Open-Source Experimental B3G Networks Based on Software-Radio Technology*

Christian Bonnet, Hervé Callewaert, Lionel Gauthier, Raymond Knopp, Aawatif Menouni,
Yan Moret, Dominique Nussbaum, Illia Racunica, Michelle Wetterwald
Institut Eurécom, B.P. 193
06904 Sophia Antipolis, France
firstname.lastname@eurecom.fr

ABSTRACT

We describe the overall architecture of an experimental software radio system providing direct interconnection with an IPv6 backbone network developped in the context of several publicly-funded research projects. RF and acquisition equipment ranges from high and low-power basestations (Radio Gateways) to reconfigurable terminals and can be made available to the research community for experimentation with real-time radio resources. Software can be configured for both real time deployment scenarios and radio network simulation on networked PCs. We describe issues related to interconnecting a third-generation cellular radio air-interface with an IPv6 backbone and its consequences on wireless networking architecture.

1.INTRODUCTION

A primary research activity of the mobile communications department of Institut Eurécom is the development of real-time reconfigurable radio platforms. Our platforms are designed using open-architectures at both the hardware and software levels and are primarily PC-based. Similar PC-based software-radio approaches are considered in [1,2]. The use of software-radio technology allows for reasonably low equipment costs and provides an ideal way to experiment with real-time radio resources. The hardware and software solutions solutions are made available to the research community by http://www.wireless3G4Free.com.

This equipment is used to innovate and experiment in areas related to Beyond-3G (B3G) wireless networks such as

- IPv6-based radio resource management for heterogeneous multiple radio-access technology wireless networks
- smart-antenna technology
- resource allocation and scheduling
- Quality of Service management

Our developments are based on the convergence of three technological trends

1. Collaborative radio standards 3GPP [3], IEEE802.xx [4]
2. Next generation mobile internet technology - IPv6 [5], Mobile IP [6],SIP [7]
3. Open-source software and operating systems - Linux [8], RTLinux [9], RTAI [10]

Software compatible with 3GPP Release 4 (Access Stratum) for UMTS/TDD radio systems is now freely available on http://www.wireles3G4Free.com under a GNU general public license (GPL) to promote academic collaboration in the area of open-3G systems. This software can be used standalone (non real-time) or with supporting RF equipment (real-time) available from www.wireless3G4Free.com. It is hoped that our openness policy will lead to further collaborative open-architecture projects based on our current and future platforms.

At present, our platforms are used by several open-projects funded by the French Ministry of Finance under the label of the RNRT (http://www.telecom.gouv.fr/rnrt, in French), namely PLATON, ERMITAGES, @IRS++, RHODOS, LAO-TSE. At the European level our UMTS/IPv6 platform is an integral part of the MobyDick IST project (http://www-int.berkom.de/mobydick,http://www.cordis.lu/ist/), where methods for the direct interconnection of a 3GPP access-stratum to an IPv6 core network are proposed.

The end result of these collaborative projects is that several experimental reconfigurable B3G radio networks are being deployed in European countries, at the very least France and Germany, where unpaired 3G spectrum is available for research purposes. The wireless3G4Free.com group has been

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*Eurecom's research is partially supported by its industrial partners: Hasler Stiftung, Swisscom, France Telecom, La Fondation Cegetel, Bouygues Telecom, Thales, ST Microelectronics, Hitachi Europe and Texas Instruments.

granted one 5 MHz channel (1900-1905 MHz) for use in Sophia Antipolis, France. An experimental IPv6 network consisting of both UMTS/TDD and 802.11 components is currently being deployed in Sophia Antipolis in order to experiment with techniques for managing radio resources in a multi air-interface heterogeneous network. A smaller-scale network will be deployed on the University of Stuttgart campus in the context of MobyDick.

This paper describes the different platform components and their functionalities. Section 1 deals with the different hardware components (RF and acquisition) for Radio Gateways (basestations) and reconfigurable terminals. In section 2 we describe the software technologies for the different testbeds (real-time operating systems, coding of signal processing, simulation environments and open-source radio protocol implementations). Finally, in section 3 we describe innovations in wireless networking protocols leading to all-IPv6 wireless infrastructures. We present some conclusions in section 4.

2.HARDWARE ARCHITECTURES

Our current radio equipment is designed for unpaired spectrum using Time Division Duplex (TDD) multiplexing with a 5 MHz channel bandwidth. The RF equipment operates in any of the 1900-1920 MHz IMT-2000 TDD bands but different frequency bands can potentially be supported if required. Components have been developped for both low and high-power multi-antenna basestations, dubbed *Radio Gateways (RG)*. This equipment can also be reused for test terminals with a simple software modification. Smaller form-factor test terminals (PCMCIA/CardBus) are currently being prototyped and include a wideband (tunable in 3-6 GHz) RF front-end and dual-antenna operation.

2.1 Radio-Gateways

Eurecom's RGs can be configured with two different power classes, namely :

- low-power (25 dBm/antenna element, -40 dBc ACLR. 7 dB noise figure) pico-BTS, multiple antennas.
- high-power (34 dBm/antenna element, -45 dBc ACLR, 5 dB noise figure) micro-BTS, multiple antennas.

Both configurations are composed of an RF module and PCI acquisition card per antenna element. The high-power configuration requires an additional front-end power amplifier and low-noise amplifier.

The basic RF module for RGs was co-designed with Philips Semiconductors (Sophia Antipolis) and is in the form of a 19-inch rack (similar to an Ethernet switch). Its transmit functions are comparable to those of a high-end digital signal generation testbench (14-bit sampling) with the added capability of real-time operation when controlled by a RTLinux-based PC. Direct upconversion to 1.9 GHz is performed using a digitally tunable local oscillator and several stages of digitally controlled gain are provided. Its receive capabilities are similarly comparable to those of a high-end signal analyzer (14-bit sampling), again with the added capability real-time operation. Sampling clocks can be synthesized onboard or provided externally. The module can be seen along with its input/output functions in Figure 1.

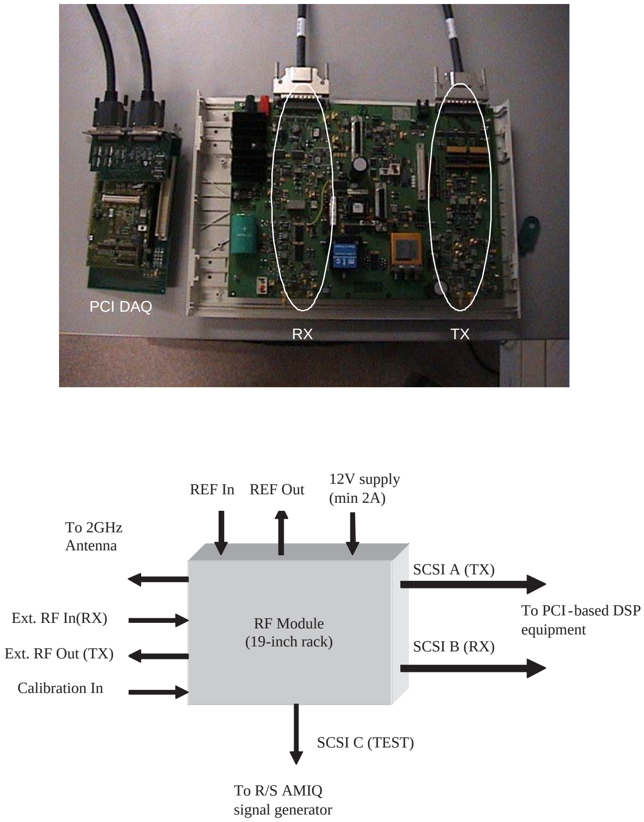
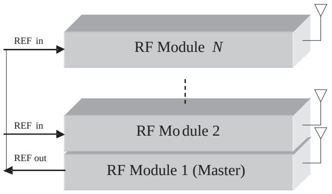
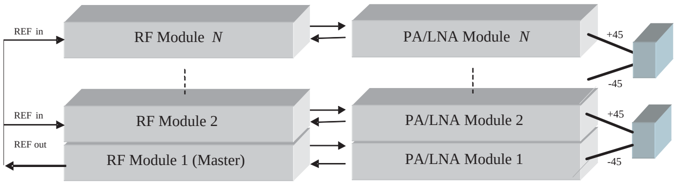


Figure 1: Basic RF Module

The module has been designed with maximum flexibility and reconfigurability in mind. It provides for standalone operation with a 2GHz antenna, or with an external high-power/low-noise module connected via low-loss cables to the external RF I/O ports. These scenarios are shown in Figures 2 and 3. It also allows for multiple-antenna operation with synchronized clocks, using the external REF I/O ports. One RF module is configured as the master and provides a stable reference frequency for up to 11 slaves. Alternately, a common ultra-stable external reference (e.g. OCXO) can be used for all RF modules. All modules can thus be synchronized with respect to their local-oscillator frequencies and sampling clocks. Calibration ports are provided for use with external test equipment (e.g. Rohde&Schwarz AMIQ/SMIQ). One port (SCSI C) can be used to calibrate the transmit chain offline using a Rohde&Schwarz AMIQ signal generator with the digital I/O option. The external calibration port (Calibration In) can be used to calibrate the receive chain using an AMIQ/SMIQ signal generator. The transmit chain can be calibrated online by feeding the transmitter output to the receiver via an on-board switching network. Power is supplied by a standard 12V power supply (2A minimum) and thus the module can be connected to a car battery for testing in a high-mobility environment if used as terminal equipment.

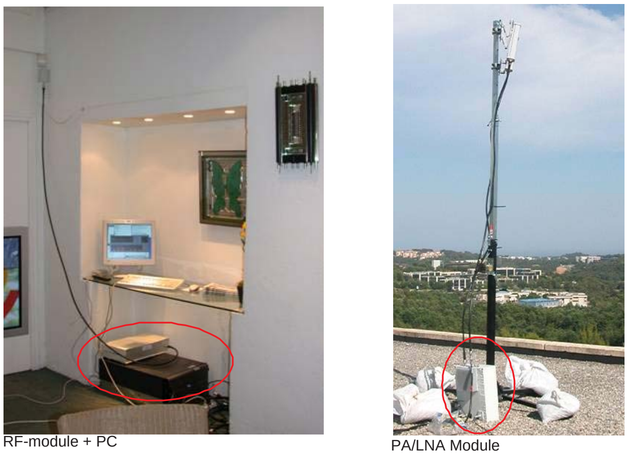


Low-power scenario (a)



High-power scenario (b)

Figure 2: Low (a) and high-power (b) multi-antenna scenarios



RF-module + PC

PA/LNA Module
(rooftop installation)

Figure 3: RG deployment scenarios

Digital signal acquisition/generation is provided via a home-made PCI-based acquisition card. It consists of a Xilinx XCV300 (Virtex) FPGA along with a standard bus-mastering PCI controller. Standard ultra-SCSI cables provide a connection with the RF module. The FPGA is used solely for signal acquisition at the present time since all signal processing is performed in software on the host PC.

2.2 Terminal Equipment

The RG RF module can be used as terminal equipment as described in the previous section. In addition, a low-cost reconfigurable terminal is currently under development. It consists of a state-of-the-art FPGA (Xilinx Virtex 2) which performs both signal acquisition/generation and front-end signal processing (filtering, DFT, resampling). It furthermore provides a CardBus interface for Laptops, Panel-PCs or embedded PCs. The RF portion consists of both a 1.9 GHz transceiver as well as a wideband tunable front-end (3-6 GHz). The latter will be used for research in adhoc networking targeted at public-safety communications and provides both spectral agility and reconfigurability in a small form-factor. The current prototype is shown in Figure 4.

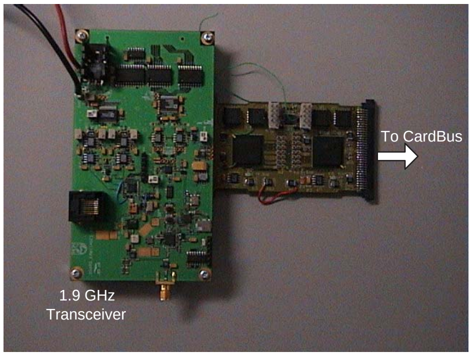


Figure 4: Reconfigurable Terminal Prototype

2.3 RF Emulators

For the purpose of protocol development and testing of real-time applications, a cabled RF emulation environment running at an intermediate frequency (70 MHz) can be provided. These platforms retain all the real-time functionality without needing to deploy a live network and to worry about issues related to the RF sub-system. Several configurations can be accomodated (e.g. 2 RGs and 2 terminals, 1 RG and 3 terminals, etc.)

3.SOFTWARE ARCHITECTURES

Real-time software runs on the RTLinux/GPL operating system maintained by FSMLabs which allows for hard real-time operation in the open-source Linux environment. Since

Linux is rich in innovative networking functionality, it provides an ideal platform for developing experimental B3G networking equipment. Our target architectures are assumed to be PC-based (laptops, desktops, high-end servers, embedded PC) and specialized device drivers for our RF equipment and real-time radio protocol software have been developped for this environment. In addition to the real-time code a simulation environment compiled using the same source code can be used to develop new PHY/MAC algorithms using a discrete-time RF simulator. We describe in more detail below the software components of our systems. All software components, in the form of a CVS-tree, are freely-available under a GNU GPL from http://www.wireless3G4Free.com.

3.1 RTLinux

RTLinux [9] is an extension to the Linux Operating System which supports real-time interrupt handlers and real-time periodic tasks with interrupt latencies and scheduling jitter close to hardware limits. Worst case interrupt latency on a modest PC is under 15 microseconds from the moment the hardware interrupt is asserted.

The basic idea behind RTLinux is that Linux code that enables/disables interrupts is replaced with code which enables/disables soft interrupts. Hard interrupts are now handled by the real-time micro-kernel. If Linux is supposed to handle the interrupt it is passed on to the Linux kernel which services it as a soft interrupt. Due to this separation, the Linux kernel cannot disable interrupts to real-time threads. The result is that Linux drivers work as normal (provided they were written properly) and do not influence real-time threads. This allows for special real-time tasks to be added to the operating system with guaranteed performance without affecting (except for execution speed) normal Linux tasks.

Although not strictly POSIX compliant, RTLinux strives at providing a POSIX-like interface, namely:

- a real-time thread library (pthreads)
- real-time schedulers
- real-time external interrupt handling
- SMP (symmetric multi-processing) functions

3.2 Intel SIMD Programming

Our signal processing algorithms make use of the native Intel SIMD fixed-point and floating-point instructions (MMX,SSE,SSE2) for obtaining maximum processor efficiency on Pentium processors. Our code is written primarily for the GNU gcc C compiler, with assembly intrinsics for MMX/SSE instructions. Some special routines have been written using the freely-available Intel C compiler for the Pentium 4 (http://www.intel.com). Routines typically make use of packed 16-bit arithmetic (multiply, add, multiply+add), loop unrolling and software pipelining. Optimized routines for 3GPP modems, such as matched filtering, pulse-shape filtering, FFT-based channel estimation, Viterbi and Turbo decoders are provided.

3.3 RF Simulation Software

The RF simulation mode is designed to operate on a network of PCs, although a single machine is the minimal configuration. The ideal running environment would be a Linux cluster. A simple compiler directive allows code to be compiled either for the simulation environment or real-time operation. In the simulator no hardware specific code is compiled and code executes in user-space rather than kernel space, while maintaining the same multi-threaded structure as the real-time code. Signals are exchanged between a set of RGs (potentially on different machines) and a set of terminals (also on different machines). The exchange is accomplished via a TCP/IP client/server socket interface and a third entity which controls the signal flow, which we call a *channel server*. This arrangement is shown in Figure 5. The channel server is a multi-threaded process, typically running on a powerful machine, which simulates the RF portion of the radio network and transfers digitized signals between entities in the radio network. The TCP/IP sockets are interfaced directly in the low-level routines of the radio protocol stack which interact with the hardware sub-system during real-time operation. Each channel server thread controls the signals emanating/arriving at an antenna in the network. Each node may comprise several antennas (indicated with multiple connections between nodes and the channel server in Figure 5), in order to simulate space-time processing functionality. The channel server requires configuration information regarding the locations of the network nodes, path-loss and fading model parameters as well as power levels.

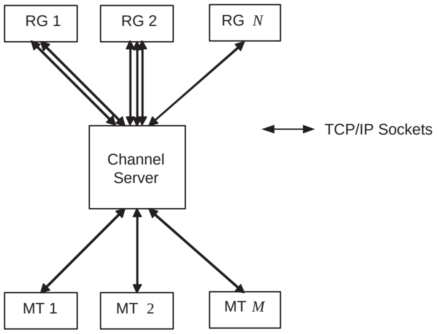


Figure 5: RF simulation environment

3.4 Radio Protocols

Implemented radio protocols (PHY/MAC/RLC) comply with the Release 4 Access Stratum specifications from the 3GPP (see http://www.3gpp.org). The generic protocol organization is shown in Figure 6. Layer 1L (PHY) interfaces directly with the acquisition hardware and performs basic signal processing (matched filtering, pulse-shape filtering, channel estimation, synchronization) and operates on a slot-by-slot basis (666 μs in the case of 3GPP modems). Layer 1H (PHY) performs channel coding/decoding and interleaving and operates on a frame-by-frame basis (10 ms in the case of 3GPP modems). Layer 2 is comprised of the MAC (Medium-Access) and RLC (Radio-Link) control layers, which are responsible for PDU scheduling on Transport Channels, packet segmentation and retransmission protocols. These also operate on a frame-by-frame basis The implementation of layers 1 and 2 comply with the 3GPP specifications to a large extent, aside from a few unsupported transport and physical channels. Layer 3 interfaces with the IPv6 protocol stack and is described in the next section.

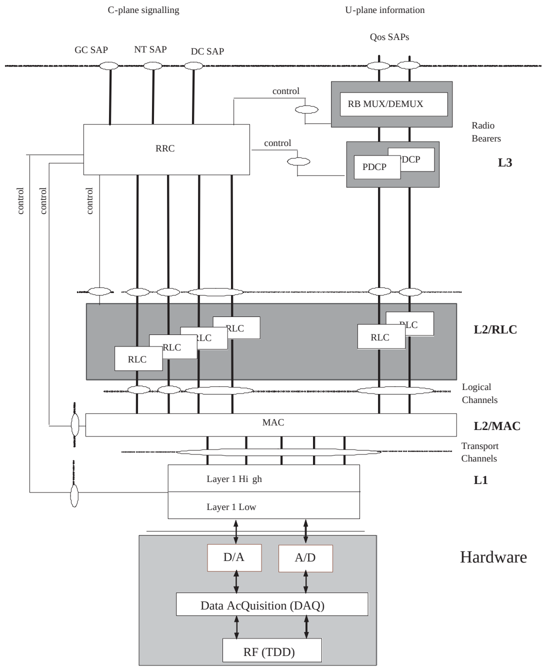


Figure 6: Access Stratum Architecture

We have presently implemented the 3.84 MChip/s mode of 3GPP/TDD operation; the release 5 HSPDA (high-speed packet access) and 1.28 MChip/s (TD-SCDMA) variants [11] are currently under development in the context of several publicly funded projects (RHODOS, LAO-TSE). Support for future radio protocols providing adhoc networking for broadband reconfigurable public-safety systems (e.g. systems in line with the MESA specifications, see http://www.projectmesa.org) are in the planning stage. Our radio equipment remains compatible with these extensions.

4. IPV6-BASED NETWORKING

Layer 3 networking deviates from 3GPP, in the sense that it provides a direct interconnection with an IPv4/IPv6-based network at the RG. This allows for experimentation of futuristic "all-IP" network infrastructures. Wireless3G4Free.com testbeds provide IPv6 networking solutions for experimental 3G/WLAN heterogeneous networks. Radio Resource Management (RRM - configuration, access-stratum QoS and mobility management) is implemented in an all-IP setting. This allows for seamless interconnection of different radio protocols running beaneath IP (e.g. WLAN and 3GPP).

Figure 7 shows the evolution of 3GPP networking entities towards the architecture considered here based on an IPv6 core network (CN). We can see from the figure that running IP to the RG has a strong impact on the overall network architecture of the system, since we short circuit some basic 3GPP networking entities (i.e. RNC/SGSN/GGSN) which results in a reduction of the number of *bearer services*. A bearer service enables the provision of a contracted Quality-of-Service (QoS) using the lower layer services. An interface that remains completely unmodified is the Radio Bearer Service which defines the access stratum configuration for the service. UMTS bearer service is also required *a priori*. The need for the Radio Access Bearer Service, however, is questionable. The CN Bearer Service as well as the Iu Bearer Service are definitively not present in the proposed all-IP architecture since the corresponding interfaces do not exist. This has an important impact on the various interface levels that the RG must offer.

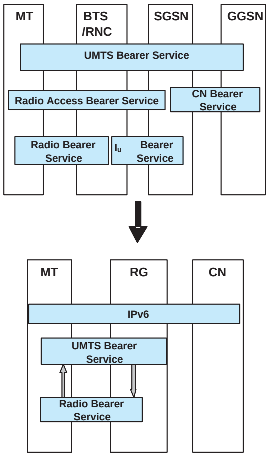


Figure 7: Evolution of 3GPP Networking towards all-IPv6

We show the modifications in the overall protocol stack in Figure 8.

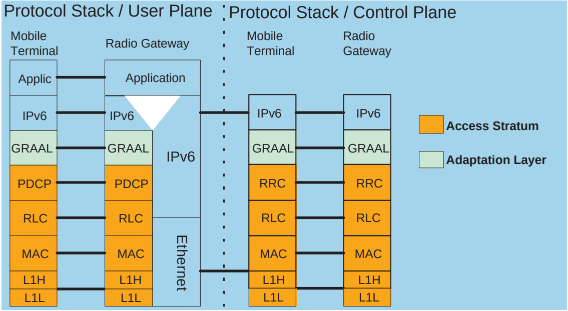


Figure 8: Overall Protocol Stack

4.1 Networking functions of the Radio Gateway

The RG is not only a Node-B or basestation since the 3GPP Node-B includes only the physical layer of the access-stratum without all protocol layers (i.e. MAC, RLC, PDCP, RRC). The RG is composed of

- The physical, MAC, RLC and PDCP layers
- access-points for data traffic via the RLC (and optional PDCP) layer which is responsible for conveying data over ”Radio access Bearers”
- A control function (*RRC - Radio Resource Control*) which provides an interface to setup and release radio bearers for signaling and data.
- an abstraction Layer (*GRAAL - Generic Radio Access Abstraction Layer*) which provides the middleware for interfacing IPv6-based mechanisms for signaling and user traffic with 3GPP-specific mechanisms for the access network (e.g. for mobility, call admission, etc.)

One can therefore view the RG as a Node-B and a subset of the RNC (Radio Network Controller). A function which is typically not contained in the RG (but present in the RNC) is RRM whose algorithms must jointly manage radio resources several adjacent cells.

The RRC provides the interfaces and signaling procedures between the low-layer access protocols (PHY/MAC/RLC) and the networking protocols (Broadcast, Paging, Connection management) and entities (e.g. RRM). Specifically it provides procedures for

- Connection Establishment/Release
- Radio Bearer Establishment/Release
- Broadcast and Paging mechanisms
- Measurement reporting (e.g. RF, traffic)

The RG uses IP-based QoS information to route packets on the appropriate radio bearers which is accomplished via the GRAAL. A 3GPP cell is further considered as an IPv6 subnet, and thus in this sense, the RG is a router for the users in the subnet/cell. The GRAAL performs the following functions:

- User plane
  - Classifier for Radio Bearer (and thus users as well)
- Control plane
  - Establishment/Release procedure of Mobile Station
  - Establishment/Release procedure of Radio Bearer
  - Mapping between UMTS and DiffServ QoS attributes
  - Broadcasting (in Radio Gateway) of
    - Neighbor Discovering messages (Router Advertisement, etc)
    - Neighboring cells list
    - Neighboring cells quality list (in Mobile Station for IPv6 HandOvers)
  - Computation of the IPv6 Link-local address

3GPP specifies that the mapping between application QoS attributes and the 3GPP bearer service attributes is an operator and/or implementation issue. Therefore, a mapping mechanism is required between the QoS parameters for IP-based applications and 3GPP QoS parameters. IP QoS work is being conducted within Internet Engineering Task Force (IETF). This work focuses on two main streams for QoS control, namely the Integrated Services (IntServ) [12] and Differentiated Services (DiffServ) [13] architectures. The IntServ architecture aims at providing the QoS in an end-to-end manner like ATM. It allows users to communicate their QoS requirements to routers on the data path by means of a signaling protocol. The DiffServ architecture specifies the IP header bit usage to differentiate between different QoS classes. The main objective of DiffServ is to specify a QoS mechanism based solely on the contents of the IP header fields rather than on an end-to-end signaling protocol. We assume that our applications use either IntServ or DiffServ in order to specify their requirements in terms of QoS.

As an example of QoS classification performed by the GRAAL, suppose that a mechanism such as DiffServ is used in the CN and consider two cases. The first case is when no radio bearer is established. Here, we suppose that the GRAAL will have to ask for a radio bearer (RRM is queried for access stratum resources and the CN for authentication and accounting) with a given QoS deduced from scanning the Codepoint of the first IP packet to be transmitted. The second case is where a radio bearer is established and the IP layer interacts with directly with PDCP/RLC. Here the IP layer invokes the DATA request/indication primitive to send and receive data in the user plane of the access stratum.

4.2 Radio Resource Management - RRM

RRM is carried out in a centralized fashion across a group of RGs which allows for joint management of radio resources in different cells and potentially across different access technologies. In the all-IP setting considered here the RRM entity is a server located in the CN which performs the following functions for the set of client RGs it manages:

1. automatic access stratum configuration based on QoS-based service requests
2. interference mitigation (power control, dynamic channel allocation)
3. low-level mobility management (e.g. soft handover control)
4. joint resource allocation across several access technologies (e.g. UMTS/WLAN)
5. measurement collection

It provides the remaining radio-specific functionality normally found in the RNC in a 3GPP network and can run, for instance, in one of the RGs of the network (a so-called master RG). The simulation environment considered earlier can also include the functionality of the RRM component of the radio network.

5. CONCLUSION

This article summarized the overall architecture of an experimental software radio system providing direct interconnection with an IPv6 backbone network. The ongoing development of this system was carried out in the context of publicly-funded projects at the French National (RNRT) and European levels (IST 5th Framework). The resulting RF and acquisition equipment ranges from high and low-power basestations (Radio Gateways) to reconfigurable terminals. This experimental networking equipment can be made available to the research community through http://www.wireless3G4Free.com. Our implementation makes use of the hard real-time extension to the Linux operating system known as RTLinux and our software developments are all freely-available in the public-domain. Software can be configured for both real time deployment scenarios and radio network simulation on networked PCs. We have described some of the novelties related to interconnecting a 3GPP air-interface with an IPv6 backbone and their consequences on wireless networking architecture as well as issues related to radio resource management in all-IP networks.

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