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Very Tight Coupling between LTE and WiFi: a Practical Analysis

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The use of the large number of deployed WiFi access points is an interesting solution to offload LTE networks. In the perspective of convergence between fixed and mobile access, it is possible to connect WiFi access points to eNodeBs. With very tight coupling, WiFi and LTE flows are merged just below the IP layer. The objective is to accelerate the process of attachment to a WiFi Access Point and to allow dual WiFi/LTE transmission while providing a seamless experience to the end user. In this paper, we show an implementation of very tight coupling on a testbed based on the OpenAir Interface framework and perform some experiments for different scenarios.

Keywords: HetNets, Cellular offload, LTE-WiFi coupling

1 Introduction

A significant increase of the data traffic has been observed recently on cellular networks. One solution to face this challenge is to offload the traffic through WiFi networks. This is very interesting as the operator can take advantage of the unlicensed WiFi spectrum and the huge number of deployed WiFi Access Points (APs). To provide a unified LTE/WiFi access, there are three main levels of coupling between the two technologies [KLG14]:

In *Loose coupling*, WiFi and LTE networks are physically independent. As the two networks are connected to the internet, the User Equipment (UE) can use both. However, to use WiFi, the UE (UE) first scans for available WiFi APs. It needs to authenticate on the selected AP and then can start to send or receive data. Note that the UE should manage two IP addresses: a vertical handover (WiFi-LTE) breaks the connection except if specific procedures (e.g. Multipath Transport Control Protocol (MPTCP)) are implemented.

In *Tight coupling*, WiFi APs are directly connected to the cellular Evolved Packet Core (EPC) network. However, the UE still needs to use WiFi security mechanisms which are time consuming. These solution were standardized by the 3GPP in release 10 [3GP12].

In *very tight coupling*, WiFi APs that are covered by an LTE eNodeB (eNB) are connected to that eNB. The connection can be direct or based on a layer 2 network (typically the aggregation network as shown in Fig.1). The data traffic can be offloaded to WiFi while the control functions (e.g. security, mobility, etc) are kept in the LTE network. In addition, simultaneous transmission over both LTE and WiFi are made possible.

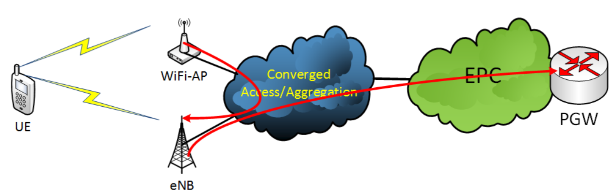

Figure 1: Very Tight Coupling Architecture

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2 Very Tight Coupling Between LTE and WiFi

Very tight coupling between LTE and WiFi was first proposed in [Lag14]. In parallel, Qualcomm was studying a similar approach called LTE/WiFi Link Aggregation and recently presented a test-bed [QUA]. However, Qualcomm specification is not public. The 3GPP [3GP13] also proposed the same idea of dual connectivity over a single PDCP instance. However, 3GPP proposition is still limited to macro and small-cells coupling while we propose to use it for WiFi-LTE coupling.

In very tight coupling, WiFi APs that are covered by an eNB are connected to that eNB (Fig.1). By this, it is possible to reuse the Packet Data Convergence Protocol (PDCP) of the LTE protocol stack for WiFi transmission. One of the functions of PDCP is to provide security by ciphering upper layer packets. Thus, when PDCP is used on WiFi, we avoid using WiFi security protocols. The authentication process can be bypassed and only a simple attachment procedure to the WiFi AP is enough. Hence, it takes less time to the UE to connect to an AP and to start sending traffic over WiFi which allows users who stay only for a short time into a WiFi AP coverage to be offloaded.

LTE/WiFi dual connectivity proposed in very tight coupling is very different from vertical handover used by other coupling solutions. The idea is to keep the control plane over LTE while the data plane is sent over both LTE and WiFi. This mainly aims at keeping the entire control into the network. Today, the decision to make or to break a connection over WiFi is taken by the UE. Even though mechanisms such as ANDSF or Hotspot 2.0 allow the network to have some influence on the choice of the WiFi network, the final decision still has to be taken by the UE. This may lead to non-optimized decisions and thus to Quality of Experience (QoE) degradation. In very tight coupling, the connection control (i.e. making and breaking connections) is moved entirely to the network which has a global view of the load on the different LTE cells and can also have information about WiFi networks, e.g. using mechanisms based on Access Network Query Protocol (ANQP). Thus, UEs are moved to WiFi only if offloading is necessary (e.g. the LTE cell is too loaded) and if the target AP can provide a satisfying QoE to the end user.

WiFi and LTE radio interfaces have different characteristics in terms of delay and throughput. Using them in parallel may lead Packets Data Units (PDUs) to arrive in the wrong order to the PDCP entity and a reordering function is thus necessary. In this case, a buffer is used to store PDUs if there is one or several missing PDUs in the received sequence. A timer is used to prevent infinite storage. The timer is started each time a PDU is stored. When it expires, the missing PDUs are considered as lost and all PDUs present in the buffer are delivered to the upper layer. Such mechanism allows an in-sequence delivery to the upper layer.

3 Architecture of the testbed

Our testbed is based on Open Air Interface (OAI), which is an open source platform developed by Eurecom [OAI]. It proposes a complete implementation of the different elements of a Release 10 LTE network. OAI can be used to emulate an eNB and a UE, but also the different parts of the EPC. In real LTE equipment (i.e. UE and eNB), some layers of the protocol stack are implemented within the hardware (e.g. PDCP), which allows faster execution. In OAI the entire protocol stack is executed as a software by the operating system. This increases the execution time and thus limits the achievable throughput.

For our experiments, an OAI eNB and an OAI UE are deployed on two distinct computers both using a USRP B210 RF card. A third machine is used as a WiFi AP and is connected to the eNB through an Ethernet network. We implemented three new modules: a WiFi integration module that adds and remove an adaptation layer to allow the transmission of PDCP PDUs over WiFi, a selection procedure that chooses the outer interface (WiFi or LTE) according to the selected policy, a full PDCP reordering mechanism with buffer and timer management.

We propose two different testing scenarios. In a full LTE-offload, all the data plane is offloaded to WiFi when an AP is available. In a LTE/WiFi aggregation scenario, WiFi is used simultaneously with LTE. If the RLC buffer is empty, the packet is sent on LTE, otherwise it is sent on WiFi.

We run the experiment with and without the PDCP reordering feature. When it is activated, the reordering timer needs to be calibrated to minimize the impact on higher layers. The TCP Retransmission Timeout (RTO) is usually equal to twice the Round Trip Time (RTT).

Indicator	Full LTE-offload	LTE/WiFi aggreg. and reordering	LTE/WiFi aggreg. and no reordering
Mean global throughput (Mbps)	3.15 +- 0.11	2.05 +- 0.27	3.09 +- 0.20
Mean throughput when WiFi is used (Mbps)	5.24 +- 0.16	2.71 +- 0.59	4.65 +- 0.39
Mean LTE throughput (Mbps)	1.59 +- 0.20	1.56 +- 0.19	3.84 +- 0.44

Table 1: Different indicators for the three scenarios

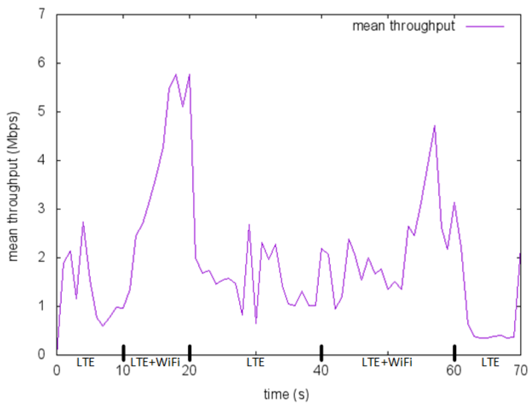

Figure 3: LTE/WiFi aggreg. and PDCP reordering

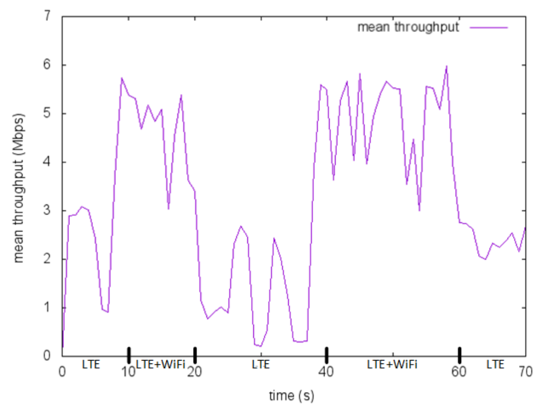

Figure 4: LTE/WiFi aggreg. and no PDCP reordering

To avoid this timer to expire, which forces TCP to reduce its bit rate, we fix the PDCP reordering timer to twice the maximum of the average RTT on both links. For bit rate measurement, we use the iperf tool. We are interested in the downlink throughput. We thus generate TCP traffic from the eNB and do the measurements at the UE for a period equal to one minute. In order to have a low difference on the delays of the two links, we artificially increase the delay on WiFi using the Linux network emulator (NeTem).

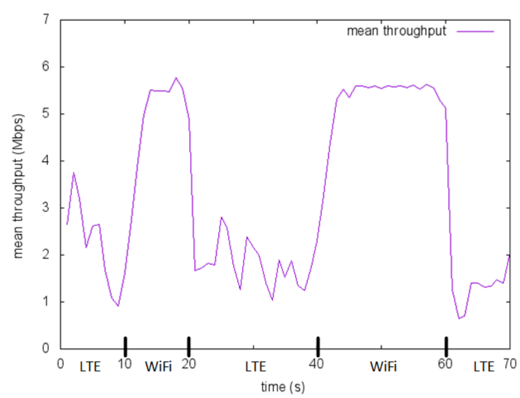

Figure 2: Full-LTE offload

4 Results and discussion

Fig.2 shows the evolution of the throughput for the Full LTE-offload scenario. In Fig.3, the bit rate is plotted for the LTE/WiFi aggregation scenario when the reordering function is activated while Fig.4 shows the bit rate when it is not used. In all scenarios, WiFi is available at two periods: from second 10 to second 20 and from second 40 to second 60. For comparison purpose, we use three indicators: the mean global throughput computed over the entire emulation session, the mean throughput when WiFi is used and the mean LTE throughput when LTE only is used. Results are presented in table 1.

4.1 *Full LTE-offload*

As can be seen in Fig2, the mean bit rate is very limited, i.e. 1.59Mbps (see table1), when LTE only is used. This is due to the unstable LTE connection which causes a high loss rate. On the other hand, WiFi can offer a better bit rate when the UE uses WiFi only and can reach more than 5.24Mbps. Hence, the overall throughput, i.e. 3.15Mbps, is higher in this case compared to the two other scenarios.

4.2 LTE/WiFi aggregation with PDCP reordering

In the first LTE/WiFi aggregation session, i.e. seconds 10-20, the bit rate is increasing and reaches more than 5Mbps. The UE first starts to send half of the traffic over WiFi and the other half over LTE. While the RLC buffer is being filled, the UE starts using more and more WiFi, which increases the bit rate. In the second session (i.e. at second 40), the bit rate does not exceed 2Mbps until it starts increasing at second 52 when it reaches 4.8Mbps.

4.3 LTE/WiFi aggregation without PDCP reordering

In this experiment the PDCP reordering function is not used, i.e. received PDCP PDUs are delivered to TCP even if there is missing ones. The throughput in this case is varying between 4Mbps and 6Mbps with an average of 3.09Mbps, i.e. better compared to when the PDCP reordering is used

4.4 Discussion

We first conclude that using LTE and WiFi simultaneously does not increase the bit rate compared to when WiFi is used alone. This is not an artifact due to some testbed specificity. This is a general behavior due to TCP loss detection mechanisms, which uses timers based on the mean RTT on the two links. If the delay on one link is too large compared to the TCP timer (i.e. the RTO), most packets of this link will be considered as lost which leads TCP to reduce its throughput. Secondly, we see that using a reordering function at PDCP may have a bad impact on the bit rate rather than increasing it. This is due to the head-of-line blocking that occurs when a delayed PDU blocks all the ones already received in the PDCP buffer. From the TCP point of view, this PDUs have not been received and are considered as lost if the timer expires. It seems better to deliver received packets to TCP without buffering at PDCP to avoid RTO expiration. Also, in the case of missing packets, TCP uses selective acknowledgement to avoid useless re-transmissions of already received packets. An interesting extension of the experiments is to check if the same results would be found with other version of TCP (TCP Reno for example).

4.5 Conclusion

We show in the full LTE-offload scenario that the UE can take advantage of the high bit rate offered by the AP while offloading the LTE network. In the LTE/WiFi aggregation case, we demonstrate that using WiFi beside LTE does not increase the throughput when the PDCP reordering function is used compared to WiFi-only if the difference between the delays on the two links is too large. However, we show that TCP reacts better when no reordering is performed at PDCP as it maintains a good bit rate when WiFi is used beside LTE.

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