Resource Management in Wireless Heterogeneous Networks (WHNs)

Liljana M. Gavrilovska[1], Vladimir M. Atanasovski[2]

Abstract – **Resources, especially in wireless networking context, are considered to be scarce and deficient. Appropriate management of resources is crucial for efficient networks' usage and users' satisfaction. This paper elaborates on the resource management issues in Wireless Heterogeneous Networks (WHNs). It explains the market and business cases for wireless heterogeneity and reflects on the most common radio resource management frameworks envisioned today. Furthermore, the paper pinpoints and explains two network architectures, i.e. the RIWCoS and the ARAGORN architecture, designed to deal with resource management under various access technologies possible. The former one is specifically tailored to meet the demands of emergency situations, whereas the latter one introduces the notion of cognitive resource management and policy regulated networking. Finally, some ideas regarding the future work in this vibrant area will be elaborated.**

Keywords – **Resource management, Wireless Heterogeneous Networks (WHNs), Reconfigurability, Interoperability, RIWCoS, ARAGORN.**

I. Introduction

Wireless mobile networks (e.g. 3G and beyond) and broadband wireless access solutions (e.g. WiMAX and WiFi) provide numerous applications and services ranging from voice to video streaming. Their constant development enlarges the spectrum of possible applications that can run on a single user device and, hence, lead to increased interest for research in the field. It also opens potentials for the operators to increase their profits through a variety in their service portfolio, while at the same time the users experience context-rich and personalized services [1]. The emerging user personalization and user centricity require integration of different wireless access solutions into a single, unified, communications platform capable of delivering seamless and transparent user mobility with high level of Quality-of-Service (QoS) for the end users. This integration leads to the notion of Wireless Heterogeneous Networks (WHNs) [2].

One of the cornerstone aspects of WHNs is the reconfigurable interoperability [3]. The interoperability allows a mechanism for operators to offer various access solutions to their subscribers, whereas at the same time users can roam seamlessly through the access heterogeneity. The reconfigurability requires management of different resources in heterogeneous environment. This brings great benefits, both for the operators and the users. The increased level of service personalization, the accommodation of all users' demands and the integration of various wireless access networks become the driving force behind. It leads to the development of a multi-access, heterogeneous, personalized and user transparent communicating environment, i.e. 4G [4], Fig. 1.

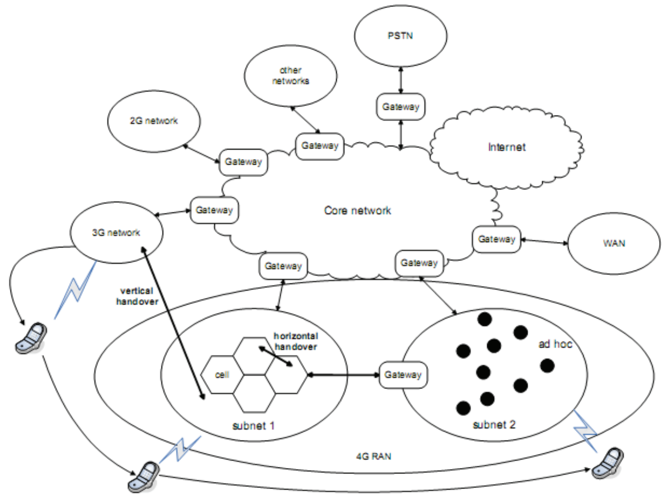

Fig. 1. A typical future WHN [3]

The interoperability among different wireless systems requires novel resource management principles. Namely, the heterogeneous environment poses serious limitations and challenges for the mechanisms responsible to accommodate the users' satisfaction and the efficient networks usage. The notion of resource in WHN context becomes spanned across different wireless access networks, each with its own distinct networking possibilities. Therefore, depending on the actual WHN setup and in terms of being owned by a single or multiple operators, there may be different approaches to the resource management aspect.

This paper will give a general overview of resource management in wireless heterogeneous context. It will elaborate on the relevant resource management frameworks that can be used to monitor and control the resources in wireless heterogeneous networks. Moreover, the paper will give insight into two novel concepts specifically targeted at resource management in wireless heterogeneous systems. These concepts, i.e. the RIWCoS approach [5] and the ARAGORN approach [6], shed new light in the resource management domain for WHNs.

The paper is organized as follows. Section II describes the notion of wireless heterogeneity along with some business case analysis and emerging standards in the field. Section III elaborates the most prominent radio resource management

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architectures for WHNs today. Section IV depicts the RIWCoS approach to resource management in WHNs under emergency situations, whereas section V discusses cognitive resource management techniques adopted in the ARAGORN approach. Finally, section VI concludes the paper.

II. The Case Behind Wireless Heterogeneity

The 4G paradigm [4] defines a seamless concept which is cost effective, simple, operable and personalized according to the users' needs. It should support the paradigm shift from technology centric to user centric concepts and should provide "anytime, anywhere, anyhow and always-on" connectivity in a seamless manner. The creation of a unified communicating platform will open up certain questions, such as how users' demands will be mapped to the network resources, but will also allow the operators to develop new services and business models in more flexible and efficient manner.

The evolution and the emerging variety of different wireless systems with different characteristics require integration into a single platform capable of supporting transparent and seamless user roaming, while not interrupting active communications. This process is followed by the development of new user devices designed to deal with the various network platforms and protocols.

The implementation of WHNs is strongly facilitated by the lately emerging IEEE 802.21 standard [7]. This standard aims to provide a Media Independent Handover (MIH) functions to heterogeneous environments allowing for seamless and transparent user roaming. Most of the work in this paper assumes that either MIH or MIH-alike functions must be implemented in order to provide heterogeneous networking. Moreover, the IEEE 802.21 standard allows for easier introduction of resource management schemes, which are the focal point of this paper.

This section reflects on the business case behind WHNs and introduces the IEEE 802.21 standard that facilitates both resource management and interoperability in WHNs.

A. Business Case

WHN encompass a variety of different wireless access solutions. Users should be able to move seamlessly and transparently in such an environment performing Vertical Handovers (VHOs) through different access technologies. This roaming situation reflects on the business case of WHNs. The general idea is given in Fig. 2. It shows how different aspects (such as network and proxy advertising or load balancing) impact on different roaming situations. Fig. 2 can be used to derive possible business strategy and models for operators of WHNs.

The possible business models for multiple access, stemming from Fig. 2, are shown on Fig. 3. The actual implementation of a certain business model will depend on the policy of the network operators.

Research, deployment and implementation of new wireless systems require definition of appropriate scenarios. Developed as a strategic management tool in military context, scenarios are used in order to predict the outcome of implementing new systems considering all possible assumptions and uncertainties (economy, adoption of new technologies). Different and detailed analysis of specific scenarios for WHNs can be found in the full scenarios development on Fig. 4.

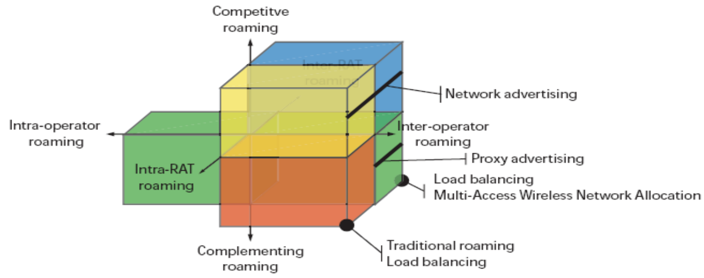

Fig. 2. Roaming scenarios

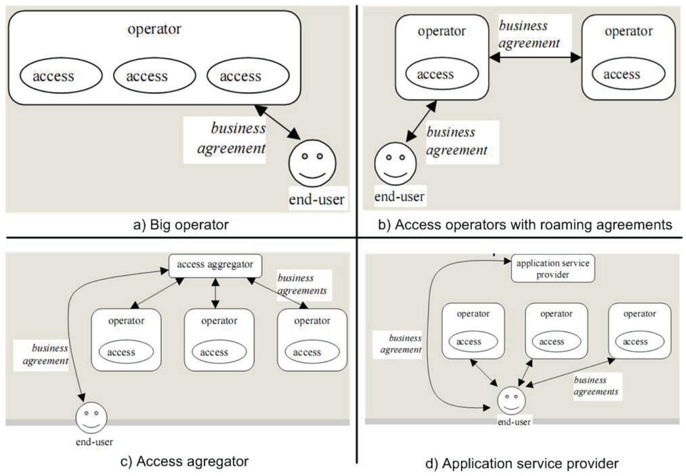

Fig. 3. Proposed business models for multiple access

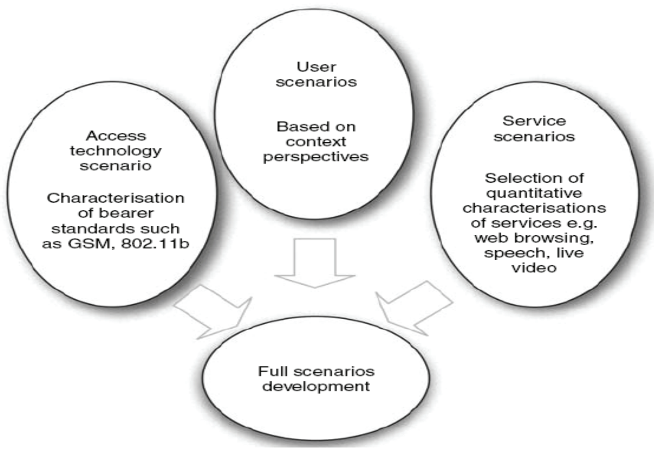

Fig. 4. Full scenarios development

The roaming scenarios and the proposed business models need an underlying technology for interoperability. There is an emerging standard in this field, i.e. the IEEE 802.21, which tackles this issue supporting seamless VHOs. The following subsection discusses the IEEE 802.21 standard in greater details.

B. IEEE 802.21

A key enabling technology of the interoperability in heterogeneous networks is the lately emerging IEEE 802.21 standard [7]. Prior to its introduction, the VHOs in heterogeneous environments depended heavily on pure Mobile IP [8] (or related protocols) functionalities leading to high handover latencies and, thus, high disconnection times and high number of dropped packets during VHOs. The main target of the IEEE 802.21 standard is the seamless mobility through heterogeneous environments, i.e. the ability of a user to transit through different Radio Access Technologies (RATs) without the need to restart the connection every time a switch to a different network is made. The actual implementation of the standard requires knowledge on the network types, the policy rules, the roaming criteria etc.

The IEEE 802.21 standard facilitates the handover between different wireless networks in heterogeneous environments regardless of the type of medium. The standard names this handover as Media Independent Handover (MIH). The goal of IEEE 802.21 is to better and ease the mobile nodes' usage by providing uninterrupted handover in heterogeneous networks. For this purpose, the handover procedures can use the information gathered from both the mobile terminal and the network infrastructure.

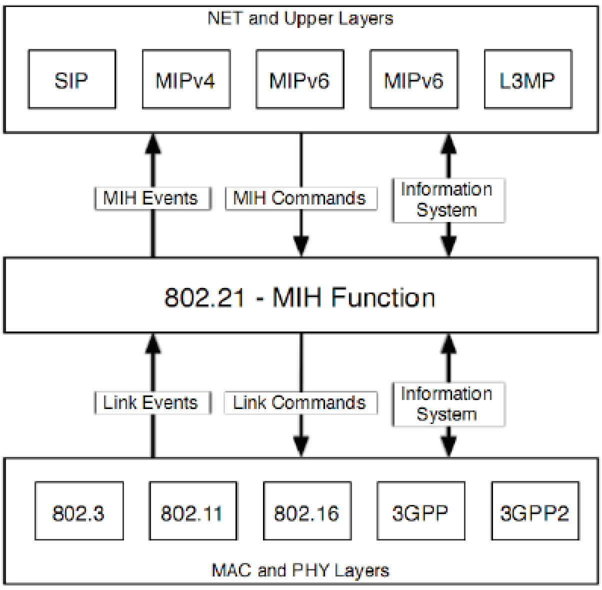

Fig. 5. IEEE 802.21 architecture

The heart of the 802.21 framework is the Media Independent Handover Function (MIHF), Fig. 5. The MIHF will have to be implemented in every IEEE 802.21 compatible device and will be responsible for communication with different terminals, networks and remote MIHFs providing abstract services to the higher layers using a unified interface (L2.5 functionalities). MIHF defines three different services: Media Independent Event Service (MIES), Media Independent Command Service (MICS) and Media Independent Information Service (MIIS). MIES provides events triggered by changes in the link characteristic and status. MICS provides the MIH user necessary commands to manage and control the link behavior to accomplish handover functions. MIIS provides information about the neighboring networks and their capabilities.

The IEEE 802.21 standard is still in its formative stages. However, the interest that exist both in academia and industry shows that it may be the key enabler for seamless handovers and transparent roaming in heterogeneous networks. Related work in the field may be found in [9-14], where the IEEE 802.21 framework was used to deliver lower VHO disconnection times, QoS based VHO, cross-layer based VHO and provide assistance to mobility management, respectively. It is clear that the IEEE 802.21 technology will make a major contribution towards the reconfigurable interoperability aspect of the future generation wireless communications systems.

Having the basic features of wireless heterogeneity and interoperability defined, the following section will elaborate on the most prominent resource management principles and architectures for WHNs today.

III. Resource Management Principles

The resource management is the key enabler of seamless and transparent user roaming and efficient user personalization in a WHN context. There are few main concepts for future resource management implementations envisioned today. They are based on different solutions and algorithms implemented in several architectures:

- *MRRM* (Multi-access Radio Resource Management) [15],
- *CRRM* (Common Radio Resource Management) [16] and
- *JRRM* (Joint Radio Resource Management) [17]

which can follow either a centralized or a decentralized approach. Following subsections discuss different WHN resource management architectures in greater details.

A. MRRM Architecture

The multi-access RRM (MRRM) is based on three main architecture principles: *network-centralized* MRRM functions, *network-distributed* MRRM functions and *terminal* MRRM functions, Fig 6.

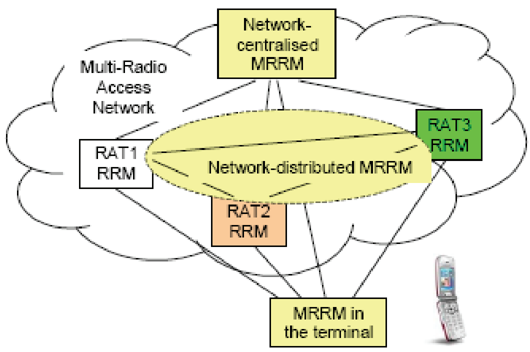

Fig. 6. MRRM alternatives

Network centralized MRRM means that one or more central entities are coordinating different RAT specific RRM entities. This type of architecture has some disadvantages like the border effect that is appearing between two neighbour RATs that are not connected directly with a peer-to-peer link. In addition, it requires a hierarchical infrastructure meaning that more specific and complicated messages should be processed. Furthermore, no SP (Service Provider) or NP (Network Provider) would have all the RATs under its own umbrella. In terms of RRM, different providers should reveal their network topology to each in other to set the RRM entities with the required information for managing the network.

Network distributed MRRM approach does not rely on a specific MRRM entity. Instead, the corresponding functionality is distributed between RAT specific RRM entities through peer-to-peer relations. This principle is already supported today between WCDMA and GSM/EDGE according to the 3GPP specifications, wherein e.g. cell load information can be exchanged between WCDMA radio network controllers (RNC) and GSM/EDGE base station controllers (BSC). The distributed architecture may theoretically have problems with scalability because of the exponential growth of the number of links between the RRM entities in the network in correlation with the incensement of the RRM entities. But in practice this can be solved with using peer-to-peer connections only between the neighbouring RATs (Fig. 7).

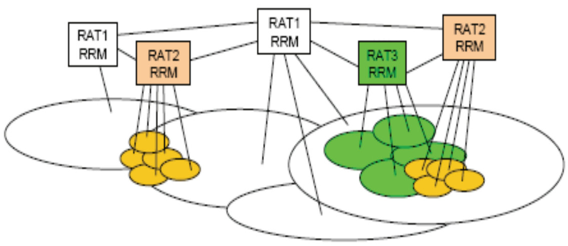

Fig. 7. Distributed architecture

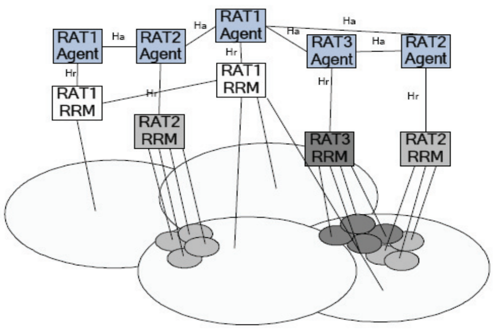

Fig. 8. Use of agents

The distributed MRRM solution implements a Multi Agent System (MAS) in its architecture for collecting the status information of the underlying specific RAT and the information of neighbouring agents, Fig. 8. Based on the obtained information, the agent deals with various issues such as coexistence, optimizations etc. The Hr interface is used to carry information between the RAT and the corresponding agent. Through this interface, an agent collects radio network information such as parameters related to radio resource, parameters about performance etc. and sends control factors to the RAT. The Ha interface (Agent-Agent interface) is used to carry information concerning inter-network resource adjustment and coordination and status information of each other.

The terminal based MRRM results in MRRM functions and decisions left to the terminal. This would still typically include some support from the network, i.e. each network RRM entity could provide information to the terminal on which it bases its MRRM decisions.

B. CRRM Architecture

The CRRM architecture is based on a centralized functionality and solution. The idea of CRRM is to co-exist with the given RRM of the different RATs and to coordinate their operation. Every RAT is based on specific and local multiple access mechanism exploiting in turn different orthogonal dimensions, such as frequency, time and code. CRRM is based on the picture of a pool of radio resources, belonging to different RATs, but commonly managed, as shown in Fig. 9.

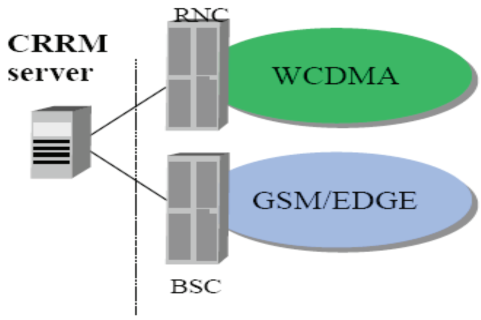

Fig. 9. CRRM pool of RAT

The additional dimensions introduced by the multiplicity of RATs available provide further flexibility in the way how radio resources can be managed and, consequently, overall improvements may follow. 3GPP has discussed and standardized CRRM, where GSM and EDGE as well as WCDMA are managed in an integrated fashion through the CRRM server.

The lowest degree of interaction would be when the CRRM only dictates policies for RRM operation. CRRM operation responds to an external Policy Decision Function (PDF) that defines the set of high-level policies to be applied when managing radio resources. In this approach, the CRRM is considered simply as a Policy Enforcement Point (PEP) that translates the specific policies into an adequate configuration of the RRM algorithms. Notice that almost all functionalities reside in the local RRM entity, which is responsible of the initial RAT selection at the beginning of a session and the decision to execute an intersystem or vertical handover between different RATs in the middle of a session, taking into account the intra and intersystem measurements provided by the mobile terminals as well as the cell measurements from other RRM entities. The interaction between CRRM and RRM is limited to the policy specification and update, so it is expected to occur at a rather long-term time scale. In this case, the local RRM entity is the main responsible of the undertaken decisions (i.e. the RRM is the master of the different decisions).

In the case of higher degree, CRRM not only provides the policies that configure the local RRM algorithms but it is also involved in the RAT selection and vertical handover algorithms by deciding the appropriate RAT to be connected to. The local RRM entities provide RRM measurements including the list of candidate cells for the different RATs and cell load measurements, so that the CRRM can take into account the availability of each RAT for the corresponding mobile terminal. The RAT selection either during vertical handover or in the initial RAT selection case would respond to the specific policies, e.g. establishing correspondences between RATs and different services or user types. This solution would require CRRM decisions to be taken at a very short time scale in the order of milliseconds, with the possibility to execute frequent RAT changes for a given terminal. Consequently, this poses hard requirements to the reconfigurability capabilities of the mobile terminals, difficult to achieve with current technology. CRRM responsibilities could rely not only in selecting the appropriate RAT, but also the specific cell for the selected RAT. Thus, CRRM would be involved in each intrasystem handover procedure and would require a more frequent measurement exchange. Similarly, joint congestion control mechanisms could be envisaged to avoid overload situations in any of the underlying access networks.

C. JRRM Architecture

Joint Radio Resource Management (JRRM) is presented by Siemens. The core concepts of this management system are *service-split* and *multi-homing*. JRRM splits the service into fundamental part and enhanced part and the former is delivered by RAT with large coverage range, e.g. UMTS. JRRM aims at the support of intelligent interworking between different RATs using a central controller to manage the overall capacity of the sub-networks. The architecture of JRRM is quite similar to the one of CRRM, except that JRRM is not restricted to UMTS and GSM only. Moreover, JRRM complements the CRRM approach by several modifications and additional features. A very tight coupling allows this joint managing of traffic streams between the involved networks and the terminals. Joint radio resource scheduling and admission control are therefore required to optimize spectral efficiency, handle various traffic types and QoS constraints and schedule traffic adaptively. In particular, optimal QoS can be achieved with traffic splitting supported by adaptive radio multihoming, which in turn provides multiple radio access for a single terminal in order to allow the terminal to maintain simultaneous links over RATs. The major issues in JRRM are *traffic prioritization and splitting* (whereby the incoming traffic is split over two or more substreams and the important information goes through a reliable RAT, the rest through other RATs) and *synchronization* (whereby packets belonging to a substream are multiplexed back to original traffic stream in the receiver based on proposed synchronization schemes).

The JRRM architecture is based on the assumption of co-existence of different RATs with different profiles and is illustrated in Fig. 10. Each RAT needs an efficient interworking between traffic volume, measurement function, traffic scheduler, load control and admission of control function. The Traffic Estimation module (TREST) informs the administrative entity Session/Call Admission Control (SAC) in every subnetwork on the predicted traffic and planned traffic information in order to update the priority information of each connection and the admission decision within the network.

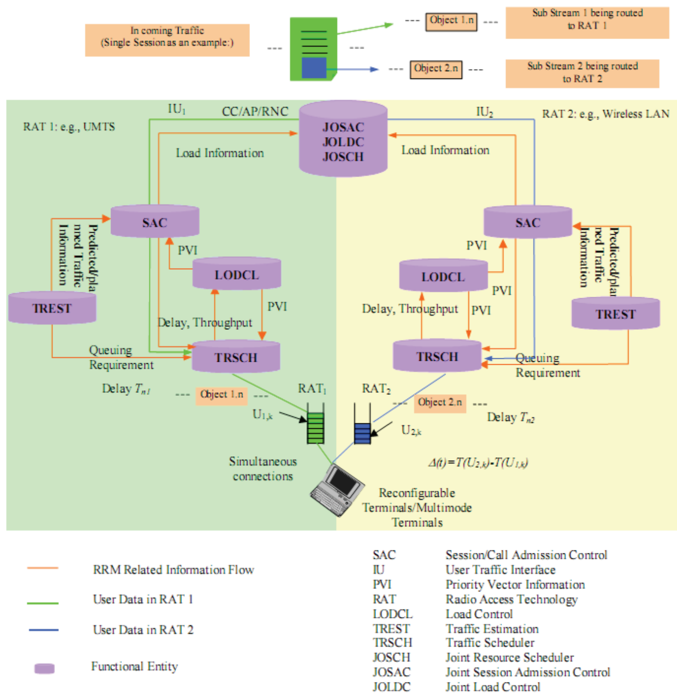

Fig. 10. JRRM Architecture

The analyzed resource management schemes in this section are the most common ones envisioned for future implementations in WHNs. However, they only provide framework guidance to practical implementations which can vary depending on the actual WHN focus. Following sections will discuss two novel approaches to resource management, utilizing the previously defined frameworks, developed within ongoing internationally funded research projects.

IV. The RIWCoS Approach

The Reconfigurable Interoperability of Wireless Communications System (RIWCoS) project [5] aims to integrate different wireless communications technologies into a single, easy-to-use, user transparent platform capable of dealing with various situations and users' needs. The focal point of the project is the usage of the emerging IEEE 802.21 standard in an emergency situations context. This standard facilitates both the interoperability (interconnection among different wireless systems) and the resource management aspects, thus leading to a real reconfigurable environment.

The RIWCoS approach to resource management relies on the notion of MIH User defined within the IEEE 802.21 standard [7], Fig. 11. The MIH User uses the services of the lower MIH Function (MIHF) in a standardized way. To encompass all possible user scenarios envisioned within RIWCoS, the resource management system defines both users Resource Management (RM) modules (residing in the user nodes) and network RM modules (residing in the network nodes). At this stage, the RIWCoS resource management system has only user RM modules specified in great details and implemented in a simulation environment.

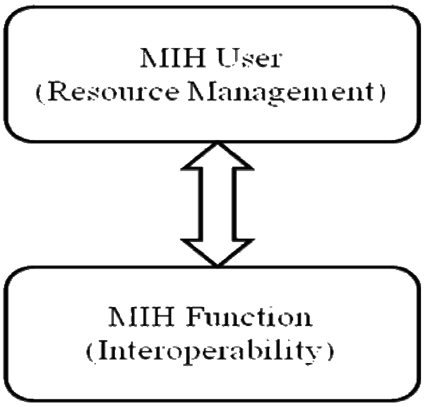

Fig. 11. RIWCoS's usage of IEEE 802.21

Fig. 12 depicts the general architecture of a user RM module defined in the RIWCoS project. The Application block presents the user application that needs certain network resources. Different applications have different requirements in terms of bit rate and delay, but it is also important for the network what type of user started that application. Therefore, the message sent from the application that triggers the work of the RM module (*StartApp* message) has three parameters: *userSIM*, *bitrate* and *delay*. This message is then transferred to the U&AProfile (User&ApplicationProfile). The U&AProfile is the block in which the StartApp message is processed in 5-bit *U&A* message that identifies the user class (2 bits for 3 possible classes) and the application type (2 bits for 4 application categories). The last bit in the U&A message is gained from the BatteryCondition sub block and presents additional battery consumption feature (save battery mode and normal battery mode). This bit will be used further to select the mode in which the Decision block will work (one out of three possible). The LRes repository is a database that stashes the information about the targeted networks (newly detected networks). Because the information about possible networks is available through the MIIS part of MIHF, the LRes has the same structure as the format suggested in the IEEE 802.21 standard. There are around twenty information elements that are defined in the standard, though all of them are not needed for proper functioning of the RM module.

The modes in which the Decision Block can operate are, in priority order: Emergency Mode, BatteryLowMode and Normal Mode. In the Normal Mode, the Decision block does simple switching of the user demands gained from the U&A message to what is available as a resource in the LRes. In the BatteryLowMode (used when the 5th bit in the U&A message is set as '1'), the Decision block selects the technology that best fits the battery saving, thus reducing QoS (the selected technology may not be best fitted for the QoS of the application). In the Emergency mode (started when LinkDown trigger from IM module is received), the RM module uses specially designed algorithm implemented in user and network RM modules for sorting applications and serves them as sorted. The communication with the LRes repository is needed (*Get_Info*, *Push_Info* messages) for appropriate design of the ranking list.

The Network Discovery module has an interface towards the IM module for receiving MIH messages that carry relevant information about the networks in the users' vicinity. It uses *Store_Info* message to fill the LRes database and its work is triggered by the Decision block with the *Gather_Info* message.

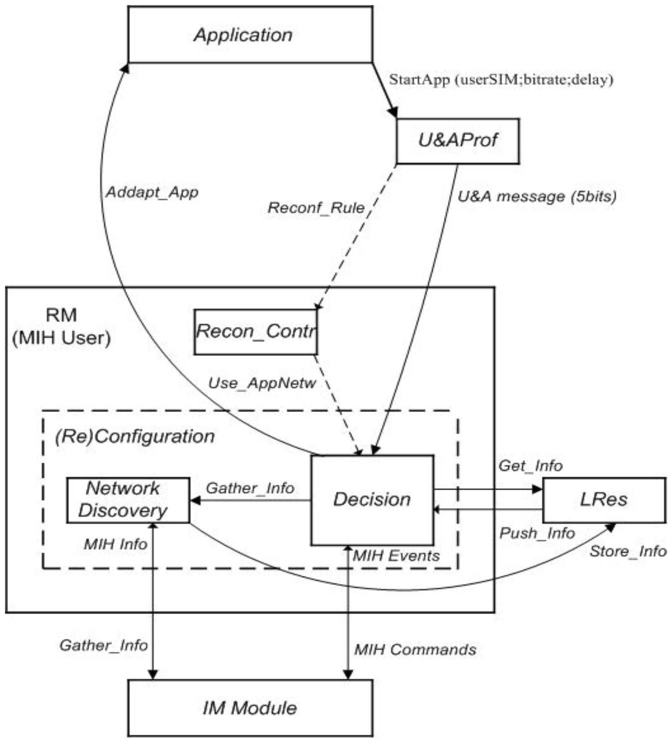

Fig. 12. General architecture of the RM user module

The Recon_Contr is a block left for additional reconfigurability constrains. It can learn and store users' behavior, thus providing further upgrade of the system (cognition). For example, through this module the decision of the Decision Block can be made much easier - predefined decisions. Also, this block can be used for upgrading users' profiles. It can send additional messages to the Decision Block (Reconf_rule) to satisfy some users' preferences. This block will coordinate e.g. exchange of SIP logic based messages to adapt application demands in emergency cases (*Adapt_App* message)

The RIWCoS architecture encompasses certain features that make it specifically tailored for emergency situations. One of them is the Sorting Applications in Emergency Situations (SAES) algorithm [18]. SAES is a hybrid based RAT selection mechanism implemented both in users' and in networks' RM modules. It tags every application with a *priority coefficient* which is calculated proportionally to a history of vertical handovers exhibited by the applications in normal mode of operation. This coefficient is then used to serve the applications in emergency situations.

The performance of SAES can be compared with a simple Service Based Policy mechanism (SBP). SBP operation is rather straightforward, e.g. for a voice application it always tries and connects to a cellular network, whereas for a data application it always tries to connect to a WiFi hot spot. Both SAES and SBP algorithms were implemented in MATLAB, where two parameters: *network load* and *blocking probability*, are used for comparative performance analysis. The simulation scenario is defined as a heterogeneous wireless network with multiple active access networks struck by an emergency situation which leaves only two networks in an operable mode. The performance analysis starts when the emergency situation occurs and the new incoming sessions are being served only by the survived networks, which have full radio coverage of the simulation area. One is an emulation of a cellular network with a capacity of 14.4 Mbps and the other is an emulation of a wireless network (WMAN) with a capacity of 30 Mbps. The imperilled users, once the emergency occurs, will immediately try to connect to one of the two active networks, without considering the influence of other users (greedy strategy). The effect of the greedy strategy (overloading the most suitable network) is a common characteristic for mainly all existing RAT selection mechanisms including SBP. SAES is designed to minimize this effect. Moreover, every user can have more than one active application (session). Three types of applications are defined, i.e. data, voice and background. The voice applications are defined with G.711 codec, meaning a 64kbps raw bit rate is needed for optimal working. The data applications are defined with a 0.5 Mbps bit rate. The background traffic can be defined as an additional application, like e-mail, chat, sensor monitoring etc. Only 4 kbps are assigned to this application. The network's physical and MAC layers are abstracted in order to isolate the effects from the specific wireless technologies below. It is assumed that the IEEE 802.21 support performs seamlessly thus justifying this assumption. Both algorithms are analyzed under the same conditions, i.e. applications bit rate, number of users, number of active sessions and network load prior to the emergency occurrence.

Fig. 13 depicts the load of both networks depending on the number of incoming sessions. It is assumed that every user has an active voice application, 20% of all users have additionally an active data application and 10% run all three, i.e. voice, data and background application. The load in the cellular network is higher than the one in the wireless network, since the majority of sessions are voice and their primary target is the cellular network, so the capacity limit of the cellular network is being reached faster. SAES outperforms SBP in terms of efficient use of network capacity, which is more evident for the wireless network. Namely, SAES admits more sessions in the networks from the same number of incoming sessions compared to SBP. Therefore, the load in the networks is higher when implementing SAES.

Figure 14 depicts the blocking probability (P_B) of both algorithms for a different percentage of voice and data applications. When the distribution of applications per user is the same as in Fig. 12, SAES has lower P_B. This is due to the fact that SAES uses the free capacity of the wireless network to admit new sessions and users that are blocked when SBP is used. If the percentage of the data applications increases, then SBP performance improves. It is evident from Figure 2.6 that when 40% of the applications are data, both SBP and SAES converge to the same values for blocking probability. It should be noted that the performance analysis presented here was based on equal conditions for both algorithms. In reality, SAES is expected to show an even higher efficiency, because it can degrade applications' bit rate. This gives SAES an advantage compared to other RAT selection mechanisms in terms of network load and blocking probability. However, this bit rate decrease should be balanced with the decrease of user perceived quality of service.

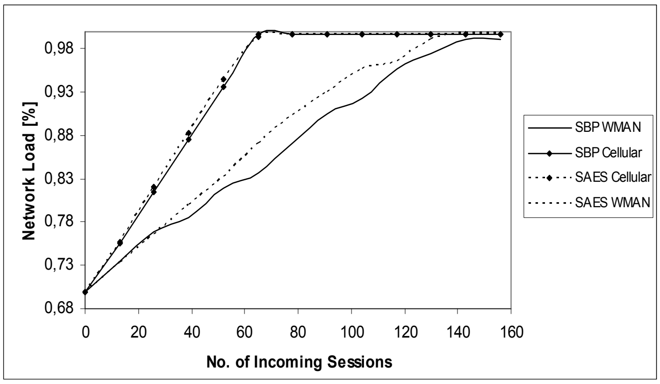

Fig. 13. Network load performance of SAES

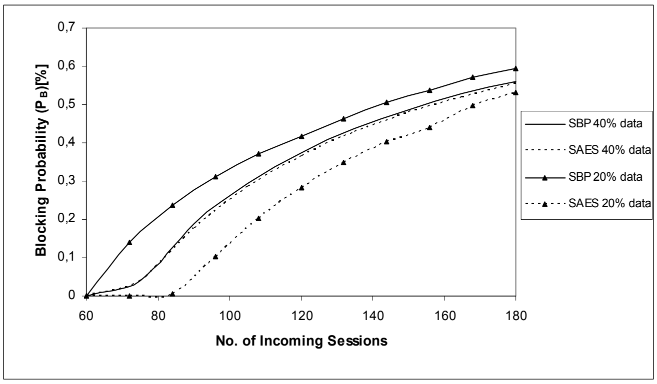

Fig. 14. Blocking probability

SAES is specifically tailored to meet the demands of emergency situations and provide increased efficiency of serving imperilled users under emergency scenarios. The main difference between SAES and today's common mechanisms (e.g. SBP) is that SAES introduces application fairness, regarding past quality experiences, by using priority coefficients. This enables maximization of the number of served users and applications. Another novelty in SAES is that emergency services have priority in the emergency mode and the fact that SAES frees network capacity by degrading the application performance.

This section elaborated on the RIWCoS architecture and its capability to manage the available resources in WHNs, especially under emergency situations. The following section will discuss the notion of cognitive resource management in WHNs by depicting the Cognitive Resource Manager (CRM) defined within the ARAGORN project.

V. The ARAGORN Approach

CRM (Cognitive Resource Manager) is one of the newly based concepts that should be able to support new optimization goals and evolving air interfaces. It is based on the principle of Software Defined Radio (SDR) approach that provides modular, extensible and easier to implement frameworks than the existing ones. The CRM approach is based on the principle of being ran in a distributive and adaptive way through all communication nodes.

The CRM can be interpreted as a cognitive decision unit and like an operating system. It is tightly coupled with an optimization toolbox (on the MN side) and the global network optimization, information that is accumulated from the protocol stack, historical data etc. The architecture of the CRM is given on Fig. 15.

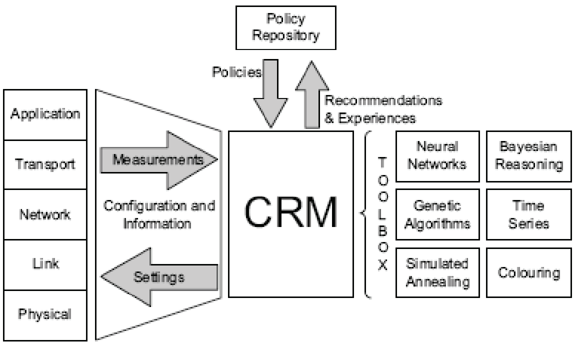

Fig. 15. Architecture of CRM

It is evident that the CRM has access to all of the protocol layers for measurements and settings through the configuration and information block. The cluster containing these interfaces is called UNI (Universal Network Interface). The UNI is capable of abstracting the different protocols and technologies making the technology-independent cross-layer optimization possible. The main objective in the research groups is focused on developing the link-layer part of UNI also known as ULLA (Unified Link Layer API). The toolbox within the CRM architecture is the main entity responsible for applying all the management decisions based on different algorithms implemented in it.

The basic difference between CRM and classical Radio Resource Management (RRM) is in the software implementation. In other words RRM is monolithic software and CRM is not. In fact it is a collection of modules and independent run-time threads and processes. CRM should be seen partially as an operating system type of entity with its own scheduler and flexible set of processes carrying out measurement, optimization and (re)configuration functions. The CRM's modularity allows for incorporation of other mechanisms that also affect the resource management capabilities of the ARAGORN system. One such mechanism is elaborated in greater details in the following subsection.

A. Policy Regulated Networking

One of the novel features related to resource management in WHNs and especially in cognitive environments, being defined within the ARAGORN project, is the policy regulated networking [19]. Policing a wireless network system provides means to control system behaviour and ensure accurate and efficient usage of available network resources. Current wireless systems employ radio pre-programmed or hardwired policies intermingled with the firmware [20]. Consequently, today's policy systems are accessible mostly only to radio engineers and it is difficult or even impossible to change them. The possible separation of the policing paradigm from the radios' firmware can lead to more adaptive and flexible behaviour of networked devices. In this manner, the policies can be written and dynamically changed from stakeholders and can be loaded on different types of radio devices [21].

Policies can be supplied by a regulator authority, a network operator and/or a system user [21]. They contain rules and constraints which should be respected by the involved entities in order to achieve the goals imposed by the stakeholders. The resulting set of policies determines the system behaviour and its (possible) modifications result in changed behaviour of the networked radio devices. Therefore, a policy based wireless system can constraint the decision making process and configuration within the radio network, ensuring system manageability and stability without numerous interactions and exchanging excessive control information. It leads to the development of cognitive wireless networks able to autonomously perform efficient resource management.

Policy enforced cognitive radio networking yields two essential system components, i.e. *Policy Enforcing Point (PEP)* and *Policy Decision Point (PDP)*, Fig. 16. The PEP performs actions for controlling user data flow in compliance with the policies from the PDP. It enforces cognitive devices to respect the policy rules and change its behaviour in accordance to the policies when needed. As a result, the PEP is in charge of optimization and learning, while the reasoning capabilities are located in the PDP. The PEP entity must be located in every cognitive radio device, whereas the PDP can be located only in certain cognitive nodes which have a policy reasoning engine employed. In case of a fully distributed architecture, the PEP and the PDP are located in every cognitive radio device [22].

PEP is an entity, usually equipped with sensors and RF transceiver, used to sense the radio environment and measure certain parameters in order to detect spectrum holes, available networks, estimate current location, time etc. Based on the information for current radio environmental conditions and incorporated system strategies, it creates transmission requests, sends them to the PDP and acts upon received replies from the PDP (Fig. 16). The PEP allows transmissions only upon reception of a positive reply from the PDP.

Otherwise, i.e. if a negative reply is received, the PEP needs to create a new transmission request with a new set of parameters. In this case the returned reply can be used from the PEP to learn how to adapt to the policy condition in order to operate quickly and effectively [21].

PDP is an entity which performs the decision process for each transmission request from the PEP. It is also referred as a *Policy Engine (PE)* and consists of a *policy Database (DB)* and a *Policy Reasoner (PR)* [21]. The policy DB is used for storing all policies in the system, while the PR performs the process of reasoning. It receives policy requests from the PEP and, after checking compliance with the database, returns a transmission reply to the PEP. The reply can be either "allowed", if all policies approve the requested transmission, or "not-allowed", if at least one active policy is violated [23].

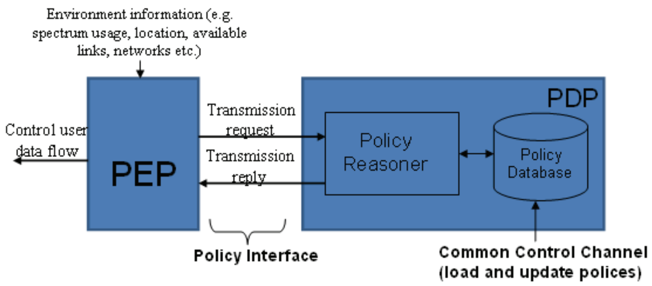

Fig. 16. Policy based cognitive radio system

The resource management aspects in a policy regulated cognitive radio system are reflected in the policy management, i.e. policy distribution, scheme. It is the key part of the policy management framework. The regulators' and operators' policies, after their acceptance and validation, are stored into the databases on the central policy servers. These are the regulators and operators' central policy servers, respectively, for both types of policies (Fig. 17). The regulators' and operators' polices are then timely disseminated and distributed to the correspondent DBs of the PEs equipped nodes via the CCC, where only authenticated entities can load polices. User defined policies are derived from users' preferences and are directly stored into the DB of the local PE after their acceptance and validation.

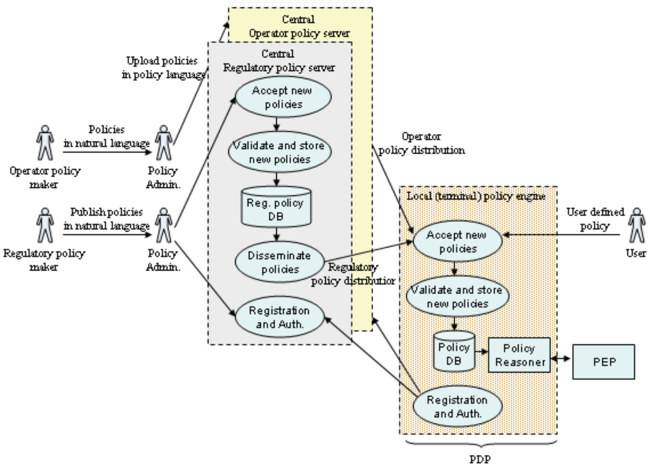

Fig. 17. Policy management architecture

Policies are written using a policy representation language. They allow policy expression in a simple and unambiguous manner and are built on a reach set of ontologies which describe the knowledge about the radio environment. The ontologies' sets must be extensible in order to express all policy relevant attributes and to satisfy all policy requirements coming from stakeholders. Also, additional features such as accreditability, functions, computations and orderings must be supported. Many needed ontologies for policy reasoning are covered by CoRaL [24] allowing expression of knowledge about radio, radio environment and radio capabilities. Moreover, CoRaL is extendable and allows creation of new ontologies for different purposes.

The policy reasoning features within the PE can be realized using different PRs. The PRs must satisfy several technological requirements such as being lightweight, interactivity, able to provide anytime solutions, predictability, satisfy underspecified requests etc. They must often operate in resource-limited nodes in cognitive radio environments. A suitable PR, that is adopted for the analysis in section 4, is the XG Prolog Policy Reasoner [25], developed by DARPA. More advanced PR solution, providing additional features, is the XG Maude Policy Reasoner [26], also developed by DARPA, however it only operates on 64-bit platforms.

This section analyzed the resource management concepts defined in the ARAGORN project. The modularity within the ARAGORN system offers great potentials for introducing different mechanisms in the architecture. ARAGORN's resource management aspects today are fundamentally different from classical resource management and provide additional functionalities, such as cognition, policing etc., which will inevitably become a crucial part of future resource management solutions for WHNs.

VI. Conclusions & Future Work

The plethora of wireless network solutions and the increased personalization towards 4G developments yield the integration of various wireless systems into a single wireless heterogeneous platform. The integrated Wireless Heterogeneous Networks (WHNs) are envisioned as a unified platform for delivering enriched ubiquitous services to users, while providing transparent and seamless user mobility. However, to be truly able to unleash their potentials, WHNs must embrace novel concepts in key areas such as interoperability and resource management.

Efficient resource management presents an emerging topic in the wireless world today. The heterogeneity of the wireless environments stresses its importance even further. Resources are very scarce and deficient, therefore must be scrutinized carefully. The problem of resource management in WHNs is fundamentally different from the one in isolated wireless systems since resources are not uniform nor they (may) belong to a single operator. The resource management is one of the key aspects of the developments towards enriched services for end users, enriched service portfolios for operators and increased personalization in WHNs.

This paper analyzed the most prominent resource management architectures and conceptual frameworks for

WHNs today. It pinpointed their advantages and disadvantages and discussed its implications on practical implementations. Additionally, the paper presented two novel resource management concepts currently being tackled in ongoing internationally funded research projects. The first one, i.e. the RIWCoS approach to resource management, utilizes the framework provided by the IEEE 802.21 standard in order to exhibit efficient resource management under various scenarios, especially in emergency situations. The second one, i.e. the ARAGORN approach to cognitive resource management, shows into the future direction of cognitive WHNs systems able to reconfigure and communicate on-demand in an autonomous manner.

There is plenty of work ahead for resource management mechanisms in future WHNs. Many aspects must be efficiently solved in order to accommodate for the various resource management schemes in heterogeneous context. Authors believe that the interoperability is the crucial focal point in WHNs, which, once standardized and solved, will provide seamless underlying mechanism for resource management. Additional research topics that directly or indirectly affect resource management are the emerging dynamic spectrum access schemes [27], teletraffic modeling of WHNs, data acquisition and representation (through e.g. sensor networks in WHNs), inter-operator relations, service monitoring, new billing mechanisms in WHN context etc. It all leads to tighter integration of compound networks in heterogeneous environments and seamless and transparent experience for end users.

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