LWIP and Wi-Fi Boost Flow Control

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Abstract*—3GPP LWIP Release 13 technology and its pre-standard version Wi-Fi Boost have recently emerged as an efficient LTE and Wi-Fi integration at the IP layer, allowing the combined use of LTE and Wi-Fi radio resources by the user. This solves the contention problems of Wi-Fi cell by routing uplink traffic over LTE, thus enabling an optimum usage of the unlicensed band for downlink. In this paper, we present a new feature of Wi-Fi Boost, its radio link management, which allows to smartly steer the downlink traffic between both LTE and Wi-Fi upon congestion detection. This customised congestion detection algorithm is based on IP probing, and can work with any Wi-Fi access point. Simulation results in a typical enterprise scenario show that LWIP R13 and Wi-Fi Boost can enhance network performance up to 5x and 6x over LTE-only, and 4x and 5x over Wi-Fi only networks, respectively, and that the proposed traffic flow control can further improve Wi-Fi Boost performance over LWIP R13 up to 19 %. Based on the promising results, this paper suggests to enhance LWIP R13 user feedback mechanisms in future LTE releases.

I. Introduction

Due to the increasing number of more powerful user equipment (UE) and more appealing user applications, wireless networks have been witnessing and will continue to see an explosive traffic growth in the years to come [1]. Indeed, recent forecasts indicate that mobile network operators will need to enhance their network capacity by a factor of 100x in oder to meet their customer demands by 2020 [2]. In this context, the interworking between Long Term Evolution (LTE) [3] and Wireless Fidelity (Wi-Fi) [4] networks has gained a lot of attention during the recent years. LTE can leverage licensed carriers to realise quality of service and act as a mean of controlling ad-hoc Wi-Fi deployments, while Wi-Fi itself can allow operators to cost-effectively densify their networks and gain access to a large bandwidth in the unlicensed spectrum. The efficient integration of both technologies represents a good opportunity to improve the overall spectral efficiency of future wireless systems and realise effective traffic offloading/aggregation between them both.

In order to realise this efficient LTE and Wi-Fi integration, a Third Generation Partnership Project (3GPP) Release 13 (R13) standard, named LTE Wi-Fi Radio Level Integration with IPsec Tunnel (LWIP), is gaining momentum within the industry [5] [6] [7]. The foundation for LWIP R13 is Wi-Fi Boost which realised the first internet protocol (IP) layer LTE and Wi-Fi integration [8] [9] [10]. For LTE and Wi-Fi anchored applications, Wi-Fi Boost allows uplink (UL) on cellular and downlink (DL) on Wi-Fi, so that UEs can seamlessly and simultaneously draw on the strengths of both networks.

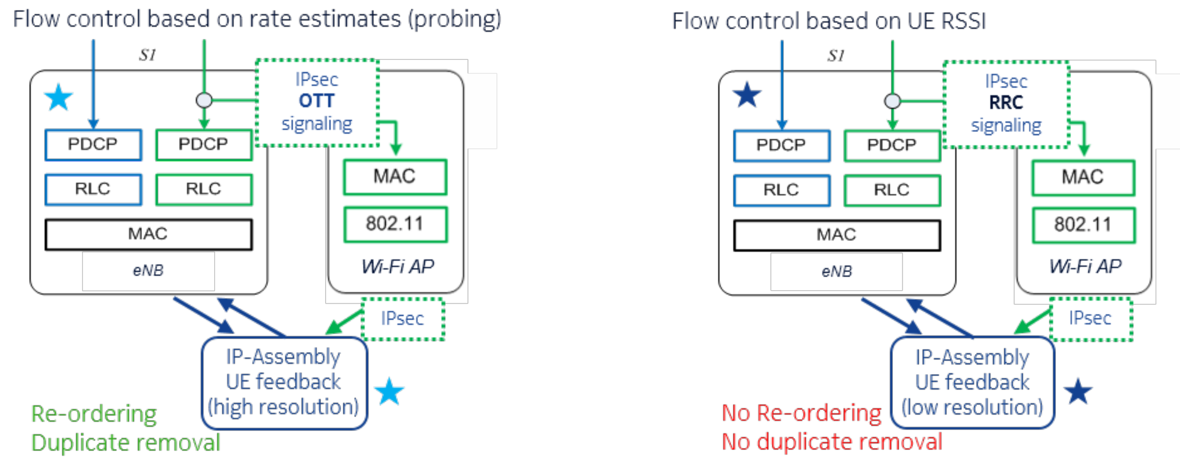
Wi-Fi is already commonplace in enterprises today, but it is not enough and it is not perfect. Moreover, Wi-Fi is limited in scalability, and quality issues still persist. In particular, IT managers are concerned about UL interference problems, poor range and unfair service quality, which is granted simply on the proximity of one UE to the access point (AP) compared to another, the so-called *capture effect* [11]. Looking more closely at Wi-Fi's limitations, several problems can be traced to the time sharing mechanism between the UL and the DL, i.e. Wi-Fi's carrier sense multiple access/collision avoidance (CSMA/CA), as well as the contention between the UE uplinks [12] [13] [14]. In contrast, an LTE-based system does not have this problem of UL conflicts because it uses centralised scheduled access mechanisms.

Wi-Fi Boost, the pre-standard LWIP R13, presents a solution to the above mentioned issues, and has been firstly targeted at enterprises where it has several benefits:

- Wi-Fi Boost uses LTE access for UL and frees up the enterprise's existing Wi-Fi network for DL. This means enterprise UEs get the best possible upload and download performance, as well as excellent indoor cellular coverage through LTE eNBs.
- Wi-Fi Boost allows operators to leverage vast incumbent Wi-Fi installed APs to supplement LTE capacity. The solution works without any hardware or software upgrade on Wi-Fi infrastructure, and only requires a software upgrade on LTE eNBs and UEs.
- A unique feature of Wi-Fi Boost is the local access mode, which adds great value to operators' offer beyond just providing an additional access using small cells. Local access allows the UE to choose either LTE or Wi-Fi for UL applications anchored in the enterprise core. This means much better quality of experience and support of higher capacity for business-impacting enterprise applications such as Lync, Skype, Jabber, Webex, Video conference etc. Since Wi-Fi Boost, integrates LTE and Wi-Fi accesses at the IP layer, local access is possible via a simple software upgrade involving routing and tunnel configuration on the LTE eNBs and UEs.

Due to these advantages, Wi-Fi Boost and now its standardised version LWIP R13, are industry game changers because:

- They open the door to position small cells into the enterprise market. They can also enable new partnerships between LTE operators and Wi-Fi providers, especially in environments such as large enterprises and outdoor public Wi-Fi, where hundreds of Wi-Fi APs are already deployed with several additional years of service expected, and it is highly desirable that there is no impact to the



(a) Wi-Fi Boost architecture.

(b) LWIP R13 architecture.

Fig. 1: Wi-Fi Boost and LWIP R13 architectures.

deployed Wi-Fi infrastructure.

- These solutions have been tested for LTE UL but are designed in principle to work on 3G as well. With 5G not far away in some markets, Wi-Fi Boost and LWIP R13 offers a path towards 4G-5G interworking and in fact multi-technology interworking.
- 3GPP standardisation of LWIP R13 has been supported by major UE vendors, and will drive the UE ecosystem. The loose integration between LTE and Wi-Fi paths at the IP layer simplifies the device implementation and can potentially be delivered as a software upgrade in existing LTE eNBs, as mentioned before.

Wi-Fi Boost and LWIP R13 are thus the foundation for realising the ‘all-wireless enterprise’ vision, and represent a large step forward towards 5G multi-radio access technology.

In this paper, we further investigate a new feature of Wi-Fi Boost, its radio link management, which allows to steer the DL traffic between both LTE and Wi-Fi upon congestion detection. In more detail, it continuously monitors the quality of the Wi-Fi link and moves the UE over to LTE or back to Wi-Fi, without service interruption.

The rest of the paper is organised as follows: In Section II, the architectures of Wi-Fi Boost and LWIP R13 are introduced. In Section III, the new flow control algorithm devised for Wi-Fi Boost is presented. In Section IV, simulation results, which show the performance of Wi-Fi Boost with the proposed flow control algorithm with respect to LTE only, Wi-Fi only and LWIP R13 technologies, are discussed. Finally, in Section V, the conclusions are drawn.

II. Boost and LWIP R13 Architectures

In this section, the Wi-Fi Boost and LWIP R13 architectures are presented, while describing their common features as well as their main differences. Fig. 1 illustrates such architectures.

As mentioned in the introduction, Wi-Fi Boost is the pre-standards version of LWIP R13, and thus both technologies share the same interworking philosophy, as well as other important functionalities. These main commonalities are described in the following:

- Both Wi-Fi Boost and LWIP R13 use as DL anchor the LTE eNB, and utilise IP layer as the split/aggregation point, as shown in Fig. 1. The user plane traffic between the UE and the LTE eNB over the Wi-Fi path is carried over an IPsec tunnel between them both, and thus is completely transparent to the Wi-Fi infrastructure. Note that the IPsec tunnel termination point on the network side is a functional entity defined as LWIP-security gateway, which is a logical function and be hosted at the LTE eNB or can exist as a separate node based on the deployment architecture. This allows the cellular operator to leverage existing Wi-Fi deployments to supplement LTE capacity without any hardware or software upgrade on the Wi-Fi infrastructure, which represents a major benefit for operators with vast Wi-Fi rollouts. Operators can just deploy a reduced number of LTE eNBs to control and enhance the performance of an existing large population of Wi-Fi APs.
- Both technologies are able to take advantage of the DL and UL split concept i.e. UL on LTE and DL on Wi-Fi [10]. By redirecting UL traffic from the Wi-Fi network (unlicensed band) to the LTE network (licensed band). there is no contention to resolve inside an individual Wi-Fi cell using the CSMA/CA protocol, which avoids the delay introduced by such contention and ensures a completely collision-free operation inside each cell. As a result, Wi-Fi operates only in the DL and works on a cell-centric scheduled basis (DL Wi-Fi traffic is scheduled by the Wi-Fi AP), enabling the most efficient use of Wi-Fi’s large bandwidth,
- An IPsec tunnel is used to transmit DL traffic from the LTE eNB to the UE through the Wi-Fi AP in a secure manner. It is important to note that the IPsec tunnelling protocol appends an IPsec header to the DL IP packets that travel from the LTE eNB to the UE over the Wi-Fi AP. The IPsec overhead is 66 bytes plus padding (if the inner IPsec packet plus 2 bytes IPsec trailer is not a multiple of 16 bytes, padding is needed). Such overhead

may be negligible for large IP packets, e.g. file transfer protocol (FTP) packets of 1500 bytes, but may be a burden for small IP packets of just few hundreds of bytes. Since most of the internet traffic uses 1500 bytes IP packets, this should not be a major concern.

Although Wi-Fi Boost and LWIP R13 share the most salient features, there are differences between them, which are summarised in the following:

- One of the main differences between Wi-Fi Boost and LWIP R13 is the way in which the above mentioned IPsec tunnel is set up. Wi-Fi Boost uses over the top proprietary signalling to establish the IPsec tunnel, which only requires a software upgrade on LTE eNBs. In contrast, LWIP R13 benefits from a standardised approach to this, and the IPsec can be established using layer radio resource control (RCC) signalling.
- Another important difference between both technologies is the flow control/traffic steering capabilities at the LTE eNB. Due to its pre-standard and proprietary nature, the Wi-Fi Boost solution allows for a more powerful radio link management, at the expense of the software upgrades required at the UE side in order to realise the necessary cooperation/feedback[1]. In contrast, LWIP R13 provides a standardised UE feedback framework, in which the UE can report RSSI measurements on neighbouring Wi-Fi APs to the LTE eNB. This permits a more universal approach to link management. However, RSSI feedback does not allow congestion detection and thus flow control capabilities are limited[2] (traffic steering only occurs when the strength of the serving path is weak). Section III will present our proposed Wi-Fi Boost flow control algorithm with congestion detection, and Section IV will provide a comparison between the performance of such Wi-Fi Boost flow control algorithm with congestion detection and that of LWIP R13 based on RSSI measurements.
- IP re-ordering and duplicate discard at the UE is another distinctive feature that can be made available in Wi-Fi Boost, but it is not present in LWIP R13. However, it is important to note that since link switching at LWIP R13 only happens when the strength of the serving path is weak, re-ordering and duplicate discard are not major issues. These features become important when considering aggregation, and IP packets arrive at the UE simultaneously via different paths. Frequent mobility also makes IP re-ordering and duplicate discard desirable features in the presence of link switching.

[1]LWIP R13 does not support the Xw interface, and thus there is no provision to feedback flow control information from Wi-Fi APs to the LTE eNB. As a result, only flow control algorithms based on UE feedback are explored in this paper. Even if an Xw interface was supported, getting Wi-Fi AP feedback is not trivial due to network topology challenges. e.g. terminating an Xw interface on each Wi-Fi AP is cumbersome, and collecting Wi-Fi AP feedback from a plurality of Wi-Fi APs at a WLAN controller may not always be feasible. Therefore, even in systems built on with Xw interface, UE feedback is supported, while Wi-Fi AP feedback is an optional feature.

[2]LWIP R13 also allows UEs to report the BSS load element to the LTE eNB via RRC WLAN measurement report message, if this information is available at the UE, thus allowing congestion detection. However, unlike RSSI reporting, which is mandatory, the BSS load is an optional element in the WLAN measurement report, and thus not universally available at Wi-Fi UEs.

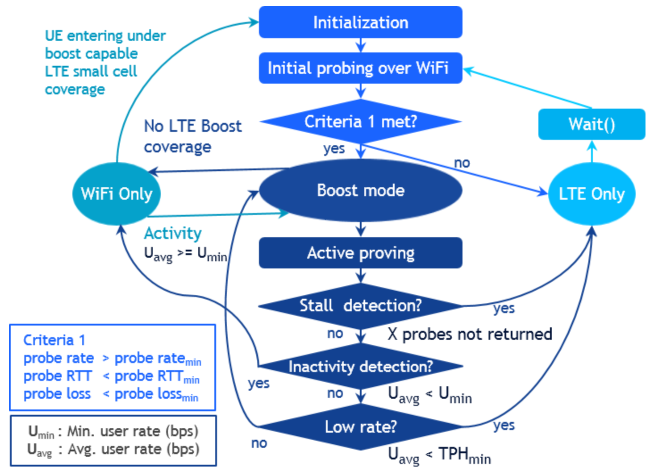


Fig. 2: Flow control algorithm diagram.

III. Radio Link Management

In this section, our proposed Wi-Fi Boost flow control algorithm with congestion detection is presented. In essence, UEs will tend to connect to the Wi-Fi path, and switch to the LTE path if congestion is detected in the Wi-Fi path. UEs may be switched back to the Wi-Fi path if such congestion disappears. This flow control algorithm could be used as basis for realising load balancing strategies, but they are out of the scope of this paper. As a working assumption, we assume that radio link statistics can be obtained from the MAC of the LTE eNB for the LTE path, but that such statistics are not available from the Wi-Fi AP for the Wi-Fi path in a general non-collocated Wi-Fi deployment (e.g., from a different vendor). Probing over the Wi-Fi path is used to assess its performance and generate the necessary statistics.

In the following, the initial phase (which takes place at connection setup) and data phase (which takes place when UE data is flowing) of the proposed flow control algorithm are described in detail. Fig. 2 illustrates the algorithm.

A. Initial Phase

Upon connection request, the LTE eNB will estimate which is the most suitable path for the given UE. This is done by the RAN connection manager (RCM), a new logical entity deployed at the LTE eNB to realise Wi-Fi Boost. A UE will be connected to the Wi-Fi path if the received signal strength of the Wi-Fi pilot is larger than -82 dBm in the 20 MHz channel, and it will be served data if the initial probing results meet a predefined criteria; Otherwise, it will be served data via the LTE path.

In order to probe the Wi-Fi path, the RCM sends to UE u though the Wi-Fi path x_u^{ini} IP probe packets of size s_u^{ini} bits during a test period of t_u^{ini} seconds at a rate of r_u^{ini} Mbps.

Upon probe reception, the UE connection manager (UCM), a new logical entity deployed at the UE to realise Wi-Fi Boost, gathers the following statistics: *i)* fraction of probes lost, probeLost_u, *ii)* average probe delay, probeDelay_u and *iii)* average probe throughput, probeRate_u. Once the UCM receives the last probe, this sends back to the RCM a probe ACK with the statistics over such test period.

Then, if the RCM receives the probe ACK and the following criteria are met:

- the fraction of probes lost is lower than a threshold, $\mathrm{probeLost}_u < \mathrm{probeLost}_{\mathrm{max},u}$,
- the average probe delay is shorter than a threshold, $\mathrm{probeDelay}_u < \mathrm{probeDelay}_{\mathrm{max},u}$, and
- the average probe rate is higher than a threshold, $\mathrm{probeRate}_u > \mathrm{probeRate}_{\mathrm{min},u}$,

the RCM routes UE IP data packets over the Wi-Fi path; Otherwise, it will route packets over the LTE path. Note that all mentioned thresholds are quality of service dependent.

It is important to note that if the UE is routed over the LTE path, the RCM will proceed with an initial probing phase every $t_u^{\mathrm{ip}} = 2\,\mathrm{s}$ during the data transmission in order to check whether the Wi-Fi path is suitable for the transmission.

B. Data Phase

If the Wi-Fi path has been selected, the RCM performs active probing to check whether the quality of the Wi-Fi path is still suitable to carry UE's traffic, or it has degraded due to congestion. In the latter case, the RCM would switch the UE over the LTE path.

In order to probe the Wi-Fi path while the actual data transmission is taking place, the RCM sends to the UE though the Wi-Fi path an active IP probe of size s_u^{dat} bits inserted within the UE IP data packets every t_u^{dat} seconds.

Upon active probe reception, the UCM calculates the average UE throughput, $U_{\mathrm{avg},u}$, in between this active probe and the previous one, and feeds back to the RCM the computed value using an active probe ACK. In contrast to the initial probes where only the last probe was acknowledged, all active probes are acknowledged.

Then, upon active probe ACK reception, the RCM puts the average UE throughput, $U_{\mathrm{avg},u}$, over a moving average filter, $\hat{U}_{\mathrm{avg},u}$, and may take the following decisions:

- Stall detection: If x_{stall} consecutive active probe ACKs are missing, the RCM switches the UE over the LTE path.
- Inactivity detection: If the number of bits transmitted in between two probe ACKs is smaller than a threshold, $U_{\mathrm{avg},u} < U_{\mathrm{min},u}$, meaning that the UE generates a small amount of traffic, the RCM switches the UE over the LTE path and the UE may decide to switch to Wi-Fi only mode to save resources.
- Congestion detection: if the filtered average UE throughput is smaller than a threshold, $\hat{U}_{\mathrm{avg},u} < TPH_{\mathrm{min},u}$, the RCM switches the UE over the LTE path.

Otherwise, the RCM keeps the UE IP data packets over the Wi-Fi path. Note that all mentioned thresholds are quality of service dependent.

It is important to note that if the UE is re-routed over the LTE path, the RCM will proceed with an initial probing phase every t_{ip} seconds in order to check whether the Wi-Fi path is suitable for the transmission.

Moreover, the following constraints to switching apply:

- No more than one UE is switched every t_{switch} seconds in any direction in order to avoid massive switching, ping-pong and instability issues in the presence of congestion.
- No UE is switched to the LTE path, if the resulting average UE throughputs of the existing LTE UEs after switching such UE would be smaller than a threshold r_{switch}. Round robin assumptions can be used to estimate the LTE UE performance after switching.

IV. Simulation Results

In this section, simulation results are presented to validate the performance of presented Wi-Fi Boost flow control algorithm in terms of FTP capacity. The performance evaluation is conducted over an enterprise area of $50\,\mathrm{m}\times 120\,\mathrm{m}$, where there is a LTE eNB located at the centre of it and several Wi-Fi APs are deployed within the enterprise. Most simulation assumptions in terms of LTE eNB and UE deployment as well as antenna gain, path loss, shadowing and multi-path fading modelling follow the 3GPP recommendations in [15], where the InH model is used to model the enterprise propagation characteristics. Since the focus is only on the DL performance, UL performance is not characterised in the paper. The assumption is that there is enough UL bandwidth to accommodate the UL diverted traffic, e.g. TCP ACKs, data channels. 100 simulation drops are performed, and in each drop 10 seconds are simulated.

a) Wi-Fi AP deployment: 2 Wi-Fi channels of 20 MHz in the 5 GHz band are considered, and 2 AP are deployed in the enterprise where the inter-AP distance is 60 m. Each AP has a transmit power of 24 dBm, and selects upon deployment the channel in which the least traffic load and interference is observed. Two omni antennas with a 5 dBi gain are considered.

b) UE deployment: 1, 4, 20, 26 or 32 UE are uniformly deployed within the enterprise, where the minimum AP-to-UE distance is 3 m. Each UE has a transmit power of 18 dBm, and associates to the AP with the strongest pilot, provided that this pilot was detected at or above -82 dBm in the 20 MHz channel. Two omni antennas with a 0 dBi gain are considered, thus allowing 2×2 MIMO transmissions. Fast fading channel gains are generated based on a UE speed of 3km/h.

c) Services: All UEs use a bidirectional FTP service (3GPP FTP traffic model 2) The FTP file size is 0.5 Mbytes in the DL and 0.25 Mbytes in the UL, while the mean reading time is 0.1 s (leading to a high demand of 40 Mbps and 20 Mbps per UE in DL and UL respectively). Note that a simplified TPC model is used, where TCP ACK are generated in response to FTP traffic, in which 1 TCP ACK is sent for every 3 TCP data packets.

Other relevant Wi-Fi parameters are set as follows: DIFS= $34\,\mu$s, SIFS= $16\,\mu$s, time slot = $9\,\mu$s, TXOP=3 ms [15]. Refer to [10] for a more detailed description of the simulator.

A. Benchmarked Technologies

Four system configurations are considered:

1) *LTE only*: All traffic DL and UL is carried by the LTE eNB in the licensed band.
2) *Wi-Fi only*: All traffic DL and UL is carried by the Wi-Fi APs in the unlicensed band.
3) *LWIP R13*: Traffic is split according to the discussion in Section II. DL FTP traffic and DL TCP ACKs are routed over WiFi, while UL FTP traffic and UL TCP ACKs are routed over LTE. As explained before, WiFi MAC ACKs remain in the WiFi network. Note that due to the static

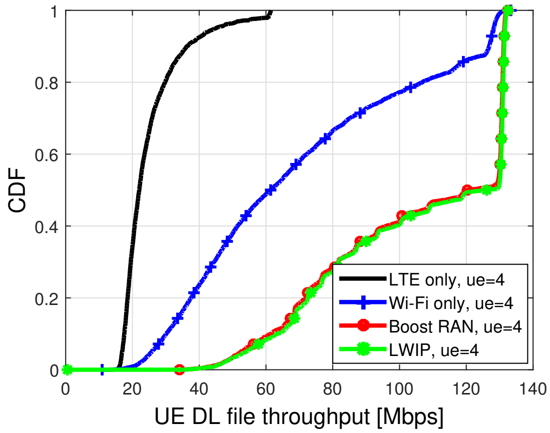


Fig. 3: UE throughput CDF for the 4 UE/enterprise case.

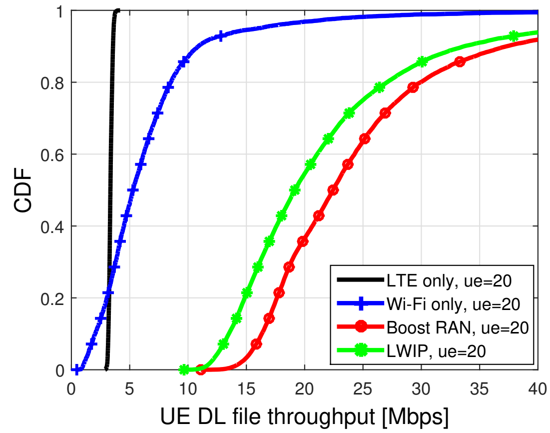


Fig. 4: UE throughput CDF for the 20 UE/enterprise case.

nature of the UEs in our simulation, LWIP R13 cannot leverage its RSSI radio link management.

4) *Wi-Fi Boost*: Traffic is split as in the LWIP R13 case. However, the congestion detection and DL steering mechanism presented in Section III kicks in to optimise overall enterprise performance when the UE does not get the desired performance.

Note that the Wi-Fi Boost flow control algorithm is configured with the following parameters:

- Initial phase probing:
  $s_u^{\text{ini}} = 12000\,\text{bits}$, $t_u^{\text{ini}} = 0.1\,\text{s}$ and $r_u^{\text{ini}} = 5\,\text{Mbps}$.
- Initial phase decision-making:
  $\text{probeLost}_{\text{max},u} = 0.1$, $\text{probeDelay}_{\text{max},u} = 0.5\,\text{s}$ and $\text{probeRate}_{\text{min},u} = 5\,\text{Mbps}$.
- Data phase probing:
  $s_u^{\text{dat}} = 160\,\text{bits}$ and $t_u^{\text{dat}} = 0.003\,\text{s}$.
- Data phase decision-making:
  $x_{\text{stall}} = 3$, $U_{\text{min},u} = 0.5\,\text{Mbps}$ and $TPH_{\text{min},u} = 5\,\text{Mbps}$.

Note that the IPsec overhead per IP packet is 66 bytes, and that the data phase overhead is minimal as only 160 bits are transmitted at most every 0.003 s.

B. Performance Comparison

For reference purposes and according to our simulations, let us first note that the peak UE throughput (single UE case) for the LTE only case was 63 Mbps (10 MHz bandwidth, 2x2 MIMO, 64 QAM), while that for the Wi-Fi only case was 140 Mbps (20 MHz bandwidth, 2x2 MIMO, 256 QAM). As LWIP R13 and Wi-Fi Boost do not leverage aggregation, their peak UE throughput were equal to that of the Wi-Fi only case, 140 Mbps.

Fig. 3 shows the UE throughput cumulative distribution function (CDF) for the case where there are 4 UEs in the enterprise. The LTE only case provides a median throughput of 21.93 Mbps/UE, while the Wi-Fi only case provides a larger median throughput of 60.93 Mbps/UE. This is because the Wi-Fi only case benefits from more cells (2 instead of 1), more bandwidth (2x20MHz instead of 1x10MHz) and a larger peak modulation (256QAM instead of 64QAM). Results also show that LWIP R13 and Wi-Fi Boost have a substantial gain over the Wi-Fi only case of around 2x. This is due to the offloading of UL traffic from the unlicensed to the licensed band and the resulting collision-free usage of the unlicensed spectrum for DL (the so-called Boost effect). Note that LWIP R13 and Wi-Fi Boost perform equally. Because of the low traffic load in the scenario, there is no congestion and the flow control algorithm of Wi-Fi Boost presented in this paper does not kick in.

Fig. 4 shows the UE throughput distribution for the case where there are 20 UEs in the enterprise. Now, the LTE only case provides a median throughput of 3.37 Mbps/UE, while the Wi-Fi only case provides just a slightly larger median throughput of 7.3 Mbps/UE. Even if Wi-Fi has more cells, more bandwidth and and a larger peak modulation, the Wi-Fi performance is significantly degraded in comparison to that of LTE due to the inefficient sharing of resources between nodes and the contention/collision issues in the former. Moreover, and as in the previous scenario, LWIP R13 significantly outperforms the Wi-Fi only case with a gain of around 2.6x due to the Boost effect. The gain is larger than before because the larger traffic load and contention degrades further the performance of the benchmark, the performance of Wi-Fi. It is important to note that this time Wi-Fi Boost provides a 17 % gain over LWIP R13. Because of the larger traffic load in the scenario, the congestion detection mechanism is activated and some UEs are switched from Wi-Fi to LTE, thus providing a better sharing of overall resources with the subsequent performance increase.

Fig. 5 shows the UE throughput distribution for the case where there are 32 UEs in the enterprise. Due to the even larger traffic load, and the resulting larger contention and congestion, the gap between the performance of the LTE only and Wi-Fi only cases reduces further. This shows how CSMA/CA becomes more and more inefficient as the traffic load increases. Moreover, due to the larger congestion, the performance gain of LWIP R13 and Wi-Fi Boost with respect to the Wi-Fi only case is again larger. LWIP R13 and Wi-Fi Boost can enhance network performance up to 5x and 6x over LTE only, and 4x and 5x over Wi-Fi only networks, respectively, which is in inline with the results in [10]. For the same reason, due to the larger congestion, the performance gain of LWIP R13 over Wi-Fi Boost is also larger, around 19 %. This shows how an intelligent selection of the serving path that does not only rely on RSSI measurements can provide a better LTE and Wi-Fi interworking and enhance the

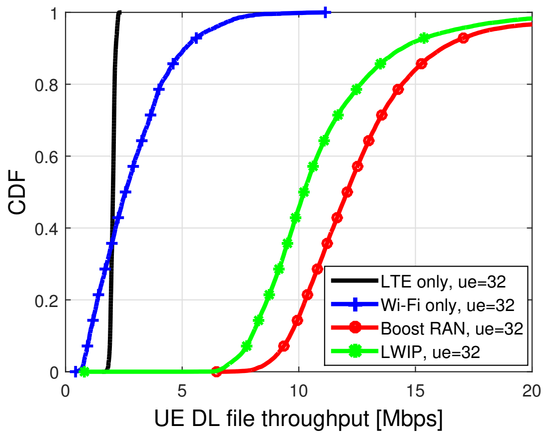


Fig. 5: UE throughput CDF for the 32 UE/enterprise case.

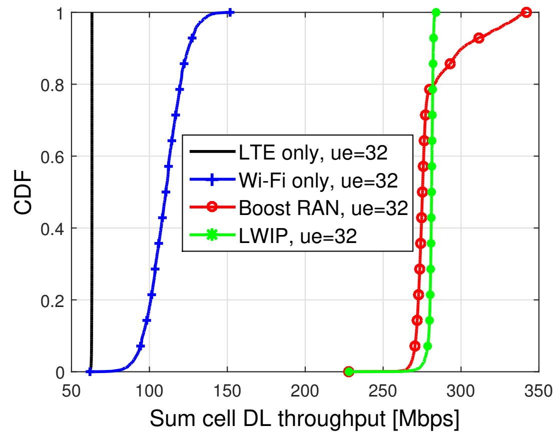


Fig. 6: System throughput CDF for the 32 UE/enterprise case.

UE performance. This indicates the need for enhancing LWIP R13 UE feedback in future LTE releases by providing timely UE estimations to the LTE eNB on short-term throughput to detect congestion.

Fig. 6 shows the system throughput (sum throughput of all cells) distribution for the case where there are 32 UEs in the enterprise. The sum cell throughput is the sum of throughput of all cells in the scenario. Since there is only one LTE eNB in the scenario, the LTE only case provides a median cell sum throughput of 63 Mbps, around its peak throughput. Instead, the Wi-Fi only case provides a median cell sum throughput of 110 Mbps. Congestion prevents achieving the peak throughput of the Wi-Fi cells. For the LWIP R13 case, since such contention disappears due to the Boost effect, the system reaches the Wi-Fi peak throughput, i.e., 2×140 Mbps $=$ 280 Mbps. Finally, results show how around 20 % of the time congestion is detected, the proposed flow control algorithm mechanism kicks in, and some UEs are switched to the LTE eNB. This allows to leverage the licensed spectrum achieving a top throughput of up to 340 Mbps, around the combined peak throughput of all cells together. A more aggressive switching with a larger $\mathrm{probeRate}_{\mathrm{min},u}$ would provide a better use of the licensed spectrum. However, this may come at the expense of underutilising the unlicensed spectrum, which results in a degradation of UE and sum throughput. We recommend to explore machine learning techniques to optimise the algorithm parameters with respect to the scenario conditions.

V. Conclusion

In this paper, we have presented the architectures of 3GPP LWIP R13 technology and its pre-standard version Wi-Fi Boost, while highlighting its main common features and differences. Moreover, we have also proposed a Wi-Fi Boost flow control algorithm with congestion detection to make LTE and Wi-Fi integration more efficient, where such congestion detection mechanism is based on IP probing and can work with any Wi-Fi AP. In essence, UEs will tend to connect to Wi-Fi path, and switch to the LTE path if congestion is detected in the Wi-Fi path. UEs may be switched back to the Wi-Fi path if such congestion disappears. Simulation results in a typical enterprise scenario show that LWIP R13 and Wi-Fi Boost can enhance network performance up to 5x and 6x over LTE-only, and 4x and 5x over Wi-Fi only networks, respectively, and that the proposed flow control algorithm can further enhance Wi-Fi Boost performance over LWIP R13 up to 19 %. Based on lessons learned, this paper suggests to enhance LWIP R13 UE feedback in future LTE releases by providing UE estimations to the LTE eNB on short-term throughput to detect congestion. This would allow to realise the presented flow control algorithm for Wi-Fi Boost in LWIP.

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