Very Tight Coupling between LTE and Wi-Fi for Advanced Offloading Procedures

Xavier Lagrange
Telecom Bretagne - IRISA D2
Rennes, France
Email: xavier.lagrange@telecom-bretagne.eu

***Abstract*—Wi-Fi access points are now widely deployed by customers or by the operators. This represents an interesting solution to offload the LTE networks. In this paper we propose a very-tight coupling solution between LTE and Wi-Fi, which can be used to enhance the offloading procedures. In this architecture PDCP (Packet Data Convergence Protocol) is used as the common layer between LTE and Wi-Fi and the security procedures defined for LTE are reused for Wi-Fi transmission. It is thus possible to use Wi-Fi transmissions even when a terminal is covered by a Wi-Fi access point for a short period. We describe the entities of this architecture, the protocol stack and describe how user packets are transmitted.**

I. Introduction

4G networks are now widely deployed around the world. Users can enjoy high bit rate transmission. This stimulates the usage of smart phones and thus generates a dramatic increase of the load of cellular networks. According to an Ericsson report [1], a typical laptop will generate 11 GB, a tablet 3.1 GB and a smart-phone around 2 GB per month by the end of 2018.

Most smart-phones have at least a Wi-Fi Interface controller and an LTE one, which can be both simultaneously used. Using Wi-Fi access points is thus a natural solution to offload LTE networks. Such Wi-Fi access points can be specifically deployed by an operator or can be residential gateways that customers have at home. In the latter case, the gateway should be configured to allow other customers to use it to access the Internet (concept of community networks).

Wi-Fi as an offload solution for cellular networks has been studied by the research community (see for example [2]) and several commercial solutions are already available (see for example [3]). It is also standardized by 3GPP.

Different levels of coupling 3GPP and non-3GPP accesses are defined in 3GPP technical specifications. How to connect both trusted and non-trusted Wi-Fi access points is defined in release 8. By Release 10, the possibility to simultaneously use several access technologies is specified. With *Simultaneous multi-access connectivity*, a UE can have one connection (associated to an APN, Access Point Name) on a cellular access and a non-3GPP access (with another APN). With *IP Flow Mobility*, it is possible to choose on which access each IP flow is transmitted and to seamlessly move the flow between accesses. *Non-seamless Offload* provides the same possibility but without any support of session continuity. In all proposed configurations, non-3GPP access gateways are connected to the Evolved Packet Core (EPC) network, namely to the Serving Gateway (SGW) or the Packet Data-Network Gateway (PGW). No proposal for a really integrated and unified WiFi-LTE access has been envisaged. This can be explained because generally Wi-Fi access point are connected to the Internet through a fixed access infrastructure and base stations are connected to the cellular core network through a different transport network.

Very high bit rate access is now available for a lot of customers in large cities with the emergence of optical transmissions (FTTH, Fiber To The Home). With FTTH, the line bit rate can reach 10 Gb/s with Passive Optical Technology (PON) and data rate up to 100 Gb/s are anticipated for long-term PON evolution [4]. With such large capacity, operator can use the same optical infrastructure both for the residential Internet access and for mobile backhauling (i.e. the link between the nodes of the radio access networks, namely base stations, radio network controllers,...). Such convergence between mobile and fixed access is studied by the FP7 COMBO project [5]. It opens the way to a very tight coupling between Wi-Fi access points and LTE base stations. The objective of this work is to propose an architecture where the radio access network is really multi-technology: Wi-Fi access points are connected to base station and are seen as an integral part of the evolved UMTS Terrestrial Radio Access Network (eUTRAN). It is thus possible to develop very fast access procedures in order to enable terminals that are under the coverage of a Wi-Fi access point even for a short time to use the Wi-Fi technology for data transmission.

Very tight coupling was already proposed for UMTS in the early 00's by [6] and is discussed in [7]. Similarly to the solution called "WLAN as UMTS AS approach" in [6], Wi-Fi access points are connected to the radio access networks. However, in our proposal, there is no need for an Radio Network Controller emulator because there is a direct connection to eNodeBs. Furthermore, we suggest to maintain the RRC connection in the cellular network even when some data are transmitted through a residential gateway in order to have a simple and efficient dual connectivity mode.

In section II, we recall the architecture of LTE and the protocol stack on the radio interface. In section III, we describe the functional entities of the new architecture and the proposed protocol stack to have very tight coupling. In section IV, we explain how user data packet are transmitted. Section V

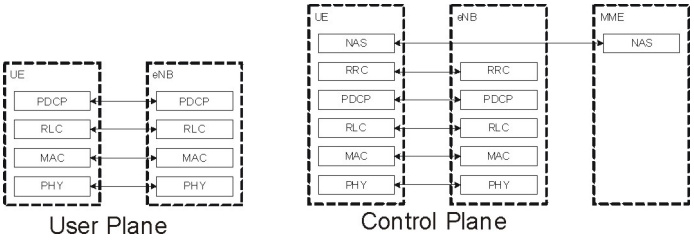

Fig. 1. LTE protocol stack on the radio (Uu) interface (source: 36.300 fig 4.3.1-1 and 4.3.2-1)

concludes the paper.

II. Architecture and Protocol Stack of LTE

The protocol stack of LTE on the radio interface is shown in figure 1. The same low layers are used both for the control plane and for the user plane : Physical (L1), Medium Access Control (MAC), Radio Link Control (RLC) and Packet Data Convergence Protocol (PDCP). Different levels of quality of service (QoS) can be simultaneously offered to parallel sessions because several RLC entities can be active at the same time. Each RLC entity corresponds to one logical channel and is uniquely identified for a given UE by a Logical Channel IDentifier (LCID), which is coded on 5 bits.

When a User Equipement (UE) has at least one active session (i.e. data are transmitted either on the downlink or on the uplink), it is in *ECM connected* mode and a radio connection is established. A Radio Network Temporary identifier (RNTI) is assigned to the UE as long as the radio connection is active. That RNTI uniquely identifies the UE in the radio access network and is coded on 16 bits. Each transmission by or to a UE is associated to its RNTI, which is sent in the downlink control indication.

The main function of PDCP [8] is to allow the transmission of both the data and signalling in a unified way. PDCP manages the compression and decompression of both the header and the content of IP data packets. It can cipher and decipher data units both in the user and control planes and can manage integrity protection and verification in the control plane (see figure 2). Each PDCP Protocol Data Unit (PDU) is identified by a Sequence Number (PDCP SN), which is put in the header. This makes it possible to ensure in-sequence delivery of upper layer PDUs and to eliminate duplicated low-layer Service Data Units (SDU) in case of re-establishment of lower layers (e.g. handover). The max size of a PCDP PDU is 8188 bytes. Note that each PCDP PDU can be uniquely identified within a given radio access network by the following fields : PCDP SN, LCID and RNTI. In other words this triplet identifies the transmission of a data block on a given bearer of a given UE.

III. Description of the Architecture

A. Reminder on Access and Aggregation Networks

Many technologies can be used to provide a fixed access to the internet to residential customers. One of the most popular is ADSL (Asynchronous Digital Subscriber Line), which reuses the twisted pair that was initially deployed for the telephony service. The set of pairs between a local office and the customer premises is called the access network. The Residential Gateway is connected to a DSLAM (Digital Subscriber Line Access Multiplexer). The full IP protocol stack is not included in the DSLAM but in a POP (Point Of Presence) in order to group the trafic of users over a regional area. POPs and DSLAMs are connected through an aggregation network, which is generally based on long-distance Ethernet. In order to isolate the traffic of each user of group of users, VLAN (Virtual Local Area Networks) are defined over Ethernet. They can prevent eavesdropping and avoid mixing of traffic while keeping the possibility of broadcasting a message to all users in the same VLAN. Note that VLANs in VLANs can be defined thanks to the IEEE 802.1ad (also called QinQ).

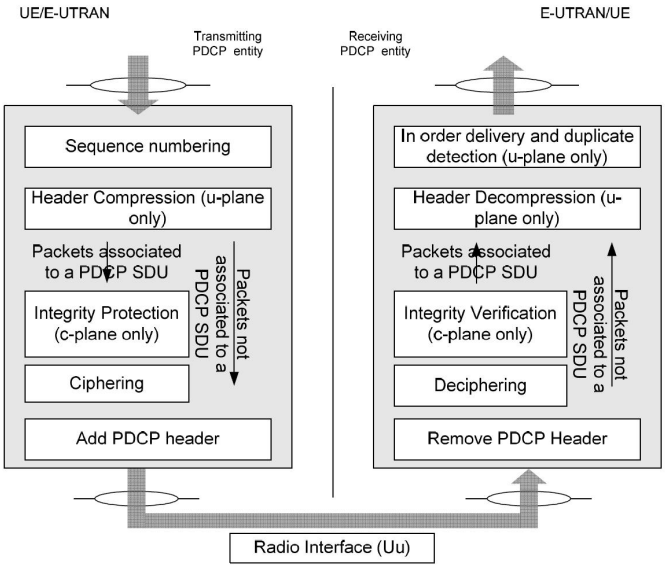

Fig. 2. Functional view of PCDP layer (source: 36.323 fig 4.2.2.1)

An emerging technology for high bit rate access is PON. Like for ADSL, there is an access network and an aggregation network. An ONU (Optical network unit) is installed in the customer premises and an OLT (Optical Line Terminal) between the access and the aggregation network (see [9] for further details).

B. Main functional entities

We propose a very tight coupling between Wi-Fi access points and LTE eNodeBs. The main idea is to connect Wi-Fi access points that are covered by an eNodeB to this eNodeB. Such tight coupling is made possible by putting security functions and the L3 protocol stack of the gateway in the network. In other words residential gateways as well as access points specifically deployed by the operator are virtualized. The device deployed in the customer premise or in hot spot is then called a *virtual residential gateway* or vRGW and

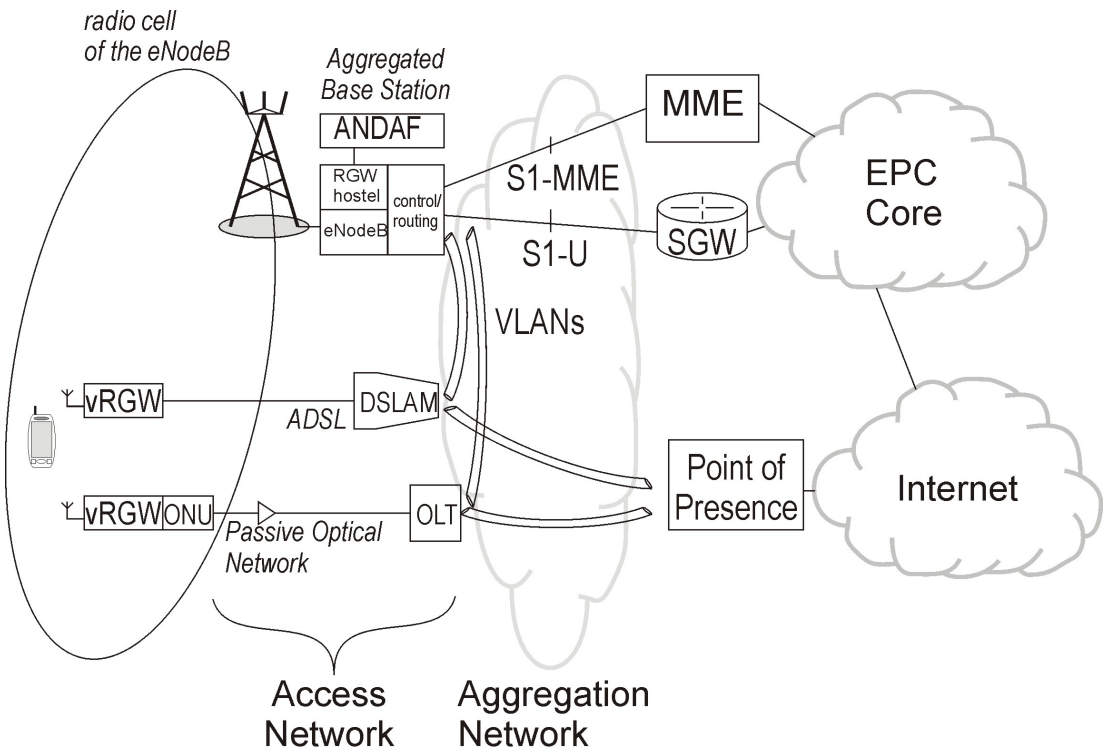

Fig. 3. General principle of HetNet architecture with very tight coupling

the device that hosts security and L3 functions is called a *gateway hotel* as it is possible to implement gateway functions of several customers in the same piece of equipment (see figure 3). The gateway hotel together with the eNodeB is called an *aggregated base station*. Note that for the sake of simplicity, we include public access points deployed by the operator under the acronym vRGW.

Regarding the physical layer, two options are possible:

- Option A. The virtual gateway is both a layer-2 bridge and a Wi-Fi access point. Wi-Fi frames are demodulated and decoded by the virtual gateway and transmitted to the gateway hotel. If the virtual gateway includes an Ethernet control interface, the Ethernet frames can be systematically transmitted to the gateway hotel or they can be locally managed (i.e. Layer 3 functions over Ethernet are kept in the virtual gateway).
- Option B. The virtual gateway is a simple remote radio head (RRH) regarding Wi-Fi and an layer-2 bridge for Ethernet. The Wi-Fi signal is just converted in a baseband signal, sampled, quantified and transmitted to the gateway hotel (concept of Digital Radio over the Fiber, DRoF). In that case the gateway hotel includes all Base Band Unit (BBU) functions (demodulation, decoding, framing) for Wi-Fi and for LTE (see figure 4). The aggregated base station thus includes LTE BBUs (L-BBU) and Wi-Fi BBUs (W-BBU).

With Option A, there is no strict delay constraints on links. Hence, virtual gateways can be connected to an access network different from the one of the eNodeB. A VLAN can be set in the aggregation network to connect Wi-Fi access points to their serving eNodeB. With Option B, the interface between vRGW and the Gateway hotel should typically be compliant with the Common Public Radio Interface (CPRI) [10]. In that case, the propagation delay should be low enough to avoid a dramatic reduction of the throughput of Wi-Fi access points as shown in [11]. However, it is possible to have coordination between vRGW, for instance to have a frequency allocation procedure that minimises interference between neighboring vRGW.

In all cases, residential gateways can still be used to access the Internet as a fixed access service. More precisely, the residential gateway can broadcast two Service Set IDentifiers (SSID): one corresponding to the Internet access and the other for the Wi-Fi offload service.

The main principle of the proposal is to keep all control functions (security, mobility, session management) in the LTE network and to use Wi-Fi only to transmit data. Tight coupling between LTE and Wi-Fi makes possible to help the terminal to very quickly set up L2 connection with Wi-Fi access point. The objective is to allow terminals that are covered by a residential virtual gateway for a short period (10 seconds to 1 minute) to use the Wi-Fi network to off-load the cellular network.

When data are transmitted through Wi-Fi, the LTE radio connection is maintained as shown in figure 5. This is equivalent to Wi-Fi-LTE dual connectivity. If the terminal stays in the access point vicinity only for a short period, there is thus no vertical handover. If the terminal stays for a long period, then the RRC connection can be released and standard Wi-Fi-LTE

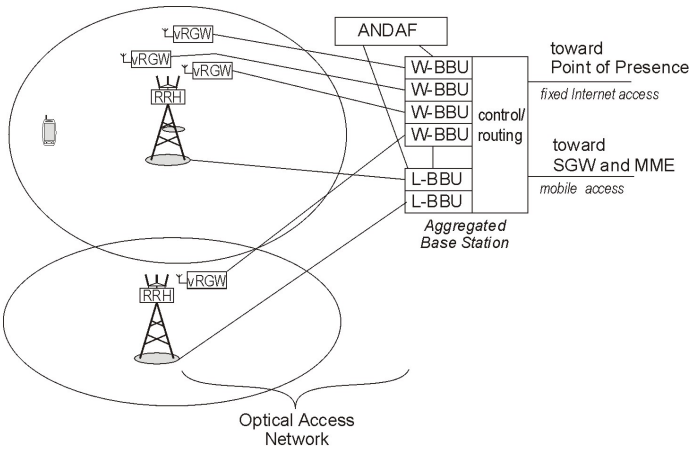

Fig. 4. very tight coupled HetNet architecture with Wi-Fi BBU (option B)

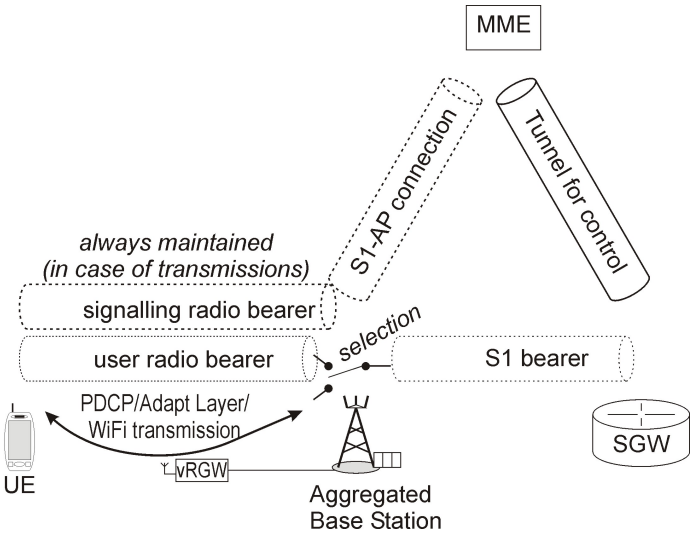

Fig. 5. Dual connectivity with very tight coupling

modes are used.

An *Access Network Discovery Accelerating Function* (ANDAF) can be implemented in the aggregated base station. This function is similar to ANDSF (Access Network Discovery and Selection Function). It aims at helping the UE to get a list of Wi-Fi access points it can access and their associated identities. The detailed functions in the ANDAF and the interface are still to be specified. The main guidelines for the specification is given below:

- information is not necessarily coded in XML (eXchange Mark Language) like for ANDSF; it can be coded in a more concise way and is integrated in Radio Resource Control (RRC) messages; this saves resource and makes possible to send a list of the characteristics of a few residential gateways (typically the frequency, the SSID) in one RRC message; the objective is to very quickly indicate potential access points to fast moving terminals,
- the list of Wi-Fi access points a terminal can access in an LTE cell can be configured by the operator or can be determined by a learning process,
- the learning process can be based on the correlation between patterns of measurements made by the UE and the identities of access points that are detected on a given location.

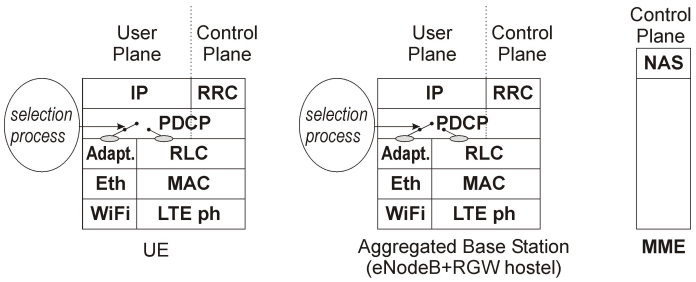

Fig. 6. Protocol stack on the radio interface with very tight coupling

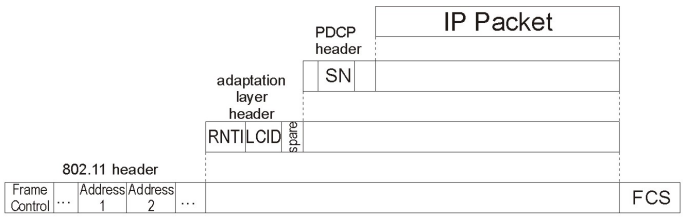

Fig. 7. Transport of an IP packet on the Wi-Fi radio interface

C. Protocol stack

The protocol stack is shown in figure 6. The LTE and Wi-Fi protocol stacks are kept unchanged with the following exception : IP data packets are encapsulated in PDCP (Packet Data Convergence Protocol) protocol data units even when Wi-Fi transmission is used. A very simple adaptation protocol is inserted below PDCP and above the MAC layer: it just adds or removes a header that includes the RNTI and the LCID associated to the bearer (see figure 7). Note that as ciphering is managed by PDCP, there is no need to use Wi-Fi-associated security procedures. The transmission in the Wi-Fi MAC layer is made in clear mode. This avoids key agreement handshake, which is time and energy consuming.

Note that an Identity Authentication Code obtained with an algorithm similar to the integrity checking of PCDP can be added. The code is computed with the following fields :

- the header at the adaptation layer (mainly RNTI and LCID),
- a secret key got from the security association set by the UE on the LTE Network,
- the PDCP sequence number.

The objective is to quickly detect false trafic injection by an attacker who reuses the RNTI and LCID of an UE.

In the terminal and in the aggregated base station, a *selection process* is added. The role of this process is to route the PDCP PDU either to the Wi-Fi or the LTE channel. The choice can be autonomously taken by the sender (UE on uplink and aggregated base station on downlink) or can be fully controlled

by the network. In that case, a specific RRC message similar to a handover is sent to the UE to ask him to transmit on the Wi-Fi channel. This message includes the SSID specifically used for the offload service and possibly the MAC address of the vRGW.

IV. Scenario of data transmission

In the following we consider a UE that is engaged in a session. Both UE and MME are thus in ECM-connected state.

When a PDCP PDU is transmitted in Wi-Fi mode by a dual-mode terminal that is close to virtual gateway, it is received by that virtual gateway and transmitted to the gateway hotel. The header of the adaptation layer includes the RNTI of the UE and a LCID. Hence, the aggregated base station can associated the received PDU in exactly the same way as for an LTE transmission. The PCDP PDU is deciphered and decapsulated to recover the original IP packet. The PDCP sequence number is checked and the packet is buffered if necessary in order to guarantee in-sequence delivery. This IP packet is then forwarded by the gateway hotel to the SGW like any other data IP packet sent by the UE in the LTE network.

Note that the network could correctly receive a packet sent through Wi-Fi even if the terminal was not attached to the virtual gateway. Of course, for security reason, the network can have a strict admission policy and consider only packets sent by terminals that have successfully made a full L2 attachement. Furthermore, the aggregated base station can maintain an association table between the identification of the UE in the Wi-Fi domain (e.g. MAC address) and the RNTI in order to make an additional consistency checking.

We now consider an IP packet that should be transmitted to a dual-mode terminal. When it is received by the eNodeB on the S1-U interface, it is put in a ciphered PDCP PDU. According to the routing decision made by the eNodeB, it can be transmitted either in LTE mode or in Wi-Fi. In this latter case, the association table is used to recover the MAC address of the dual-mode terminal. When the packet is received by the UE, it is deciphered. The PDCP sequence number is checked in order to guarantee in-sequence delivery.

V. Conclusion and Research issues

In this paper, we define an architecture where Wi-Fi access points are managed as parts of eNodeB and propose the concept of aggregated base station. The proposed architecture is compliant with existing integration solutions of Wi-Fi in LTE networks. Very tight coupling between Wi-Fi and LTE base stations opens the door to a better cooperation between Wi-Fi access points and to efficient offloading solutions.

The next step is to fully define the proposed extensions of the existing protocols (e.g. new message in RRC to indicate the characteristics of the access points when a UE has high probability to be covered in Wi-Fi). An interesting extension is to study a multi-operator architecture and also the dynamic connection of a Wi-Fi access point to an eNodeB when the coverage of the LTE is varying as a function of the time of day. Furthermore, there are a lot of research works that can be done : variation of the end-to-end delay when WiFi offload is activated for a given session, analysis of the correlation between LTE measurements (serving base station, neighbors) and Wi-Fi coverage, optimisation of the Wi-Fi/LTE selection process, etc.

VI. Acknowledgements

The research leading to these results has received funding from the European Communitys Seventh Framework Programme FP7/2013- 2015 under grant agreement no. 317762 COMBO project.

References

[1] Ericsson, "Mobility report," June 2013.

[2] M. Bennis, M. Simsek, A. Czylwik, W. Saad, S. Valentin, and M. Debbah, "When cellular meets wifi in wireless small cell networks," *IEEE Communications Magazine*, vol. 51, no. 6, pp. 44–50, 2013.

[3] Aruba, "Carrier-class public wi-fi for 3g/4g offload."

[4] M. Andrade, G. Kramer, L. Wosinska, J. Chen, S. Sallent, and B. Mukherjee, "Evaluating strategies for evolution of passive optical networks," *IEEE Communications Magazine*, vol. 49, no. 7, pp. 176,184, Novembre 2011.

[5] FP7_project, "web pages of the combo project," 2013.

[6] S.-L. Tsao and C.-C. Lin, "Design and evaluation of umts-wlan interworking strategies," in *Proceedings of 56th Vehicular Technology Conference, VTC 2002-Fall*, vol. 2. IEEE, 2002, pp. 777–781.

[7] G. Lampropoulos, N. Passas, and L. Merakos, "Handover management architectures in integrated wlan/cellular networks." *IEEE Communications Surveys*, vol. 7, no. 4, october 2005.

[8] 3GPP, "Evolved universal terrestrial radio access (e-utra); radio link control (rlc) protocol specification," Tech. Rep. 36.322, 2013.

[9] COMBO, "Analysis of key functions, equipement and infrastructures of fmc networks," Tech. Rep. D3.1 available on http://www.ict-combo.eu/data/uploads/pdf-combo/combo_d3.1_wp3__4nov2013_orange_v1.0.pdf, 2013.

[10] CPRI, "Common public radio interface ; interface specification," Tech. Rep. 5.0, 2011.

[11] Y. Khadraoui and X. Lagrange, "Virtual Residential Gateways," in *submtitted to IEEE Vehicular Technology Conference*, 2014.