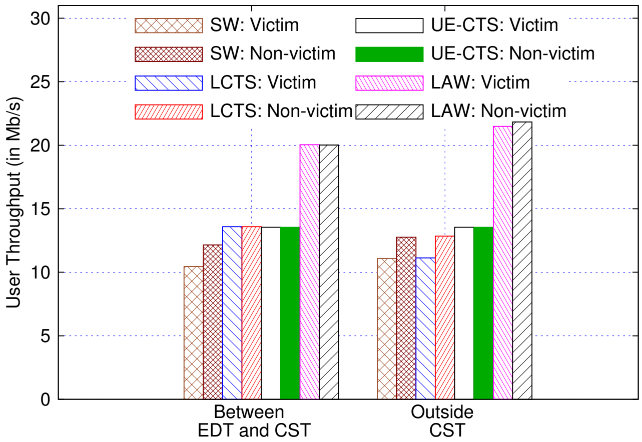


Fig. 7: User throughput for DL only traffic case.

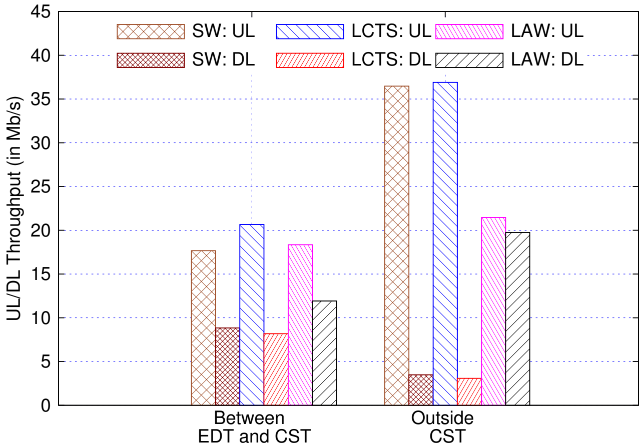


Fig. 8: UL/DL throughputs for UL+DL traffic case.

user sending regular Self-CTS (UE-CTS). The throughput results of Wi-Fi network are shown in Figs. 7 and 8 for Downlink (DL) only and both DL and Uplink (UL) traffic cases, respectively. It can be observed that the proposed LAW scheme outperforms all the schemes as it adds intelligence to Wi-Fi AP in deciding which user to serve based on LTE-U ON and OFF periods.

## 4 Conclusions and Future Directions

The proposed RLI (LWIP, LWA, and LWIR) architectures allow efficient and dynamic traffic steering based on link parameters like bandwidth, loss rate, delay, jitter, etc. Each architecture has its applicability based on the network requirements. The packet steering solution, VISIBLE, proposed on top of LWIP architecture, not only shown to improve the performance of both LTE and Wi-Fi links but also resulted in supporting TCP traffic efficiently without disturbing the semantics of TCP. The RLI architectures could be coupled with the legacy multipath protocols such as MPTCP to investigate the coupling benefits. They can also be explored to address the problem of poor video delivery and optimizations can be done to enhance the quality of video delivery by understanding the semantics of video transmission and coupling appropriately with diverse properties of multiple RATs available at users. Further, these could be extended to realize multi-connectivity feature in 5G, where different RATs would be used simultaneously to serve users. In the context of coexistence of LTE and Wi-Fi, we have proposed centralized and distributed mechanisms which addressed inter-RAT (LTE-U and Wi-Fi) hidden terminal problem and thereby resulted in improving the performance of Wi-Fi network with fairness among its users. Even though both frameworks (interworking and coexistence) look quite promising in tackling data crunch, it is unclear which of them is more energy efficient and how the telecom industry would be adopting them.

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