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RESEARCH ARTICLE

An ns-3 architecture for simulating joint radio resource management strategies in interconnected WLAN and UMTS networks

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ABSTRACT

Interconnection of different access network technologies is an important research topic in mobile telecommunications systems. In this paper, we propose an ns-3 architecture for simulating the interconnection of wireless local area network (WLAN) and Universal Mobile Telecommunications System (UMTS). This architecture is based on the architecture proposed by the Third Generation Partnership Project, being the use of virtual interfaces as its main innovation. In order to demonstrate the value of the proposed simulation framework, we implemented the UMTS and WLAN interconnection considering three joint radio resource management strategies for distributing arriving calls. From the simulations results, we can conclude that the proposed simulation architecture is suitable to test and evaluate performance aspects related to the interconnection and joint management of UMTS and WLAN technologies. Copyright © 2012 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The telecommunications research community is addressing the interconnection of different radio access technologies, such as wireless local area network (WLAN) and Universal Mobile Telecommunication System (UMTS). The goal is to provide standards that contribute to the provisioning of a global mobility solution. Terminal mobility solutions will enable seamless communications, whereas early versions of dual-mode terminals already support cellular and WLAN interfaces.

Telecommunications operators are investing in hotspot environments that integrate UMTS and WLAN networks. The integration of WLAN with third generation (3G) wireless data networks brings many technical challenges, including vertical handovers between both radio technologies, session continuity, security, common authentication, unified accounting and billing, and consistent quality-of-service (QoS) and service provisioning [1].

The Third Generation Partnership Project (3GPP) has been standardising an interconnection among heterogeneous networks, more specifically UMTS and WLAN. In this paper, we address the 3GPP's most recent integration architecture TS 23.327 [2]. From the network perspective, that is, from the home agent (HA) point-of-view, terminals are equipped with a dual interface, and the users will be able to transmit data without realising which network they are using. Such decision will be taken by the operator.

In order to study and evaluate interconnections solutions, discrete event simulation is required. In the past, the ns-2 simulator has been extensively used by the research community, but it shows signs of ageing and is being slowly replaced by ns-3 [3]. Compared with ns-2, ns-3 offers a cleaner design and modern design patterns, better performance and scalability [4], a more detailed 802.11 simulation module, and more flexibility in packet manipulation, among other advantages. A comparison between ns-2 and ns-3 is made in [5], where the authors clearly show that the ns-3 simulator is significantly more complete than ns-2. However, no simulation frameworks could be found for ns-3 that would handle mobility of flows between UMTS and WLAN.

The main objective of this paper is to describe the developments that were needed on top of ns-3 in order to study call admission and reallocation issues in these hybrid UMTS/WLAN networks. The rest of this paper is organised as follows. Section 2 describes some related works found in the literature. In Section 3, we introduce the architecture of our ns-3 simulation approach, which is based on a virtual interface device. In Section 4, we describe the simulation scenario used to demonstrate and evaluate the interconnection simulation architecture proposed in this paper. In particular, we present the three joint radio resource management (JRRM) strategies that were used in the top of this simulation architecture for distributing arriving calls. Section 5 shows the results of the simulations, which validate our proposal. Finally, Section 6 presents the paper conclusions and points some directions for future work.

2. BACKGROUND AND RELATED WORKS

Simulation of communications systems has been performed regularly in the last decades and has proven to be a powerful tool in the assessment of systems performance. Commonly used simulators include ns-2 and its successor ns-3, already introduced in the paper and usually used in academic studies, and OMNeT++ and OPNET, both usually used in industrial environments. In [6], the authors proposed the openWNS, a dynamic event-driven system level simulation platform useful for the investigation of dynamic protocol behaviour in multi-cellular mobile radio network scenarios with detailed signal interference modelling. Although the openWNS simulator presents the implementation of specific modules for several radio technologies, such as WiMAX or Wi-Fi, no reference is presented for the interconnection of those technologies.

The interconnection of cellular and wireless networks had its first relevant works in the beginning of the last decade. In [7], two main approaches for the integration of cellular and WLAN networks were proposed, also called tightly coupled and loosely coupled inter-networking. In the tightly coupled approach, integration is implemented at a network layer below the Internet Protocol (IP) layer. In the loosely coupled architecture, the WLAN network is seen as an access network ‘complementary’ to the cellular data network, not directly connected to the core of the General Packet Radio Service (GPRS)/UMTS network.

In parallel with research works, 3GPP defined a working group that is dedicated to produce standards in this area. Recently, 3GPP has launched a new release of its interconnection standardisation initiative, which incorporates cellular and WLAN technologies into a single architecture [2]. The goal of 3GPP is to define and standardise nodes at the WLAN network that correspond to nodes with similar functions presented in 3G networks. Examples of these nodes are the WLAN Access Gateway (WAG), which has a role similar to the Serving GPRS Support Node (SGSN), and the Packet Data Gateway (PDG), which can be compared with the Gateway GPRS Support Node (GGSN). A long-term evolution wireless communication standard of 3GPP defines a core network architecture, named System Architecture Evolution, where the main component, the evolved packet core (EPC), enables the connection of user terminals using non-3GPP access technologies, such as Wi-Fi. A detailed description of these new 3GPP developments is presented in [8].

There are many examples of works that, similarly to our approach, also adopt the 3GPP integration architecture. In [9], the authors propose a multi-radio management approach that enables optimised access selection and handover control for mobile users and increases the overall efficiency of network resources. The goal of this approach is the integration of multiple radio access technologies in an operator context.

Virtual interfaces, used as a way of hiding multiple real network interfaces, is an approach commonly used in the interconnection of heterogeneous networks. The virtual network interface (VNI) is an always best connected solution where a unique virtual device with multiple real network interfaces can be used [10]. Its main concept is to place an adaptation interface on top of real network interfaces. This adaptation interface considers the interactions between IP and data link layers and enables the use of a unique IP address over different wireless technologies. In [11], a distributed virtual network device is presented with the objective of working on personal area networks. The network interface is selected according to the device capabilities, the application requirements and the available access networks. In this approach, mobile devices can transmit or receive over heterogeneous networks without any interruption in the connection. In [12], a virtual interface-based approach is proposed, which can only work in a subnet. This interface is inserted between the network layer and the data link layer to provide intranetwork handovers. This device does not support heterogeneous networks, and consequently, it is not prepared for vertical handovers.

3. PROPOSED ARCHITECTURE

The proposed simulation architecture is based on [2]. The signalling aspects, such as DSMIPv6 Binding Updates, are neglected for being irrelevant to the aspects that we need to research, namely load balancing and JRRM strategies in fourth generation heterogeneous networks.

3.1. Network topology

Our architecture, represented in Figure 1, contains the same network elements of the 3GPP architecture (TS 23.327). The HA traces the care-of address assigned to the user equipment (UE). The SGSN and the GGSN are responsible for transporting packets to the UE within the GPRS network. The PDG and the WAG have similar roles for the WLAN network and provide interworking with the rest of the network. All nodes, except the UE, are interconnected via wired point-to-point (PPP) links, and IPv4 is used in the data plane. The UE represents an end-user

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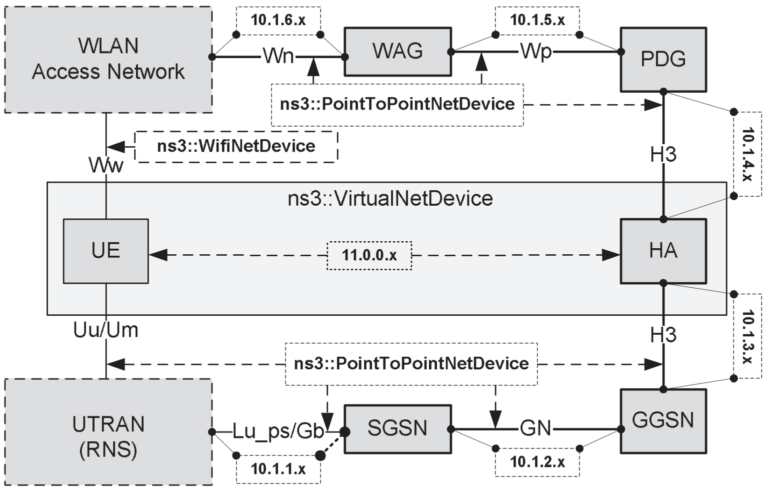

Figure 1. Modification inserted into 3GPP architecture. WLAN, wireless local area network; WAG, WLAN Access Gateway; PDG, Packet Data Gateway; UE, user equipment; HA, home agent; UTRAN, UMTS (Universal Mobile Telecommunication System) Terrestrial Radio Access Network; SGSN, Serving GPRS (General Packet Radio Service) Support Node; GGSN, Gateway GPRS Support Node.

mobile terminal with two access interfaces: UMTS and WLAN.

3.2. Tunnelling and mobility support

The system for providing mobility between 3GPP WLAN Interworking (I-WLAN) and 3GPP Systems is described in [2] and defines a solution based on the working principles of DSMIPv6. Because ns-3 has incomplete support for IPv6, we focused the framework on IPv4 only—IPv6 will be a future development—and our architecture becomes similar to MIPv4. The node WAG also functions as a *foreign agent*; that is, it terminates an MIPv4 tunnel from the HA. In the UMTS side of the network, TS 23.060 [13] indicates the use of a GPRS Tunnelling Protocol (GTP)/User Datagram Protocol (UDP)/IP tunnel between GGSN and SGSN. In our architecture, we extend the tunnel to begin at the HA. In this way, we perform the convergence of the tunnelling architectures of WLAN and UMTS branches, with great simplification and without loss of accuracy of the simulation results. The result is an *overlay network*, with two layers: end-to-end and transport. The end-to-end layer (upper layer) is composed of only the UE and HA nodes, which use home addresses (HoAs) for IPv4 interfaces and are virtually one hop away from each other. In the transport layer (lower layer), we have an IPv4-based transport network composed of the nodes WAG, PDG, SGSN, GGSN and HA.

3.3. Network stack

Figure 2 shows the network stack of our simulation architecture. The UE has an apparently simple IPv4 stack, with no tunnelling involved, and it just exchanges packets through one of the network interfaces, UMTS or WLAN using only the HoA as the source/destination. The WAG and SGSN nodes forward data packets through the UE HA tunnel. The tunnelling protocol used is GTP-U, which uses a GTP header and a UDP header on top of IPv4. The nodes GGSN and PDG are simple IP routers. Finally, the HA terminates the tunnels from WAG and SGSN and supports application servers, either local or in an external network. The grey boxes, IP′, UDP′ and GTP, represent layers that are used for tunnelling purposes only.

3.4. ns-3-based simulation framework

In order to explain how this architecture was simulated in ns-3, we refer to Figure 1, which shows the IPv4 addresses and network devices used in each type of node. It is out of scope of this paper to explain how the ns-3 simulator works, but one aspect in this scenario deserves further consideration. In ns-3, network nodes are represented by a *node* class, and each node contains a number of *NetDevice* objects. A NetDevice represents an L2 network interface. For instance, ns-3 contains a WifiNetDevice class for 802.11, CsmaNetDevice for 802.3 and PointToPointNetDevice for PPP links. We have developed a new kind of NetDevice (the *VirtualNetDevice*) that, instead of transmitting packets sent into it, forwards the packets to a user-defined callback for further processing. Moreover, the *VirtualNetDevice* allows user code to feed a packet into it, which is then treated by the *VirtualNetDevice* as if it had arrived from the network. This packet is typically forwarded up to the IPv4 stack and possibly delivered to an application. In our simulation scenario, we use *VirtualNetDevice* in two places, UE and HA, and assign 11.0.0.x/24 IPv4 addresses to these VNIs. These are conceptually home network addresses, in the Mobile IPv4 framework.

Figure 3 shows a block diagram of the simulation framework, and it may help in understanding how virtual interfaces are used and packet tunnels formed. Let us begin by analysing how packets travel from an application in the HA (or from an external network). After the packet is generated by the application, it is sent to a UDP or Transmission Control Protocol (TCP) socket, then it enters the IPv4 layer, and finally, the IPv4 layer consults the routing table. Because the applications are working with HoAs exclusively, IPv4 decides that, in order to reach a user UE with address 11.0.0.x, it should send the packet via the *VirtualNetDevice* (represented as VIF in the figure). This *VirtualNetDevice* is configured to send packets into a special module that we call Intelligent Interface Selection (IIS), which decides whether to send the packet via WLAN or UMTS access networks, and sends the packet via the appropriate tunnel. The decision is made by inspecting the TCP or UDP header of the packet and using the destination port. After a decision is made, IIS adds a GTP header, in accordance with 3GPP standards,

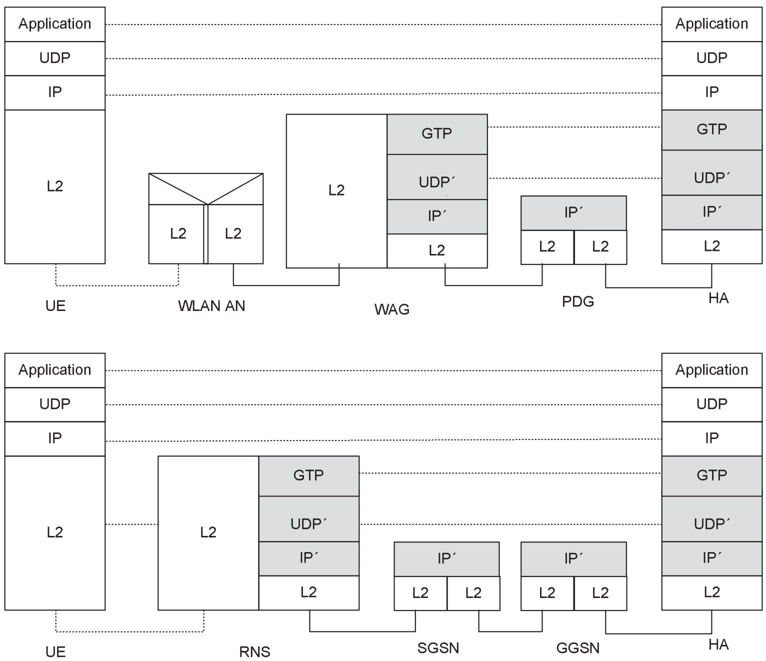

Figure 2. Modified protocols stack. UDP, User Datagram Protocol; IP, Internet Protocol; GTP, GPRS (General Packet Radio Service) Tunnelling Protocol; UE, user equipment; WLAN AN, WLAN Access Network; WAG, WLAN (wireless local area network) Access Gateway; PDG, Packet Data Gateway; HA, home agent; RNS, Radio Network Subsystem; SGSN, Serving GPRS Support Node; GGSN, Gateway GPRS Support Node.

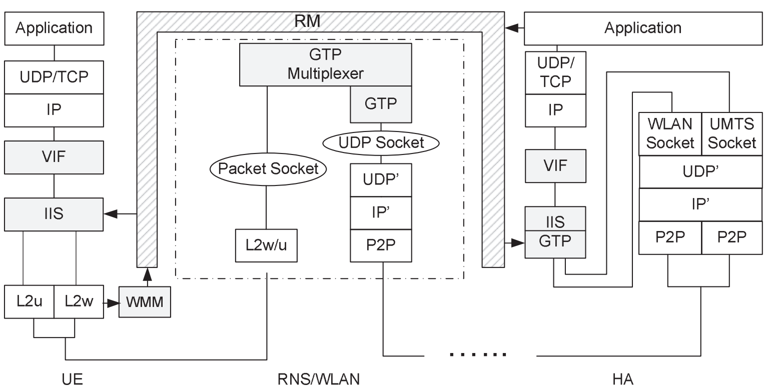

Figure 3. Block diagram of the ns-3 based simulation framework. UDP, User Datagram Protocol; TCP, Transmission Control Protocol; IP, Internet Protocol; VIF, VirtualNetDevice; IIS, Intelligent Interface Selection; WMM, wireless measurement module; UE, user equipment; RM, resource management; GTP, GPRS (General Packet Radio Service) Tunnelling Protocol; P2P, peer to peer; WLAN, wireless local area network; UMTS, Universal Mobile Telecommunication System.

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and then forwards the full packet, including IPv4 and UDP or TCP headers, into one of two UDP sockets: one is connected to the WAG and the other one to Radio Network Subsystem (RNS). As it enters this last UDP socket, the packet receives a new pair of headers, IP$'$ and UDP$'$, and is routed again by the IP layer. At the second time that the IP layer sees the packet, however, the destination address is $10.1.y.x$, and so, one of two real PPP interfaces is selected for transmission. The packet is transported by simple IP routers to either WAG or RNS, and it arrives at a UDP socket prepared to receive such packets. As the UDP socket delivers the packet to the *GTP Multiplexer* module, the outer headers, IP$'$ and UDP$'$ have already been removed. *GTP Multiplexer* removes the GTP header, and finally, it transmits the packet over a raw packet socket to the UE. In the UE, we have one WifiNetDevice (L2w in the figure) and at least one PointToPointNetDevice (L2u in the figure). These netdevices are configured to forward packets, not to the IP stack directly, but to a variant of IIS. In this case, IIS simply forwards the packet to a VirtualNetDevice (VIF), which in turn delivers the packet to the TCP/IP stack of the UE. Part of this process is illustrated by sequence diagrams; Figure 4 shows how a packet is transmitted by the HA, whereas Figure 5 shows how the same packet is received by the UE.

For the uplink case, a similar path is taken by packets. The application in UE sends a packet down the stack, with destination 11.0.0.x, and the packet is routed to the virtual interface, which delegates to the IIS the decision of what to do with it. IIS peeks into the TCP or UDP port, makes a decision on which access technology to use and transmits the packet through the chosen interface. The packet arrives at WAG or RNS, and is intercepted by the GTP Multiplexer module, which adds a GTP header and sends the entire packet with IP/UDP/GTP headers through the tunnelling UDP socket towards the HA. At the HA, the packet arrives at a real peer-to-peer interface, is processed by IP$'$ and UDP$'$ layers and is delivered at the UDP socket receiving module, the IIS. Finally, the IIS module removes the GTP header and injects the original packet (with 11.0.0.x addresses) back into the TCP/IP stack, thanks the to the virtual interface. The packet thus arrives at the server application or is routed to an external server node. The IIS module in the HA (IIS@HA) needs to know where to send each outgoing packet, via either the UMTS tunnel or the WLAN tunnel. The information that the IIS@HA receives takes the form of a list of $(TerminalIPv4, DestinationPort) \rightarrow TunnelSocket$ mappings. Thus, for each outgoing packet, the IIS module inspects the IPv4 header, and then

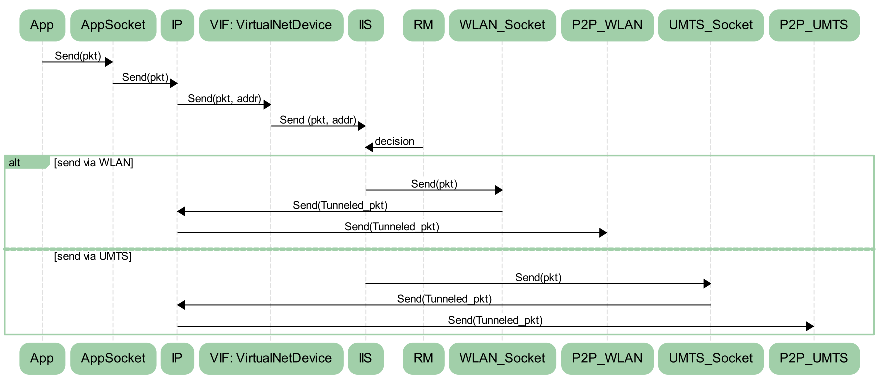

Figure 4. Sequence diagram of the home agent transmitting a packet. IP, Internet Protocol; IIS, Intelligent Interface Selection; RM, resource management; P2P, peer to peer; WLAN, wireless local area network; UMTS, Universal Mobile Telecommunication System.

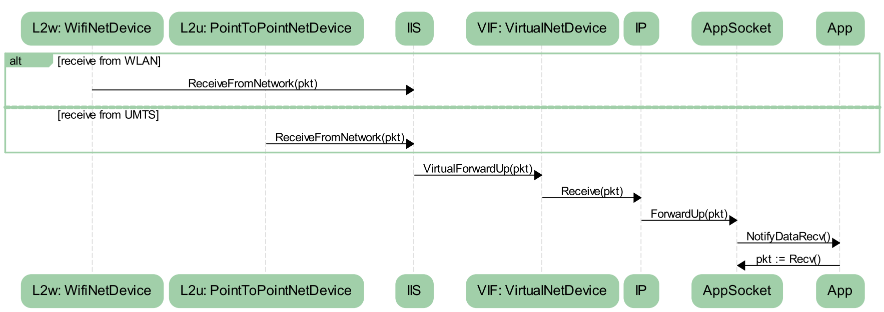

Figure 5. Sequence diagram of the UE receiving a packet. IP, Internet Protocol; IIS, Intelligent Interface Selection; RM, resource management; WLAN, wireless local area network; UMTS, Universal Mobile Telecommunication System.

TCP or UDP header; obtains the IPv4/Port pair; and also obtains the correct socket that will be used to send the flow toward the UMTS or WLAN network branches. The resource management (RM) module, not represented in Figure 3, is responsible for supplying this information as it is the module responsible for running the Call Admission and Call Reallocation integrated algorithm, and is aware of all existing flows (applications). The same RM module configures the similar IIS module running on each remote terminal, this way giving the terminal IIS the information needed to filter uplink traffic. In the terminal side, however, the mapping takes the form $SourcePort \rightarrow realNetdevice$ because the IPv4 address is already known. Although it is true that, in a real network, this kind of cross-node direct manipulation would be impossible and could be considered 'cheating', it is also clear that, by means of a dedicated control plane protocol, the same control could be implemented. However, accurately simulating such protocol was not perceived as meaningful for the type of results that we were trying to achieve, and a direct control is used in our simulation framework. To illustrate selected parts of this process, Figure 6 exemplifies a packet being transmitted by the UE, whereas Figure 7 shows how the same packet is received by the HA.

The WMM block in Figure 3 represents the wireless measurement module. It is responsible for measuring the Wi-Fi medium occupancy, estimating the available bandwidth, and reporting it back to the RM.

4. SIMULATION SCENARIO

In order to demonstrate and evaluate the interconnection simulation architecture proposed in this paper, we considered a simulation scenario corresponding to a hotspot located in a shopping centre. We adopted simulation scenarios where the number of users varies from 1 to 1000, and in the busy hour, each user is involved in average in six calls, each with an average duration of 120 s. The incoming calls follow a Poisson process with mean inter-arrival interval given by Equation (1), where U_q is the average number of users and U_c is the average number of calls made by a user in the busy hour.

$$1/\lambda = \frac{3600}{U_q \times U_c} \tag{1}$$

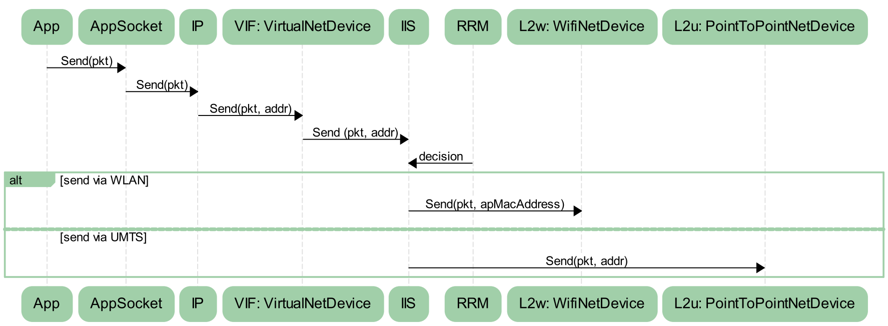

Figure 6. Sequence diagram of the user equipment transmitting a packet. IP, Internet Protocol; IIS, Intelligent Interface Selection; RRM, radio resource management; WLAN, wireless local area network; UMTS, Universal Mobile Telecommunication System.

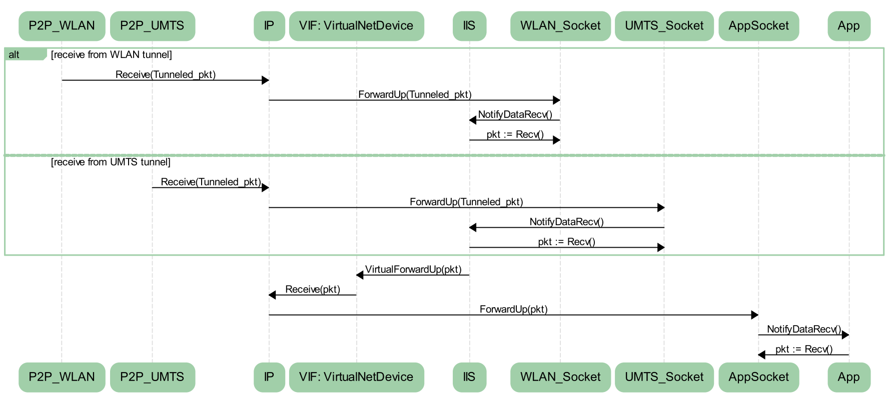

Figure 7. Sequence diagram of the home agent receiving a packet. P2P, peer to peer; WLAN, wireless local area network; UMTS, Universal Mobile Telecommunication System; IP, Internet Protocol; IIS, Intelligent Interface Selection.

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Table I. Calls per user per hour used in the simulations.

Application	Average call/user/hour
Voice	2
Video streaming	2
www	1
File Transmission Protocol	1

The simulations considered the four applications presented in the Table I, which also gives the average number of calls made by each user per hour.

We assume that the cellular devices have the capability of using both WLAN and UMTS networks. In UMTS, the load factor estimates the amount of supported traffic per base station site and is represented by η_{UL}, for the uplink direction, and by η_{DL}, for the downlink direction. The load factor is controlled to be always below a limit represented by η_{max} ($\eta_{max} < 1$). In most of the UMTS systems, the η_{max} value is not higher than 0.75, for both directions, the uplink and the downlink [14, 15]. In our work, we assumed that the uplink and the downlink are symmetric, having the same value for η_{max}. We also assumed that the user density inside the hotspot is, in average, twice the density in the remaining of the UMTS cell [16]. In this case, the load factor inside the intersection area of both technologies was considered 0.50, the remaining 0.25 being applied to the outside of the intersection area.

In the UMTS interface, a new call specifies the minimum QoS requirements that should be satisfied by the network. This request includes values for different QoS parameters, such as bit rate, delay and jitter. A new call is accepted by the call admission control mechanism, either in the uplink or in the downlink, when the load factor is below η_{max} after integrating the new call.

Comparing with UMTS, the WLAN interface usually offers a higher bandwidth and a smaller cell coverage area. On the other hand, the radio access in WLAN is most of the time uncertain, being based on the transmission silence time [17].

The strategy used for obtaining the available bandwidth in the WLAN interface (Bw_{WLAN}) consists on monitoring the channel occupation ratio, which determines the channel capacity for transmission [18]. New calls are only admitted in WLAN when the demanded bandwidth is below the available bandwidth; that is, the R_o occupation factor is below the R_{th} network occupation threshold, which can be controlled by the operator. Occupation factors R_o and R_{th} have values between 0 and 1.

We test the proposed interconnection architecture using three JRRM strategies for managing the arriving calls. The main characteristics and operations of these JRRM strategies are briefly described in the following three subsections.

4.1. Strategy based on covered area

Figure 8 illustrates how a covered area (CovAr) strategy works. The CovAr strategy directs calls preferentially to the interface associated to smaller area cell. For example, in hotspots, the calls are directed firstly to the WLAN network until it saturates, and then to the UMTS network. This strategy was presented in [19], where the authors implemented a CovAr strategy involving three access technologies: GERAN, UTRAN and WLAN.

4.2. Strategy based on load balancing

The load balancing (LBal) strategy is characterised by directing calls to the interface with the lowest load, maintaining the interfaces balanced [19–21]. Figure 9 shows

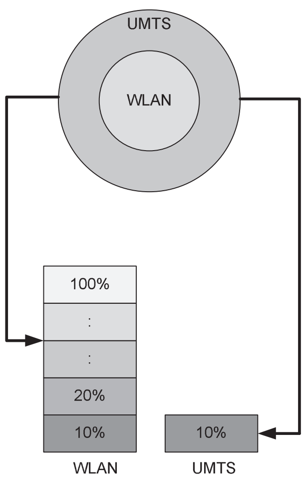

Figure 8. Covered area strategy. WLAN, wireless local area network; UMTS, Universal Mobile Telecommunication System.

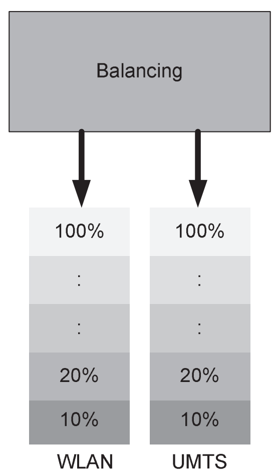

Figure 9. Load balancing strategy. WLAN, wireless local area network; UMTS, Universal Mobile Telecommunication System.

the simple case of the LBal strategy, applied to a scenario with two access network technologies. The network operators can set the algorithm according to their network conditions. Besides that, the LBal strategy can be applied through the service class, where the load is balanced according to a given class. Another possibility is to balance the load according to a predefined level. In this case, a given percentage of load is established for each interface, for example, 50% for each one. In [22], a dynamic LBal based on the service class is presented. When both systems (WLAN and UMTS) have available resources, the conversational or streaming class are preferentially directed to the WLAN interface. After that, the interactive class is balanced between UMTS and WLAN according their available bandwidth [20, 21, 23].

4.3. Strategy based on mobility tendency

The multi-radio resource management strategy called MTend aims to maximise the use of the radio resources, while satisfying the QoS requirements posed by the applications [24]. Figure 10 represents the structure of the decision algorithm used for the joint management of interconnected UMTS and WLAN radio resources under the control of the same operator. When a new call request arrives, the algorithm decides to which interface the call should be directed, based on the call characteristics and resources available. In a scenario where both networks have resources available, the strategy is based on the mobility tendency of the users, differentiating applications according to their tendency for mobility. For example, voice calls are inherently mobile because the probability of a user receiving or starting a call in movement is relatively high. Thus, this strategy gives priority to mobile applications in the UMTS network, in order to avoid vertical handovers between different network technologies. Applications usually used in static contexts (e.g. web browsing and video streaming) are accepted preferentially in the WLAN network.

For scenarios of insufficient resources, our strategy proposes two complementary mechanisms. The first mechanism consists of renegotiating the resources requested by the new call; the second mechanism considers the possibility of reallocating an accepted call from one network to the other, enabling resources to be freed in the congested network. The renegotiation and reallocation mechanisms require the monitoring of each access network so that their level of congestion can be evaluated.

The renegotiation mechanism consists of two renegotiation tries. In a case where the first try does not succeed, the system enables the application to reduce again the resources requested. Table II contains the renegotiation parameters for the applications used in our study.

The MTend strategy decision algorithm can be specified using the following formalism. The network interface selected to serve the new call is chosen according to Equation (2), where *tend* represents the decision tendency. The indicator function 1_y is 1 if the event y is true, else it is zero. P_{UMTS} and P_{WLAN} are the eligibility degrees given

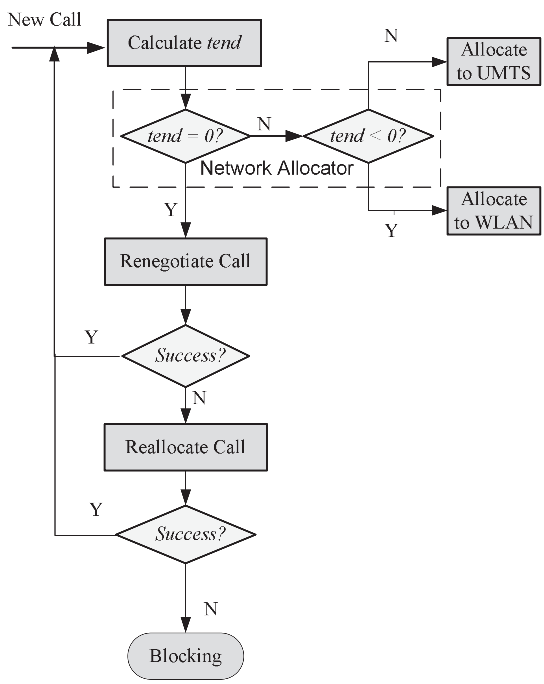

Figure 10. Joint multi-radio resource management algorithm. WLAN, wireless local area network; UMTS, Universal Mobile Telecommunication System.

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Table II. Applications bit rates and their renegotiation alternatives.

Application	Mean bit rate (kbit/s)		
	1st request	1st renegotiation	2nd renegotiation
Voice	24	12	8
Video streaming	128	64	32
www	128	64	32
File Transmission Protocol	128	64	32

Table III. Universal Mobile Telecommunication System (UMTS) and wireless local area network (WLAN) eligibility degrees according to the user mobility criterion.

Application	Eligibility degree	
	P_{UMTS}	P_{WLAN}
Voice	2	1
Video streaming	1	2
www	1	2
FTP	1	2

FTP, File Transmission Protocol.

to an arriving session, respectively, to be transported over the UMTS and WLAN interfaces, as show in Table III.

$$tend = P_{\text{UMTS}} * \mathbf{1}_{\eta a_{\text{UMTS}} \geqslant \Delta_{\eta r}} - P_{\text{WLAN}} * \mathbf{1}_{Bw_{\text{WLAN}} \geqslant r} \tag{2}$$

The ηa_{UMTS} and Bw_{WLAN} variables are, respectively, the available UMTS load factor and the available bandwidth in the WLAN interface, whereas $\Delta_{\eta r}$ is the UMTS load factor and r is the WLAN mean bit rate requested by the new call [14]. The network selected for an arriving call is given by Equation (3).

$$NetworkAllocator = \begin{cases} \text{WLAN}, & \text{if } tend < 0 \\ \text{Reneg/Realloc}, & \text{if } tend = 0 \\ \text{UMTS}, & \text{if } tend > 0 \end{cases} \tag{3}$$

5. SIMULATION FRAMEWORK EVALUATION

The simulation framework described in Section 3 enables the study of a class of problems addressing the performance of LBal algorithms and JRRM in a heterogeneous network environment. In this section, we provide the results of an experiment where we used the simulation framework proposed in this paper to compare the behaviour of the three JRRM strategies presented in the previous section. This comparison was done by analysing three commonly used parameters, namely the call distribution, the call blocking probability (CBP) and the call handover ratio. The following three subsections present the obtained results and stress how they put in evidence the suitability of the simulation framework to analyse the performance of JRRM strategies.

5.1. Call distribution

Figure 11 shows the distribution of admitted calls between the UMTS and WLAN networks made by the three strategies. The call admission ratio of each service in a given access network is defined as the ratio between the number of accepted calls of that service in that network and the total number of calls offered to the system. As it is expected, the call admission ratio of all services in both networks decreases when the number of users increases because the offered traffic increases linearly with the number of users, whereas the radio resources are kept constant. It is also clear from Figure 11 that the MTend strategy differentiates the voice calls from the other services, giving them higher priority of being accepted in the UMTS interface, which leads to a voice call admission ratio in UMTS significantly higher than the equivalent ratio for the other services. These results prove that the virtual interface mechanism can provide two different network interfaces to the JRRM strategy, enabling it to decide which interface to use when a new call arrives.

5.2. Call blocking probability

A parameter usually used to compare different JRRM strategies is the CBP. This probability is given by

$$CBP(\%) = \left[1 - \frac{C_{\text{acpt}}}{C_{\text{acpt}}}\right] \times 100 \tag{4}$$

where C_{acpt} is the number of application calls accepted and C_{acpt} is the total number of calls offered to the system.

Figure 12(a) shows the average values and the 95% confidence intervals of the CBP for the three strategies obtained in the face of calls belonging to the four applications described in Table I. These strategies present increasing probabilities with an increase of the number of users, reaching a CBP of almost 80% between 900 and 1000 users. The MTend strategy presents a performance better than the other two, having a CBP always below the other two strategies.

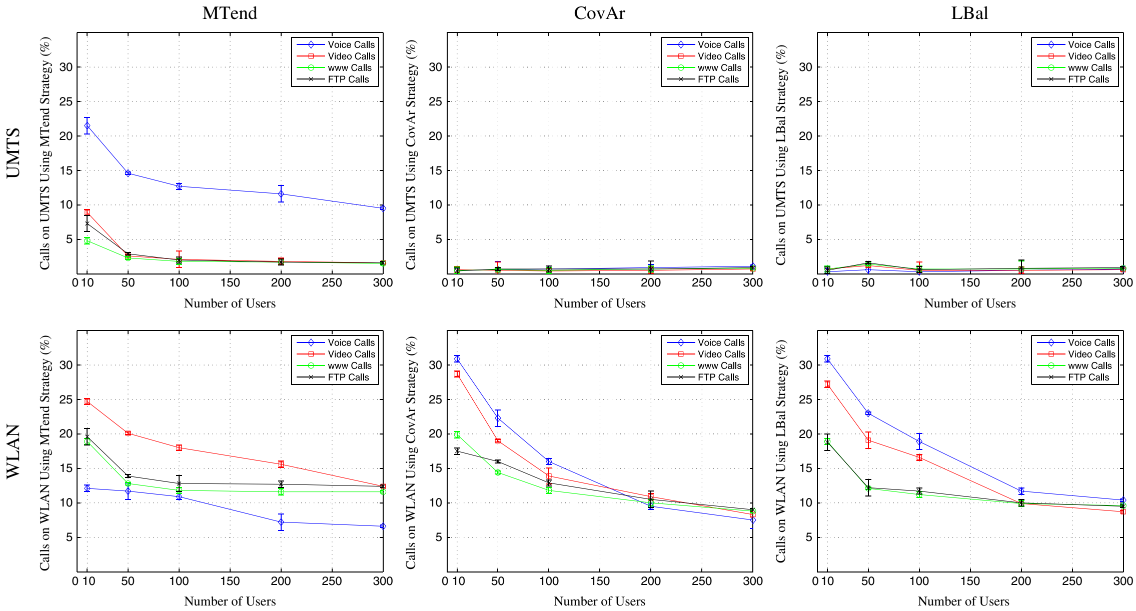

Figure 11. Joint radio resource management strategies call admission distribution on Universal Mobile Telecommunication System (UMTS) and on wireless local area network (WLAN). CovAr, coverage area strategy; LBal, load balancing strategy; MTend, mobility tendency strategy; FTP, File Transmission Protocol.

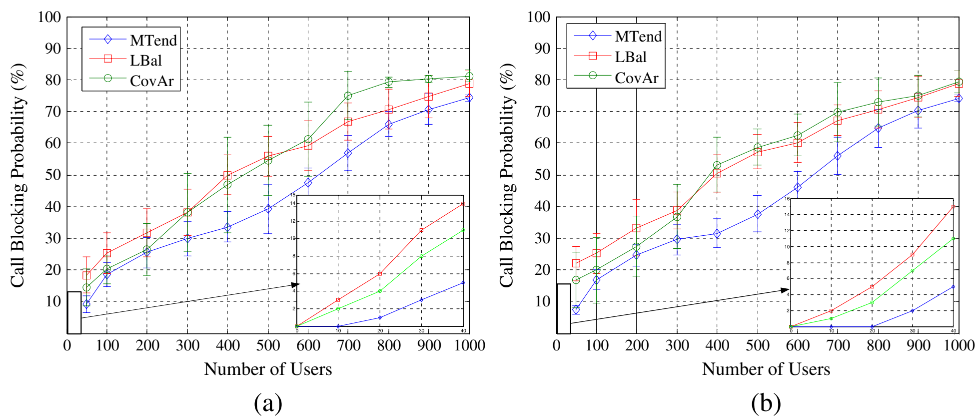

Figure 12. Call blocking probability (a) without call renegotiation and (b) with call renegotiation. CovAr, coverage area strategy; LBal, load balancing strategy; MTend, mobility tendency strategy.

The box inside Figure 12(a) shows the performance of the resource management strategies for scenarios with a reduced number of users, from 1 to 40. The MTend strategy still has a better performance than the other two strategies in those scenarios, obtaining CBPs under 2% for a number of users less than 20.

Figure 12(b) shows the average values and the same confidence intervals for CBP, now assuming that the three strategies integrate the renegotiation mechanism described in Section 4.3.

The most interesting analysis should be done for low CBPs, under 20%, which are the values considered by an operator for a real service provisioning scenario. Fixing a CBP, the gain obtained with the MTend strategy comparing with the concurrent strategy S is given by Equation (5), where $Users_S$ represents the number of users using the operator's networks with the strategy S.

$$G^{\mathrm{CBP}}_{\mathrm{MTend}\_S} = \frac{Users_{\mathrm{MTend}} - Users_S}{Users_{\mathrm{MTend}}} \tag{5}$$

Considering that the call renegotiation mechanism is active, for example, for a CBP of 2%, the gain of $G^{2\%}_{\mathrm{MTend\_LBal}} = 67\%$,, whereas for the CovAr strategy, the gain is $G^{2\%}_{\mathrm{MTend\_CovAr}} = 50\%$. It means that the operator supports 67% to 50% more users with the MTend strategy

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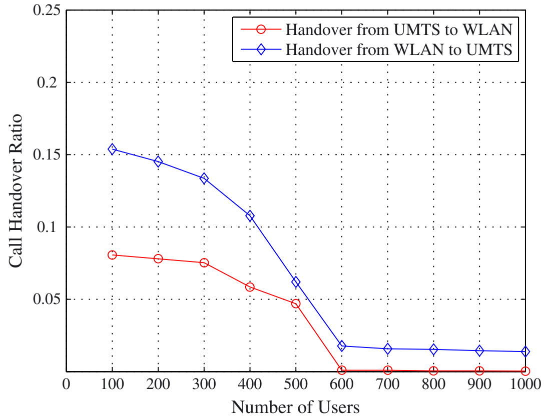

Figure 13. Call handover distribution. WLAN, wireless local area network; UMTS, Universal Mobile Telecommunication System.

than with the other two resource management strategies, for the given CBP.

It is clear from Figure 12 that the simulation framework proposed in this paper effectively enables the analysis of the CBP of JRRM strategies defined over interconnected heterogeneous networks.

5.3. Call handover ratio

The MTend strategy defines the possibility to reallocate calls from one interface to another. When an access network is saturated or causing high delays, the HA tries to reallocate a flow to another interface. This behaviour is demonstrated by Figure 13, where the fraction of calls reallocated by the MTend strategy to a different access link (i.e. flow handover) is plotted against the offered traffic, defined here as call handover ratio. The call handover ratio in both directions (i.e. from UMTS to WLAN and from WLAN to UMTS) decreases when the number of users increases, stabilising in very low values for a number of users higher than 600, which indicates that both networks reach a very congested level for those numbers of users. However, the call handover ratio from the WLAN to the UMTS is always higher than that for the opposite direction, which means that the MTend strategy maintains the WLAN interface more loaded than the UMTS interface. Because both access links share the same IP address, this reallocation mechanism is transparent for the applications.

This analysis proves that the simulation framework proposed in this paper allows not only the simulation of new arriving calls admission but also the simulation of reallocation calls from one interface to the other.

6. CONCLUSIONS

In this paper, we explore future mobile network architectures that allow the integration of heterogeneous access networks. We focus particularly on the integration of UMTS and WLAN, and on its simulation in ns-3. The proposed network architecture is based on the 3GPP WLAN/UMTS integration architecture, with minor simplifications. Thanks to the flexibility of ns-3, simulating the needed IP-in-IP tunnels was straightforward. Moreover, the 'virtual interface' module allows the terminal to use a single IP address for two different access interfaces, without requiring modifications to the standard ns-3 IPv4 stack.

We used the proposed simulation framework to compare three JRRM strategies, analysing commonly used parameters, such as the call distribution, the CBP and the call handover ratio. The results obtained during this comparison clearly demonstrate the usefulness and the value of the proposed simulation framework. We believe that, with little additional effort and maintaining the same building blocks, more access network types and call admission/reallocation algorithms can be incorporated and simulated.

APPENDIX A

An overview of abbreviations, variables and constants used in this paper is given in Tables A.I, A.II and A.III for improving the paper readability.

Table A.I. Single interface call admission control constants and variables.

UMTS call admission control	
η_{UL}	Load factor (uplink)
η_{DL}	Load factor (downlink)
η_{max}	Maximum load factor
WLAN call admission control	
R_o	Network occupation factor
R_{th}	Network occupation threshold

UMTS, Universal Mobile Telecommunication System; WLAN, wireless local area network.

Table A.II. Simulation framework abbreviations.

DSMIPv6	Dual Stack Mobile IPv6
HA	Home agent
HoA	Home address
IIS	Intelligent Interface Selection
IP	Internet Protocol
L2	Layer 2
L2u	PointToPointNetDevice (UMTS)
L2w	WiFiNetDevice (WLAN)
MIPv4	Mobile IPv4
PDG	Packet Data Gateway
RM	Resource Management
VIF	VirtualNetDevice
VNI	Virtual network interface
WAG	WLAN Access Gateway
WMM	wireless measurement module

Table A.III. Joint radio resource management abbreviations, constants and variables.

CovAr	Coverage area strategy
C_{acpt}	No. of application calls accepted
C_{acpt}	Total no. of calls offered to the system
CBP	Call blocking probability
LBal	Load balancing strategy
MTend	Mobility tendency strategy
P_{UMTS}	Eligibility degree for UMTS
P_{WLAN}	Eligibility degree for WLAN
ηa_{UMTS}	Available UMTS load factor (downlink)
Bw_{WLAN}	Available bandwidth in WLAN
$\Delta_{\eta r}$	UMTS load factor associated to a new call
r	WLAN mean bit rate requested by a new call
U_q	Average no. of users in the busy hour
U_c	Average no. of calls per user in the busy hour

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