**UNIVERSITY OF PIRAEUS** **ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ**

*ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ*

# ΒΕΛΤΙΣΤΟΠΟΙΗΣΗ ΓΝΩΣΙΑΚΩΝ ΣΥΝΘΕΤΩΝ ΑΣΥΡΜΑΤΩΝ ΔΙΚΤΥΩΝ ΥΨΗΛΩΝ ΤΑΧΥΤΗΤΩΝ

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Πειραιάς, 2010

**UNIVERSITY OF PIRAEUS** **ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ**

*PHD DISSERTATION*

# OPTIMIZATION OF COGNITIVE HIGH-SPEED COMPOSITE WIRELESS NETWORKS

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## ABSTRACT

The evolution of wireless communications during the last decades, the co-existence of different kind of networks as well as the new reconfiguration capabilities of hardware equipment (access points and users' terminals) revealed the era of Composite Wireless Networks (CWNs). However, regardless of the underlying technologies and the high complexity levels introduced in CWNs the target for the Network Operators (NO) remains the same: Users should be experiencing services at their preferred QoS levels, while the service delivery cost is the minimum possible. Considering this, the challenge for the NOs is to efficiently manage their infrastructures apart from their size and complexity so as to achieve this target. Framed within the above, this dissertation presents an approach for addressing and providing solutions for the aforementioned issues.

First, a Functional Architecture (FA) is presented in the context of CWNs while the focus is on the Dynamic Self-organized Network Planning and Management (DSNPM) functional block which targets at providing the best possible network configurations based on advanced management functionalities. Considering the numerous Radio Access Technologies (RATs), DSNPM is enhanced with efficient inter-RAT as well as intra-RAT optimization techniques, so as to provide the appropriate decisions, and will be thoroughly described. Furthermore, DSNPM includes learning functionalities addressing the high complexity issues introduced by CWNs. In particular, DSNPM is capable to gain knowledge from past interactions with the service area on the way that the solution was provided. Then, DSNPM is capable to identify in the future whether the appropriate network configuration decision is already known skipping the time consuming optimization procedure. The learning capabilities and the identification process of DSNPM were presented in detail. Finally, a platform were presented in which both hardware and software components have been implemented for the conduction of validation activities in terms of scenarios and use cases.

Keywords: Composite wireless networks, functional architecture, knowledge-based management functionality, optimization, learning

# ΠΕΡΙΛΗΨΗ

Η απότομη εξέλιξη των ασύρματων επικοινωνιών τις τελευταίες δεκαετίες, η συνύπαρξη πολλών διαφορετικών δικτύων καλύπτοντας την ίδια περιοχή καθώς και οι νέες ικανότητες αναδιάρθρωσης των ασύρματων σημείων πρόσβασης και των τερματικών συσκευών των χρηστών έχουν συντελέσει στην εμφάνιση των Σύνθετων Ασύρματων Δικτύων (Composite Wireless Networks - CWNs). Παρόλαυτά, ο στόχος των Παρόχων Δικτύου (Network Operators - NOs) παραμένει ο ίδιος, ανεξάρτητα από τις τεχνολογίες που χρησιμοποιούνται και την πολυπλοκότητα που αυτές εμφανίζουν: «Οι χρήστες πρέπει να εξυπηρετούνται στο επίπεδο ποιότητας που επιθυμούν με το μικρότερο δυνατό κόστος παροχής υπηρεσιών». Στο πλαίσιο αυτό, η πρόκληση που αντιμετωπίζουν οι NOs είναι η αποδοτική διαχείριση των τεχνολογικών υποδομών τους ανεξάρτητα από το μέγεθός τους και την πολυπλοκότητά τους. Λαμβάνοντας υπόψη τα παραπάνω, η παρούσα διατριβή παρουσιάζει μια προσέγγιση με σκοπό να αντιμετωπιστούν τα παραπάνω ζητήματα.

Αρχικά παρουσιάζεται μια Αρχιτεκτονική Λειτουργιών (Functional Architecture - FA) στο πλαίσιο των CWNs, εστιάζοντας στις λειτουργίες της οντότητας Δυναμική και Αυτο-οργανούμενη Σχεδίαση και Διαχείριση Δικτύου (Dynamic Self-organizing Network Planning and Management - DSNPM) η οποία έχει σκοπό να παρέχει την καλύτερη δυνατή διάρθρωση του δικτύου βάσει προηγμένων λειτουργιών διαχείρισης. Λαμβάνοντας υπόψη τις πολυάριθμες τεχνολογίες ασύρματες πρόσβασης (Radio Access Technologies - RATs) η οντότητα DSNPM περιέχει έξυπνες τεχνικές βελτιστοποίησης τόσο ανάμεσα στις τεχνολογίες αυτές όσο και για την εσωτερική τους διάρθρωση. Σκοπός των τεχνικών αυτών, οι οποίες θα περιγραφούν αναλυτικά, είναι η παροχή των κατάλληλων αποφάσεων για την διάρθρωση των ή του δικτύου. Επιπλέον, η οντότητα DSNPM περιλαμβάνει και λειτουργίες μάθησης με σκοπό να αντιμετωπίσει και τα ζητήματα υψηλής πολυπλοκότητας των CWNs. Πιο συγκεκριμένα, η οντότητα DSNPM μπορεί να αποκτήσει γνώση για τον τρόπο ή τις λύσεις αναδιάρθρωσης στις οποίες κατέληξε στο παρελθόν σε συγκεκριμένες περιπτώσεις. Με τον τρόπο αυτό, είναι εφικτό να αναγνωριστεί στο μέλλον εάν οι απαραίτητες αποφάσεις είναι ήδη γνωστές με σκοπό να παρακαμφθούν οι χρονοβόρες τεχνικές διαδικασίες. Οι διαδικασίες μάθησης και αναγνώρισης της οντότητας DSNPM παρουσιάζονται αναλυτικά. Τέλος, παρουσιάζεται η ανάπτυξη πλατφόρμας, στην οποία συμμετέχουν τόσο συνιστώσες υλικού όσο και λογισμικού, με σκοπό να μελετηθεί η συμπεριφορά των συνιστωσών στα πλαίσια σεναρίων και περιπτώσεων χρήσης.

Λέξεις – Κλειδιά: Σύνθετα ασύρματα δίκτυα, αρχιτεκτονική λειτουργιών, λειτουργίες διαχείρισης, βελτιστοποίηση, μάθηση

## FOREWORD

Pursuing this PhD dissertation was a long and difficult process, which required both effort and dedication. However, despite the adversities I managed to acquire remarkable knowledge in the field of telecommunication networks and services, since I was given the opportunity to be involved in numerous important research projects. None of the above would have been accomplished without the help of God and the actual support of many people whose contribution to my research, in assorted ways, was significant and deserve special mention.

First of all I would like to gratefully acknowledge my supervisor, Associate Professor Panagiotis Demestichas, whose dedication to this project as well as his academic experience, have been invaluable to me. He also urged me to take initiative on the projects I was implicated in and trusted my judgment on critical issues. In every sense, none of this work would have been possible without him. Furthermore, I would like to thank all my professors and co-supervisors who, during my ten years of study at the department, supported me when needed.

I am also grateful for the support of Lecturers Vera Stavroulaki and Kostas Tsagkaris as well as Dr. George Dimitrakopoulos, Dr. Apostolos Katidiotis, Dr. Yiouli Kritikou, Dr. Panagiotis Theofilakos and the PhD candidates Dionysis Petromanolakis, Marios Logothetis, Nikos Koutsouris, Vlasis Barousis and Manos Michailidis for the interesting discussions and the excellent cooperation we had all this time.

Needless to say, that all this work and academic course would have been impossible to be concluded without the support of my family. I am forever indebted for their undivided support and understanding all these years.

Finally I would like to express my deep love to the only woman of my life, Tonia. Her presence, patience and encouragement throughout the whole course of my work gave me the strength to conclude my PhD dissertation successfully.

Sincerely

Aggelos M. Saatsakis

## ΠΡΟΛΟΓΟΣ

Η συγγραφή της παρούσας διατριβής ήταν μια μακρά και επίπονη διαδικασία η οποία απαιτούσε τόσο προσπάθεια όσο και αφοσίωση. Ωστόσο, παρά τις δυσκολίες κατάφερα να αποκτήσω σημαντικές γνώσεις στον τομέα τηλεπικοινωνιακών δικτύων και υπηρεσιών καθώς μου δόθηκε η ευκαιρία να συμμετάσχω σε πολλά σημαντικά ερευνητικά έργα. Τίποτα όμως από τα παραπάνω δεν θα είχαν πραγματοποιηθεί χωρίς την βοήθεια του Θεού και την έμπρακτη υποστήριξη πολλών ανθρώπων των οποίων η συνεισφορά ήταν σημαντική και αξίζουν ειδική αναφορά.

Αρχικά θα ήθελα να εκφράσω την ευγνωμοσύνη μου για τις προσπάθειες του επιβλέποντά μου, Αναπληρωτή Καθηγητή Παναγιώτη Δεμέστιχα, του οποίου η αφοσίωση καθώς και η ακαδημαϊκή του εμπειρία αποτέλεσαν ανεκτίμητη βοήθεια. Επίσης, με ενθάρρυνε στην λήψη πρωτοβουλιών σε διαφορά ερευνητικά έργα και εμπιστεύτηκε την κρίση μου σε σημαντικά ζητήματα. Επιπλέον, θα ήθελα να ευχαριστήσω τους συνεπιβλέποντες και όλους τους διδάσκοντες του τμήματος οι οποίοι με υποστήριξαν και με συμβούλεψαν σε κάθε φάση των σπουδών μου την τελευταία δεκαετία.

Αισθάνομαι επίσης την ανάγκη να ευχαριστήσω τους Λέκτορες Βέρα Σταυρουλάκη και Κώστα Τσαγκάρη για την υποστήριξη τους καθώς και τους Δρ. Γεώργιος Δημητρακόπουλος, Δρ. Απόστολο Κατιδιώτη, Δρ. Γιούλη Κριτικού, Δρ. Παναγιώτη Θεοφιλάκο και τους υποψήφιους διδάκτορες Διονύση Πετρομανωλάκη, Μάριο Λογοθέτη, Νίκο Κουτσούρη, Βλάση Μπαρούση και Μάνο Μιχαηλίδη για τις ενδιαφέρουσες συζητήσεις μας και για την εξαιρετική συνεργασία μας.

Φυσικά είναι περιττό να αναφέρω πως όλη αυτή η προσπάθεια καθώς και η γενικότερη ακαδημαϊκή μου πορεία θα ήταν αδύνατη χωρίς την υποστήριξη της οικογένειάς μου. Είμαι για πάντα υπόχρεος για την υποστήριξη και την κατανόησή τους.

Τέλος θα ήθελα επίσης να εκφράσω την αγάπη μου στην μοναδική γυναίκα της ζωής μου, Τόνια. Η παρουσία της, η υπομονή της και η ενθάρρυνσή της μου έδωσε την δύναμη για την επιτυχή ολοκλήρωση αυτής της διατριβής.

Με εκτίμηση

Άγγελος Μ. Σαατσάκης

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# 1. INTRODUCTION

## 1.1. Research Area

### 1.1.1. Motivation

The evolution of future radio technologies towards more flexible and reconfigurable radio systems has been influenced from the following factors [1]:

- Advanced user applications and services
- Increasing traffic demand
- Composite wireless networks
- Efficient spectrum utilization

#### 1.1.1.1 Advanced user applications and services

Research areas that strive to understand the users' needs for future wireless systems and how users will interact with devices, systems and applications in the wireless world, determine the development of the underlying technologies. Furthermore, several new advanced service architectures (eg. Internet and ad-hoc network architectures) meet the targets of serving a great variety of services (beginning from the conventional phone calls towards complex scenarios like interactive portals for social networks or seamless provisioning of information) regardless of the user equipment while respecting user's security and privacy.

#### 1.1.1.2 Increasing demand

The increasing growth of mobile traffic in terms of subscribers, data volumes and data rates is one of the most important factors triggering the research of future radio technologies. There are more than 3 billion mobile phone users today. There are estimations that by 2017 there will be 7 trillion wireless devices serving 7 billion users [2]. To meet these expectations with the limited amount of radio spectrum, more flexible ways to share the radio frequencies among multiple services and radio networks are needed.

#### 1.1.1.3 Composite wireless networks

The co-existence of heterogeneous Radio Access Technologies (RATs) motivated the Network Operators (NOs) to build Composite Wireless Networks (CWNs) in order to provide seamless and user transparent access to multiple services decoupled from the radio platform. Moreover, the need for coordination among the different RATs (for spectrum, capacity and energy efficiency) is imposed by the users' sessions (multiple active applications) since it is possible to be served simultaneously by different RATs upon utilization of multiradio user terminal.

#### 1.1.1.4 Efficient spectrum utilization

The target of efficient spectrum utilization is to optimize the radio resources (eg. transmit power, frequency bands, channelization codes, etc) utilization in order to maximize system capacity. To achieve an efficient and coordinated use of the available resources the implemented set of functions will have to support intelligent admission of calls and sessions, distribution of traffic, load balancing, that is, a whole set of strategies that should ensure that the NO's goals in coverage and QoS levels, are met while providing as high as possible overall capacity.

### 1.1.2. Reconfigurable Radio Systems (RRS)

Considering the above, RRS are regarded as networks having high-level structures with the following system components as illustrated in Figure 1-1 [1],[3]. The entities involved in RRS are explained below.

#### 1.1.2.1 Multiradio User Equipment (MUE)

Multiradio user equipment supports reconfiguration capabilities in terms of a) installation and loading of new radio software applications and b) modification of radio parameters in terms of RAT, radio frequency band, modulation etc.

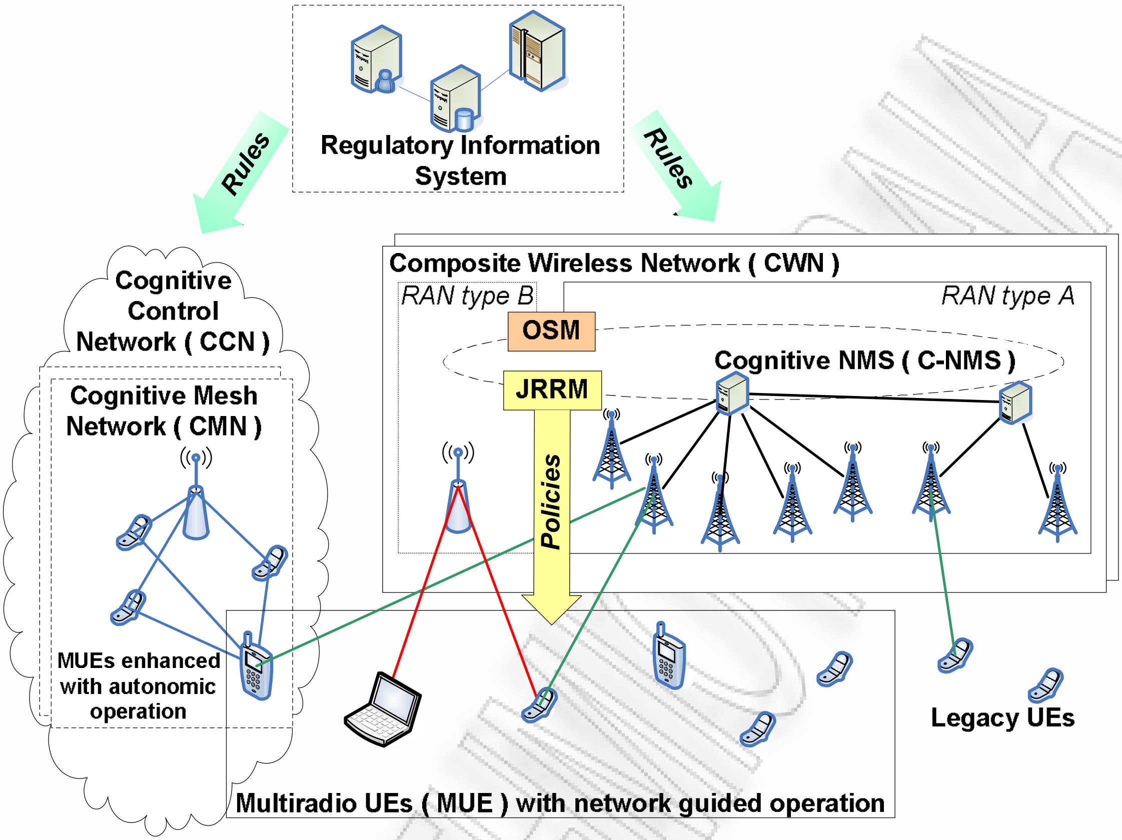

Figure 1-1: Reconfigurable radio systems high level architecture [3]

### 1.1.2.2 Composite Wireless Network (CWN)

The characteristics of Composite Wireless Networks are the following:

- They comprise a set of radio networks, heterogeneous or not
- Each CWN is operated by a single Network Operator (NO)
- The network management system is common for all the radio networks in CWN

Each radio network consists of a) user nodes (eg. MUEs) and b) general access nodes that can be also reconfigurable and may use software defined multiradio technology and are referred to as Reconfigurable Radio Base Stations (R-RBS). Furthermore, some of the radio networks in CWN may be cognitive. Research aspects regarding cognitive radio networks are envisaged to fully expose all benefits that derive from the coexistence and cooperation of versatile range of technologies, such as wide and short area networks.

They use radio frequencies in an agile manner, in which case both user nodes and access nodes deploy a common cognitive radio technology. Other radio networks may use conventional radio technologies and operate on their native frequency bands.

Operator Spectrum Manager (OSM) is an entity that enables the operator to control dynamic spectrum assignment decisions within the CWN. Joint Radio Resource Management (JRRM) is an entity inside C-NMS that enables management of composite radio resources and selection of radio access technologies for user traffic connections.

#### 1.1.2.3 Cognitive Network Management System (C-NMS)

The existence of different RATs in the same environment provides a great amount of network resources that should be efficiently managed in order to adapt better to the traffic load and demand. Network management should consider and exploit all the available network and radio resources in the maximum possible level so as to satisfy user requirements regardless of the environment conditions.

Towards that scope, cognitive networks and the underlying network management functionalities are introduced in order to deal with complex situations. Cognitive networks have the ability to dynamically select the network's configuration, through self-management functionality that takes into account the environment requirements and characteristics, NO's goals and policies, network elements' and users' profiles as well as knowledge and experience that is acquired from previous interactions with the environment and managed through machine learning techniques.

In the light of the above, a C-NMS represents a centralized cognitive management element, which collects traffic load and spectrum usage information from the CWN and allocates traffic to different radio networks in the CWN.

#### 1.1.2.4 Cognitive Mesh Network (CMN)

Cognitive Mesh Networks (CMNs) provide the capability to MUE to use also short range networks to establish ad-hoc and mesh connections among themselves. Considering also the variety of different MUE as well as that multiple CMNs can be active in the same area, each of them serving different group of end-users and services, it easy to understand the necessity of advanced management functionalities in order to address the flexibility introduced by CMNs.

CMNs and CWNs belong to two separate domains in terms of used radio frequencies and RATs. MUEs can connect to both CMN and CWN. Inside CMN domain, MUEs do not act as relay entities towards CWN for others MUEs, while each of them may connect directly to CWN by the appropriate RAT.

### 1.1.3. Towards the Future Wireless World

The evolution of mobile and wireless communications in the last decades resulted in the development of a great variety of new RATs along with new powerful user equipment. Research in this area focuses on RRS searching new ways to integrate the variety of wireless access technologies into composite systems so as to efficiently benefit from this technological evolution.

However, the realization of such communications environment entails great complexity levels for the underlying infrastructure, increasing with the continuous evolution of networking technologies. Therefore, the success of future communication systems calls for advanced management functionality both on the network as well as on the user device side, whilst ensuring decrease in the associated complexity.

The most recent trend in this direction are reconfigurable [2],[4], cognitive systems [5]-[7]. Mechanisms for perception and learning of user and environment information are one of the most important features of cognitive systems. Based on the knowledge and experience obtained through learning, cognitive systems can determine and configure their operation not only in a reactive manner, i.e. responding to the detection of problematic situations, but also proactively, so as to prevent issues undermining the optimal system function.

## 1.2. Dissertation's Contribution

This dissertation deals exactly with the "*Optimization of Cognitive High-Speed Composite Wireless Networks*". In this respect, its main contribution can be categorized at the following topics:

- Design and development of Dynamic Self-organizing Network Planning and Management (DSNPM) platform in the context of CWNs

- Design and development of Context Matching Algorithm (CMA) enhancing DSNPM platform with cognitive management functionalities
- Design and development of Context, Profiles and Policies based Dynamic Sub-carriers Assignment (CPP-DSA) algorithm for intra-RAT configuration
- Platform validation for realizing CWNs

### 1.2.1. Dynamic Self-organizing Network Planning and Management (DSNPM)

As already described, the boom of CWNs was based on the continuous development of several new RATs and their parallel operation at the same service area. However, the target for the NO's, who own such kind of networks, is to deliver services to their subscribers with the most cost efficient way in terms of a) network resources (BSs, spectrum, transmission power etc) and b) OPEX and CAPEX [8]. Reconfiguration capabilities of the radio entities inside CWNs where designed targeted to the provision of the necessary flexibility for dynamic adaptation at the network environment conditions considering traffic, network resources, interference, user requirements, user equipment capabilities and services.

Considering the above, it is easy to understand why the efficient management of CWNs is more than necessary in order to deal with the flexibility they introduce. The target of this kind of network management is not only to achieve the NO's goals (eg. low service delivery cost) but also to serve users with the best possible Quality of Service (QoS) levels. Dynamic Self-organizing Network Planning and Management (DSNPM) platform is an approach for realizing the necessary efficient management needed for CWNs. The input of DSNPM is a) *Context* which reflects the network traffic and interference levels, b) *Profiles* concerning users, TRX and c) *Policies* which derive from the NO. The target of DSNPM is to capture problems or complex situations in the service area and provide the best possible solutions by utilizing inter-RAT and intra-RAT optimization algorithms in order to find the most appropriate solution exploiting all the available network resources.

### 1.2.2. Context Matching Algorithm (CMA)

Despite the fact that DSNPM is capable of providing dynamically the necessary reconfiguration actions, the complexity introduced by the internal optimization algorithms as well as the number of possible solutions that should be checked are the major reasons for high optimization delays. In order to deal with this deficiency, DSNPM is enhanced with cognitive management functionalities as reflected by Context Matching Algorithm (CMA) which is based on pattern matching techniques. The result of this enhancement for DSNPM is the capability to learn from past interactions with the network environment in order to be able to solve future problems based on the experience gained in the past. Thus, DSNPM will be able not only to identify whether the current network situation has been optimized in the past but also to provide directly the decision skipping the time consuming optimization algorithms. Thus, as it is depicted by Figure 1-2, DSNPM may realize C-NMS in the context of CWN of RRS architecture.

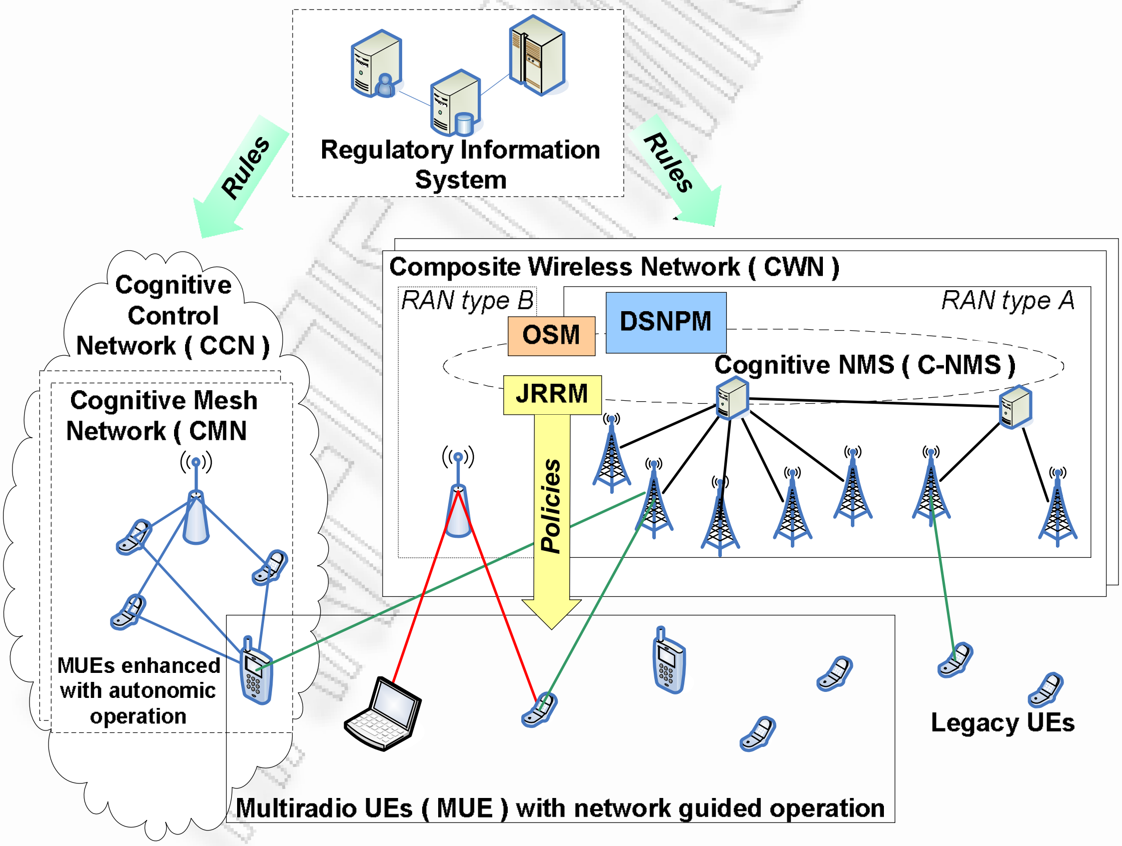

Figure 1-2: DSNPM mapped onto RRS architecture

### 1.2.3. Context, Profiles and Policies based Dynamic Sub-carriers Assignment (CPP-DSA)

The development of RATs based on Orthogonal Frequency Division Multiplexing (OFDM) technology, like LTE [1] and WiMAX [9], raised the need for DSNPM to incorporate also the corresponding optimization techniques. Since DSNPM handles management information it is possible to be considered also by the optimization techniques so as the decisions to be aligned with the goals of the NOs while respecting user requirements and preferences in order to guarantee the best possible user satisfaction.

One of the most important techniques is Dynamic Sub-carrier Assignment (DSA) which targets at finding the optimum number of sub-carriers to assign to each user so as to be served with the maximum possible QoS level. CPP-DSA algorithm was designed to find the best possible sub-carrier assignment to user's active service sessions considering not only the network environment conditions (eg. channel state information) provided by *Context* but also the corresponding user requirements as well as NO's goals provided by the *Profiles* and *Policies* entities of DSNPM, respectively. In this way this algorithm a) introduces fairness in the way that the sub-carriers are assigned and b) is capable to increase the overall system performance by utilizing the available spectrum only where and when it is necessary.

### 1.2.4. Platform Validation

In order to test the efficiency of DSNPM in the context of CWNs, a validation platform was developed for experimentation with real testbeds like the Flexible Base Station (FBS) and FemtoCell (FTC) access points manufactured by Alcatel-Lucent [10] and NEC [11], respectively.

FBS provides the means for DSNPM decisions implementation based on the reconfiguration capabilities provided. Its architecture is designed to provide the capability of dynamic reconfiguration of a) the transceivers' operating parameters based on the RATs they will be activated to and b) the spectrum assigned to each one of the operating transceivers. Furthermore, DSNPM was also connected with FTC cellular access point which is capable of routing voice or data services through legacy wideband connections. Thus, services can be offered at higher QoS levels while the operational cost for a NO is the minimum possible since there is no need for connectivity to other wireless networks. Considering the flexibility and the capabilities that FBSs and FTCs provide, it is feasible for DSNPM decisions to be implemented to the service area so as the CWN to dynamically adapt to the environment conditions.

## 1.3. Dissertation's Structure

The dissertation is structured in chapters, each of which provides a detailed description on the research activities performed with regards to the topics described in sub-section 1.2. A slight description of these chapters is outlined in the sequel.

**Chapter 2** In this chapter an approach for the definition of Functional Architecture (FA) for the management and control of RRSs is provided. The proposed FA includes several functional entities each of which is dealing with specific issues like spectrum management, network management and control, network monitoring etc. Furthermore, the interfaces among the functional entities are described in order to provide a clear view on the necessary interactions not only for collecting information but also to perform the reconfiguration actions as provided by the decision entities. DSNPM, as a decision entity of the FA, is responsible to provide the most appropriate decision considering all possible management information as well as knowledge gained in the past when dealing with similar situations. In a few words, the main contribution of this chapter is the description of how the proposed FA can be applied in the context of CWNs achieving the targets of increasing radio and network resources efficiency.

Research on the FA in the context of RRS, as it is described in this chapter, resulted in the following publications:

- G. Dimitrakopoulos, P. Demestichas, A. Saatsakis, K. Tsagkaris, A. Galani, J. Gebert, K. Nolte, "*Functional Architecture for the Management and Control of Reconfigurable Radio Systems*", IEEE Vehicular Technology Magazine, Vol. 4, No. 1, pp. 42-48, March 2009

- J. Belschner, P. Arnold, H. Eckhardt, E. Kühn, E. Patouni, A. Kousaridas, N. Alonisioti, A. Saatsakis, K. Tsagkaris, P. Demestichas, "*Optimisation of Radio Access Network Operation introducing self-x functions*", accepted to VTC2009 spring, Radio Access and Spectrum Workshop

**Chapter 3** Chapter 3 presents CMA which is an approach for identifying whether current network environment conditions have also been dealt in the past. In this case past knowledge can be exploited for fast and cost efficient network reconfiguration and adaptation. First, there is a presentation of legacy management functionality and the corresponding optimization techniques. Then, there is a general presentation of directions for introducing cognition in the management mechanisms. Finally, the mechanism for context identification is presented in detail. The target of this chapter is to introduce cognitive systems as a direction for addressing the complexity, since it will enable reaching decisions faster by considering also knowledge and experience derived from past interactions of the system with the network environment.

CMA was developed in the context of management concepts for introducing cognition in future communication systems. Research in this field resulted in the following publications:

- A. Saatsakis, P. Demestichas, "*Context Matching for Realizing Cognitive Wireless Network Segments*", Wireless Personal Communications, September, 2009, doi:10.1007/s11277-009-9807-z.
- A. Saatsakis, G. Dimitrakopoulos, P. Demestichas, "*Enhanced context acquisition mechanisms for achieving self-managed cognitive wireless network segments*", in Proc. 17th IST Mobile and Wireless Communications Summit 2008, Stockholm, Sweden, June 2008
- G. Dimitrakopoulos, P. Demestichas, K. Tsagkaris, A. Saatsakis, K. Moessner, M. Muck, D. Bourse, "*Emerging Management Concepts for Introducing Cognition in the Wireless, B3G World*", Wireless Personal Communications, Vol. 48, No. 1, pp. 33-47, Jan. 2009.

**Chapter 4** CPP-DSA algorithm is presented in detail in chapter 4, framed in the context of intra-RAT configuration capabilities of DSNPM. This algorithm considers at the same time channel state information as well as all the available management information for proper sub-carrier assignment. First, the management scheme which incorporates CPP-DSA algorithm is presented. Then, a high level description is provided of the assignment problem that DSA technique is applied to as well as several DSA algorithms trying to solve this problem. Finally, simulation results are provided showcasing the efficiency of management scheme enhanced with the proposed DSA algorithm. The target of this chapter is to present a DSA algorithm which considers also management information and it is necessary for OFDM-based technology networks in CWNs.

DSA techniques attract significant research activities considering the capabilities of OFDM-based RATs. The algorithm described in this chapter is part of the outcome of research in this area which is circulated with the following publications:

- A. Saatsakis, K. Tsagkaris, P. Demestichas, "*Exploiting Context, Profiles and Policies in Dynamic Sub-carrier Assignment Algorithms for Efficient Radio Resource Management in OFDMA Networks*", Annals of Telecommunications journal, doi: 10.1007/s12243-009-0156-4.
- A. Saatsakis, K. Tsagkaris, D. Von-Hugo, M. Siebert, M. Rosenberger, P. Demestichas, "*Cognitive radio resource management for improving the efficiency of LTE network segments in the wireless B3G world*", in Proc. 3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks 2008 (DySPAN 2008), Chicago, USA, Oct. 2008

**Chapter 5** This chapter focuses on the DSNPM implementation in the context of a CWN platform, aligned with the approach of the FA presented in chapter 2. Moreover, the DSNPM incorporates also the algorithms CMA and CPP-DSA that were described in chapters 3 and 4 respectively. The target of this chapter is to study the efficiency of DSNPM and the incorporated algorithms by exploiting the reconfiguration capabilities of FBS and FTC which will be soon available on the market.

The outcome of the implementation of DSNPM as well as its integration with other hardware and software entities of FBS and FTC, resulted in the following publications:

- A. Saatsakis, P. Demestichas, K. Nolte, W. Koenig, "*Flexible base stations and associated management functionality in the B3G world*", in Proc. Software-Defined Radio 2008 (SDR '08) Technical Conference, Washington, USA, October 2008
- A. Saatsakis, Panagiotis Demestichas, Vincent Merat, Christine Le Page, Thomas Loewel, Klaus Nolte, "*Femtocell and Flexible Base Station Cognitive Management*", Indoor and outdoor femtocell workshop (in conjunction with PIMRC 2009)

**Chapter 6** The last chapter circulates the main aspects introduced by this dissertation in the research area of RRS. Furthermore, ongoing challenges are discussed and finally the dissertation is concluded.

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# 2. FUNCTIONAL ARCHITECTURE FOR THE MANAGEMENT AND CONTROL OF RECONFIGURABLE RADIO SYSTEMS

Chapter Outline

Users' expectations towards technology, in terms of quality, service availability and accessibility are ever increasing. At the same time, the wireless world is rapidly moving towards the next generation of systems, featuring cooperating and reconfiguring capabilities for coexisting RATs, so that to cater for advanced service features, provided to users at high data rates and most important, cost-effectively. In this respect, conventional management techniques ought to be replaced by advanced schemes that consider multidimensional characteristics, increased complexity and high speeds. In this chapter a complete management framework is proposed, namely the Functional Architecture (FA). The proposed FA can be deployed in the anticipated future compound communication systems as a means to capture such unfamiliar requirements and to optimize resource management. The fundamentals and the approach followed in the architecture are discussed, and its functionality is investigated.

Keywords: Functional architecture, radio resources management, cognitive network

## 2.1. Introduction

The era of B3G wireless communications is highly heterogeneous, in that it comprises several RATs that need to cooperate with each other [1], [2], such as the Enhanced Data rates for GSM Evolution (EDGE), the Universal Mobile Telecommunications System (UMTS), the High-Speed Downlink Packet Access (HSDPA) and LTE systems specified by 3GPP, WiMAX, mobile 2G/3G networks, Wireless Local Area Networks (WLANs) [3], etc. At the same time, several innovative features, such as the flexible spectrum management [4], as well as Software Defined Radio (SDR) [5] and reconfigurability [6], will characterize future communication systems.

The migration of wireless communications to the B3G era yields a set of stringent requirements to be satisfied, such as the achievement of high QoS levels and resource utilization, as well as increased speed of decisions. However, this situation imposes also upgrades / innovations in the respective management schemes. In particular, having a versatile network environment will require intelligent management techniques, to be able to make best possible use of the available resources. First, management should exploit this versatile landscape (i.e. the availability of alternative RATs). Second, management should be performed in a distributed manner, so as to be fast, scalable and reliable. Third, management shall be attributed with cognitive networking capabilities [7], so as to dynamically select the network's configuration, by taking into account the context of operation (environment requirements and characteristics), goals and policies (corresponding to principles), profiles (capabilities), and machine learning [8] (for representing and managing knowledge and experience).

Framed within the above, in this chapter a FA for the efficient radio and spectrum resource management of the anticipated future compound communication systems is proposed and described in detail. Furthermore, the proposed FA is currently being elaborated within the working group three (3) of the RRS Technical Committee (RRS TC), created by European Standards Telecommunication Institute (ETSI) Board [9] with the aim to study the feasibility of standardization activities related to reconfigurable radio systems (including software defined and cognitive radios). It should be also mentioned that a relevant functional architecture for optimized radio resource usage in heterogeneous wireless networks is currently under standardisation within IEEE [10], [11].

The rest of the chapter is structured as follows. The basic requirements for deriving the proposed FA for B3G management and control are presented first. The detailed description of the basic functional blocks of the architecture, as well as of the interfaces among them, is given in the sequel. Then, an indicative scenario is presented showcasing the FA operation and finally, a potential mapping of the introduced FA on the LTE network and system architecture is attempted.

## 2.2. High-level view of the Functional Architecture (FA)

The proposed FA constitutes an amalgamation of different advanced resource management mechanisms, represented as functional blocks, each of which can be considered as a wrapper to the functions mentioned above. Figure 2-1 depicts a high level view of the functional blocks of FA which are (i) the Dynamic Self-organizing Network Planning and Management (DSNPM), (ii) Dynamic Spectrum Management (DSM), (iii) the Joint Radio Resources Management (JRRM) and (iv) the Configuration Control Module (CCM).

Each of the FA blocks caters for a different family of load and usage scenarios and also depends on spectrum, demand, time and geographical scales. At the management level, DSM provides long and medium term recommendations for the (technically and economically) available amount of spectrum introducing flexible spectrum management scheme. Then DSNPM caters for the medium and long term management decision of reconfigurable network segments, realizing the management domain. At the control level, JRRM exploits at a short term this information in order to optimize the DSNPM decisions in accordance with each user requests, and finally CCM implements all decisions.

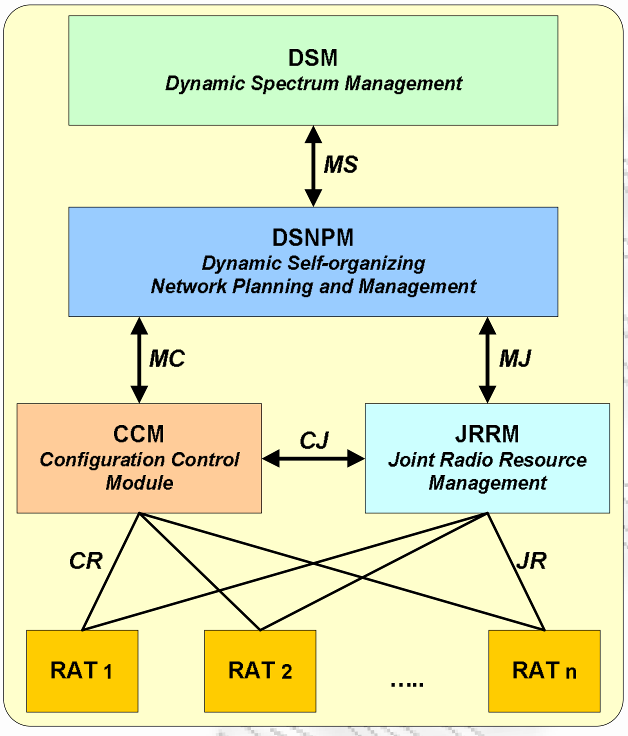


Figure 2-1: High level view of Functional Architecture (FA)

## 2.3. FA detailed description

The following sub-sections describe in more detail the targets of the FA blocks.

### 2.3.1. Dynamic Self-organizing Network Planning and Management (DSNPM)

The heterogeneity of wireless infrastructures, as well as the provision of advanced applications/services entail that management has to address the increased complexity of CWNs. Thus, a great set of the necessary requirements has to be captured and properly analysed so as to derive an appropriate functional architecture that will be characterised by efficient management. In particular, management functionality should address the following requirements:

- Personalization, so as to support various classes of users
- Support of pervasive computing, enabled by the existence of sensors, actuators and WLAN in all application areas

- Context awareness, for efficiently handling multiple, dynamically changing and potentially unexpected situations
- Always-best connectivity for optimally serving equipment and users, in terms of QoS and cost
- Ubiquitous application provision for the applications above, in all the different target environments
- Seamless mobility for rendering the users agnostic of the heterogeneity of the underlying infrastructure, while ensuring the consistency of application provision in the overall service area
- Collaboration with alternate RATs/NOs for contributing to the achievement of always-best connectivity
- Scalability, for responding to frequent invocations of the functionality, due to context changes

The aforementioned requirements for the management of CWNs, result in a set of functions that the FA should support, namely:

- Context acquisition functions for supporting context awareness.
- Profile management for supporting the requirement for personalisation and pervasive computing.
- Policies derivation functions for offering rules necessary for always-best connectivity.
- Decision making for providing the functionality for always-best connectivity.
- Collaboration functions among various technologies and providing connectivity, in a ubiquitous and seamless manner.
- Knowledge acquisition based on learning functionality, which is essential for addressing complexity and scalability.

The objective of the DSNPM functional block is to provide the medium (and long) term decisions upon the reconfiguration actions a network segment should take, by considering certain input information, and by applying optimization functionality, enhanced with learning attributes. Figure 2-2 depicts its overall description.

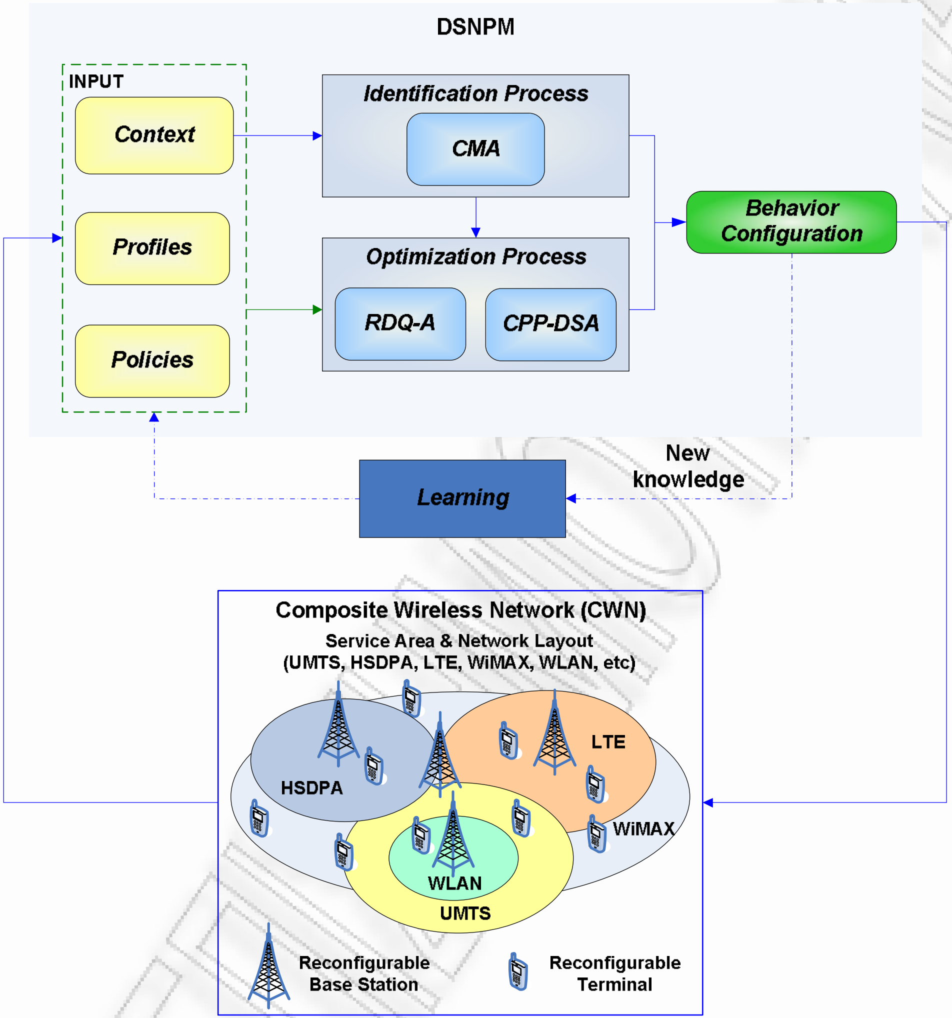


Figure 2-2: Dynamic Self-organizing Network Planning and Management (DSNPM) overview

Regarding the DSNPM input, first, *Context* functionalities are responsible to collect the status of the elements of the CWN, and the status of their environment. Essentially, each element uses monitoring and discovery (sensing) mechanisms. Monitoring mechanisms provide, for each element and a specific time period, the traffic requirements, the mobility conditions, the configuration used, and the QoS levels offered. Discovery mechanisms provide information on the QoS that can be achieved by alternate configurations. Context information will be used from the system not only to update network Key Performance Indicators (KPIs) values but also to address possible problematic situations. *Profiles* input provide information on the capabilities of the elements and terminals of the CWN, as well as the behaviour, preferences, requirements and constraints of users and applications. Furthermore, it designates the configurations that will be checked for network elements and terminals. For users, it designates the applications required, the preferred QoS levels and the constraints regarding costs. This information is necessary during the optimization process in order to decide on the most appropriate reconfiguration. Finally, *Policies* input adhere to the fact that management decisions should not only be feasible from technological perspective but also have to be aligned with NO's strategies. Policies designate rules that should be followed during context handling. Sample rules can specify allowed (or suggested) QoS levels per application, allocations of applications to RATs and assignments of configurations to transceivers.

Regarding the DSNPM decisions, they are targeted at producing a feasible network reconfiguration that can be categorized at the following levels:

- Application layer: guaranteed QoS levels assignment to applications
- Network layer: traffic distribution to specific transceivers and corresponding RATs as well as network entities interconnection
- Lower/PHY layer: Number of network element transceivers involved in decisions, RATs to be activated, spectrum selection and radio parameters configuration per RAT

The optimization process exploits RATs capabilities in terms of achievable bit rates and coverage, so as to provide users with the maximum possible QoS level. To do so, several approaches are envisaged. One approach would be to find the best configurations that maximize an objective function, which takes into account the user satisfaction that derives from the QoS levels offered, the cost at which they are offered, and the cost of the reconfigurations. The algorithms used for the optimization process of DSNPM are a) RAT Demand and QoS Assignment (RDQ-A) [12] which is targeted to provide inter-RAT configuration decisions and b) CPP-DSA which is targeted for intra-RAT configuration and will be presented in chapter 4, as part of the dissertation contribution.

DSNPM is also enhanced with learning attributes that will yield knowledge and experience. The input information concerning the current status of the service area will be processed so as DSNPM to gain knowledge on the necessary information needed to characterize in a unique way the current context as well as the corresponding solution, provided by the optimization process. Furthermore, learning can be gained also regarding profiles management, since certain user classes may be better served via a specific RAT, as well as policy derivation where past NO's policies can be stored so as to be available for future situations. Knowledge and experience may help DSNPM to predict problems and act proactively to solve them.

The identification process enhances DSNPM with the capability to identify previously tackled situations and their suitable solutions [13], [14]. The target of this process is to find the closest past context compared to the currently captured one. In case of successful context matching the corresponding past decision will be retrieved and will be applied to the network skipping the optimization process. However, if there is no similar past context in order to exploit its past decision, the optimization process will be triggered to provide the most appropriate decision. The algorithm used for that purpose is CMA and it will be described in chapter 3, as part of the dissertation contribution.

Finally, regardless of the origin of the decision (identification or optimization process), Behaviour Configuration entity is responsible to translate the decisions' details into specific reconfiguration actions. In particular, the decision may affect a) the application layer, since the target is to achieve the best possible QoS levels and b) the Medium Access Control (MAC) layer since the decisions include the set of network elements that either should be activated or deactivated as well as the RATs that should be activated and the corresponding operating parameters like transmission power, modulation schemes, channels bandwidth etc. Based on the reconfiguration capabilities of the network elements and user equipment, the decisions for the proper network adaptation to the environment conditions will be applied with the minimum possible delay and cost.

### 2.3.2. Dynamic Spectrum Management (DSM)

Cellular networks experience time and spatial varying traffic demands. Nevertheless, NOs generally dimensioned their communication networks using Fixed Spectrum Allocation (FSA) techniques to cope the "busy hour" traffic, which is the time of the peak use of the network resources. Such fixed spectrum allocations lead to low overall spectral efficiency and brings about the apparent spectrum scarcity. In future, the traffic demand is expected to be non linear and consequently put more pressure on the limited spectrum. In DSM, spectrum is allocated dynamically based on the temporal and spatial traffic demands.

The DSM functional block try to achieve an efficient utilisation of the scarce and valuable spectral resources, trying to maximise spectrum reuse amongst users, cells and systems while ensuring that mutual interference between them remains at acceptable levels. Spectrum management in wireless networks is a complex task involving number of functional activities of one or several NOs. The DSM actions of the proposed FA fall in the realm of medium and long term management of spectrum in RRSs. Its main responsibilities are:

- Evaluation of spectrum occupancy.
- Detection of long-term available spectrum bands for reassignment and sharing/trading of spectrum.
- Derivation of economical parameters for spectrum trading.
- Provision of a spectrum framework (available amount of spectrum) to RATs, based on evaluation of spectrum occupancy and system-level parameters.

It should be noted that a centralized operation of DSM is considered, meaning that DSM is located in some node having control over a set of network elements. Figure 2-3 depicts the envisaged functions that are in line with the overall requirements.

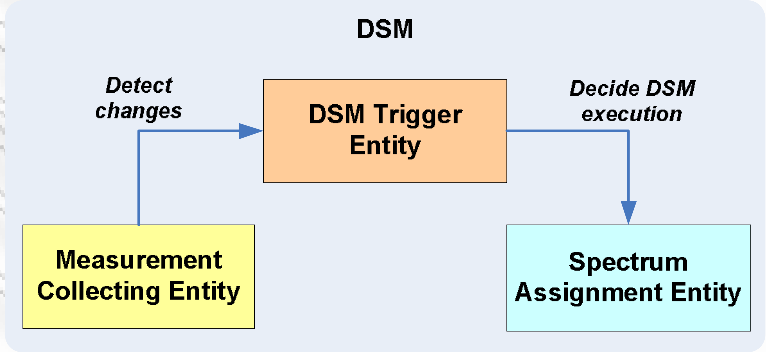


Figure 2-3: DSM functional block approach

The measurement collecting entity is responsible of collecting the measurements from the different nodes (i.e. terminals and cells) and existing in the heterogeneous environment. The DSM trigger entity is responsible of detecting the relevant changes in the traffic distribution and to decide the instant when the allocation algorithm should be executed while the spectrum assignment entity is responsible of deciding on the spectrum framework to be suggested to the various RATs during the reconfiguration process.

### 2.3.3. Joint Radio Resource Management (JRRM)

JRRM applies different functionalities to realise a common radio resource usage within different entities of a CWN as well as different resources such as radio frequency and transmission power. Depending on the actual strategy different functionalities can be employed such as traffic load shifting/balancing or re-assignment of resources. Furthermore, JRRM is responsible for bandwidth and power allocation within each sector of a planned cellular network and performs traffic shaping in order to exploit unutilized capacity at neighbouring cells or cell clusters, and could also potentially re-assign spectrum allocated to different RATs.

In particular, its main functionalities are the following:

- Access Selection, which reflects the decision upon the best radio access for (or even in) the mobile terminal based on the requested QoS (Bandwidth, max. delay, Real-time / non real-time), radio conditions (e.g. abstracted signal strength/quality, available bandwidth), access network conditions (e.g. cell capacity, current cell load), user preferences, and network policies
- Neighbourhood Information provision for efficient discovery of available accesses. This may include information on radio access technology, cell location, size, capabilities, as well as other dynamic data
- QoS/bandwidth allocation/admission control (per user session or connection based on the requested QoS of the users application(s))
- Provision of mobility and resource management directives/constraints

JRRM is a functional block that is in general distributed between the network and the user terminal. On the network side, JRRM collects information on the capacity, load and status of the different cells via a unified interface from the underlying RATs, as will be shown in the sequel. On the terminal side, JRRM is aware of the radio conditions of the active link(s) as well as from potential, measured candidate links. After sending the information on radio conditions as well as on requested QoS to the network side, the network can decide on which access to use and send a handover command to the user terminal. Alternatively, JRRM on the network side may provide policies to the terminal specifying when to utilize the available accesses. In addition, JRRM on the terminal side also takes the decision on the initial access selection (Idle-State Access Selection).

JRRM functions operate on a short term to decide the appropriate radio access technology that a terminal should be connected to in accordance with the desired services.

#### 2.3.3.1 RAT selection and Admission control

In a heterogeneous scenario framework, the decision to which RAT a given service request should be allocated becomes a key JRRM issue. Different criteria (service type, load conditions, etc) will have to be consider to accomplish this RAT selection with the final purpose of enhancing overall capacity, resource utilisation and service quality. From the customer side the scenario heterogeneity also affects since users may access the requested services with a variety of terminal capabilities (single or multi-mode) and different market segments can be identified (business or consumer users) with their corresponding QoS levels. Thus, the choice of the proper RAT and cell is a complex problem due to the number of variables involved in the decision-making process.

The conventional admission control is designed for each access system working independently among coexisting access systems and RATS. In the cooperating environment foreseen in the heterogeneous network scenario, a joint session/call admission control must be defined. This procedure will consider neighbour RAT system load to decide to which RAT the traffic is diverted. Thus, the traffic stream could be routed alternatively through the cooperating networks according to the constraints and the capacity of each.

#### 2.3.3.2 Vertical handover and load balancing

After the initial RAT selection decision, vertical handover is the procedure that allows switching from one network to another. The successful execution of a seamless and fast vertical handover is essential for hiding to the user the underlying enabling infrastructure. In general terms, vertical handover procedures may be useful to support a variety of objectives, such as:

- Avoiding disconnections due to lack of coverage in the current RAT.
- Blocking due to overloaded network.
- Possible improvement of QoS by changing the RAT.
- Support of user's and NO's preferences in terms of RATs usage.
- Load balancing among RATs.

## 2.4. Interfaces Description

FA's operation is realized by means of information exchange among its functional blocks. To do so, several interfaces are envisaged.

### 2.4.1. MS interface between DSNPM and DSM

MS is the interface between DSNPM – DSM. Through MS interface, DSM may provide to DSNPM the amount of available spectrum for the different RATs, unoccupied spectrum bands, spectrum opportunities, as well as the cost of service provision. DSNPM may send requests to DSM to request information on spectrum usage. DSM may also send notifications to DSNPM to inform about changes of the spectrum usage policies.

A summary of the considered elementary procedures is provided below:

*Spectrum Information* This procedure is used in order to request information on a certain spectrum, e.g. if it is allowed to use the spectrum, if it is a licensed or unlicensed etc. First, DSNPM sends the request to DSM providing the intended RAT and a list of frequency bands under consideration. Then DSM, as part of the response, sends the administrative status for each of the requested bands.

*Spectrum Assignment* This procedure is used to request a spectrum assignment from DSM. DSNPM sends the request to DSM providing the requested channel width, the time at which the assignment is required, the intended use and, optionally, the currently used frequency band and the geographical area for which the assignment is requested. DSM response includes the assigned bands with, optionally, permitted RATs.

*Spectrum Usage* This procedure provides information about the current spectrum usage to DSM. The information about the spectrum usage could be retrieved from the BSs configuration information and/or from spectrum measurements by utilizing sensing techniques. DSNPM request to DSM includes information on the load status in the reported frequency bands.

*Channel Reservation* Channel reservation is a pre-reservation procedure for spectrum channels allocated by DSM. DSNPM request to DSM includes the desired frequency bands. DSM informs DSNPM, by the corresponding response, about the pre-reserved channels and, optionally, the maximum pre-reservation time.

*Channel Allocation* This is the allocation procedure for pre-reserved spectrum channels. DSNPM sends the appropriate request to DSM with the frequency bands to be allocated. Next, DSM response is sent to DSNPM with the result of the allocation for each frequency band. Finally, DSNPM confirms to DSM the outcome of the allocation.

### 2.4.2. MC interface between DSNPM and CCM

MC is the interface between DSNPM – CCM. Using this interface DSNPM provides to CCM information on the network segment configurations in terms of RATs and spectrum to the available transceivers, BS configuration, as well as other configuration parameters, in order to be implemented.

A summary of the considered elementary procedures is presented:

*Configuration Notification* This procedure is used when the CCM informs DSNPM about the current configuration of the managed BSs. This may be performed according to a predefined schedule or after changes in the configuration occurred. CCM sends a request to DSNPM reporting about configuration changes made in one or several BSs while DSNPM acknowledges with the corresponding response message.

*Configuration Request* This procedure is used when DSNPM asks for specific configuration information parameters from the CCM. DSNPM sends the appropriate request to CCM providing the list of cells and/or network segment together with the identifiers of the required parameters. CCM replies with the requested parameter values.

*Reconfiguration Request* DSNPM requests reconfiguration of specific parameters, by CCM. DSNPM provides the list of cells and/or network segment with the old and new parameter values in question. CCM sends back the appropriate message confirming the reception of the request.

*Reconfiguration Execution* It is utilized by CCM in order to inform DSNPM about the execution of the previously requested reconfiguration. CCM sends the appropriate request to DSNPM providing the list of reconfigured cells and/or network segments together with the old and new values of the modified parameters. DSNPM sends back a message to confirm the reception of the notification.

*Spectrum Channel Activation* DSNPM commands the CCM with this procedure to change the deployed channels. DSNPM sends the appropriate request to CCM providing the BS and/or transceivers as well as the frequency band in question. CCM replies by a message confirming the reception of the request.

### 2.4.3. MJ interface between DSNPM and JRRM

MJ is the interface between DSNPM – JRRM. JRRM sends to the DSNPM information on the current context, i.e. the amount of resources used in each RAT and cell as well as other relevant context and status information.

Summary of the considered elementary procedures:

*Context Notification* This procedure is used by JRRM to inform DSNPM about the current context of the network. JRRM sends a message to DSNPM providing measurement results related to a number of BSs and/or transceivers. DSNPM acknowledges the data to JRRM.

*Context Request* DSNPM requests for specific context information from JRRM by utilizing this procedure. The DSNPM sends the appropriate request to JRRM providing the list of BSs and associated data items of interest. The requested context data are sent back to the DSNPM by JRRM with the corresponding response message.

*Unsolicited Resource Usage Report* This procedure informs DSNPM about the current context of the network, e.g. the average usage of resources. The procedure applies in case of a scheduled or an event driven reporting is agreed. JRRM sends the necessary message to DSNPM reporting the usage states for a list of cells and/or network segment.

*Resource Usage Report* This procedure is triggered by DSNPM in order to immediately obtain the current context of the network (which can be either fully or partially specified), e.g., the average resource usage. DSNPM sends a well specified request to JRRM providing the list of cells and/or network segment for which the report is requested. JRRM responses to DSNPM by sending back the requested usage states.

### 2.4.4. JR interface between JRRM and RAT

JR is the interface between JRRM – RAT. This interface is used to report information on the resource status such as cell load or measurements of the current active links as well as candidate links to JRRM. Moreover, this interface is also used on the terminal as well as on the network side. More specifically, on the terminal side JRRM may request measurements of the link performance from the underlying RATs. The underlying RATs may then execute the measurements and report the results back. On the network side, the same or similar information about the link performance may be exchanged between the underlying RATs and the JRRM. Additionally, this interface shall be used on the network side to exchange information about the resource usage in the network, e.g. cell capacity and current cell load.

Summary of the considered elementary procedures:

*Cell Registration* This procedure is used for the registration of a cell and/or transceiver after start-up of an access point or a BS towards JRRM. The RAT sends a request to JRRM providing the corresponding registration action and the cell description. JRRM sends back a message confirming the request.

*Update Cell Information* JRRM is informed about the cell information, e.g. the actual cell load. This procedure may be executed periodically or when some thresholds have been crossed. The RAT sends a message to JRRM providing the cell status in question. JRRM sends back the response message confirming the request.

*Pilot Channel Downlink Broadcast Configuration* This procedure is used on the network side to configure a downlink only pilot channel on which to broadcast information. JRRM sends the appropriate message to the RAT providing the cell description. The RAT sends back the corresponding message confirming the request.

*Pilot Channel Info Notification* JRRM is informed from the terminal side regarding the pilot channel information received e.g. via a broadcast/downlink only pilot channel. The RAT sends a message to JRRM providing the cell description received via pilot channel.

*Request to listen for Pilot Channel Info* This procedure is used in a mobile terminal to start or stop sending pilot channel information from the underlying RAT. Such information shall be reported via a Pilot Channel Info Notification as described above. Depending on the implementation, these notifications may also be reported without such a request.

### 2.4.5. CJ interface between CCM and JRRM

CJ is the interface between CCM – JRRM. JRRM provides CCM with all necessary information for the implementation of reconfiguration at the control level, following the JRRM decisions.

Summary of the considered elementary procedures:

*Offload Traffic* This procedure is used by the CCM to instruct JRRM to offload all traffic from a given cell and/or transceiver. CCM sends a message to JRRM providing the list of cells and/or transceivers to be offloaded. JRRM replies with the corresponding message when the operation has been completed.

*Protocol Reconfiguration Execution* It is used to describe the communication of the protocol reconfiguration to be executed by the CCM entity at the mobile device. JRRM sends the request to CCM providing the name of the protocol component to be replaced.

*Reconfiguration Management* This procedure is used to check whether the reconfiguration request can be managed by the JRRM entity residing on the network side. CCM sends the appropriate message to JRRM providing the list of the old and new parameter values in question. JRRM responds with a message confirming or refusing the request.

### 2.4.6. CR interface between CCM and RAT

CR is the interface between CCM – RAT. This interface is used for information retrieval from the different RATs, in order to be compliant with the implementation of configurations at the control level from CCM. This interface is also used by the underlying RATs to report the current configuration of the radio applications of a BS or on the terminal side as well as the reconfiguration capabilities to the CCM. Moreover, information regarding which RATs and what spectrum bands are supported by the transceivers, etc. may be included.

Summary of the considered elementary procedures:

*Device Registration* This procedure is used for the registration of a device towards CCM. The RAT sends the appropriate request to CCM providing the corresponding registration action and the device description. CCM confirms the request reception.

*Reconfiguration Request* CCM initiates a reconfiguration of the underlying RAT. CCM sends a reconfiguration message to the RAT providing the list of the requested configuration changes. The RAT acknowledges the request reception.

## 2.5. Indicative FA Operation

This sub-section presents an indicative use case, for exemplifying the FA's operation. Figure 2-4 depicts a scenario for decisions regarding the reconfiguration of a BS.

In the beginning, the BSs supporting RAT 1, RAT 2 ... RAT n, register themselves and their cells to JRRM and CCM, via interfaces JR and CR, respectively. JRRM configures load measurement in the different RATs and evaluates the load reports (again using interface JR). In a short term scenario, JRRM reacts on a load imbalance with handover commands for selected terminals in order to have an optimal network performance (informing CCM via interface CJ). However, at some time, JRRM may detect that the network configuration could be improved, e.g. a cell in RAT 1 has in average a very high load while another cell in RAT 2 is nearly not used because most terminals do not support RAT 2.

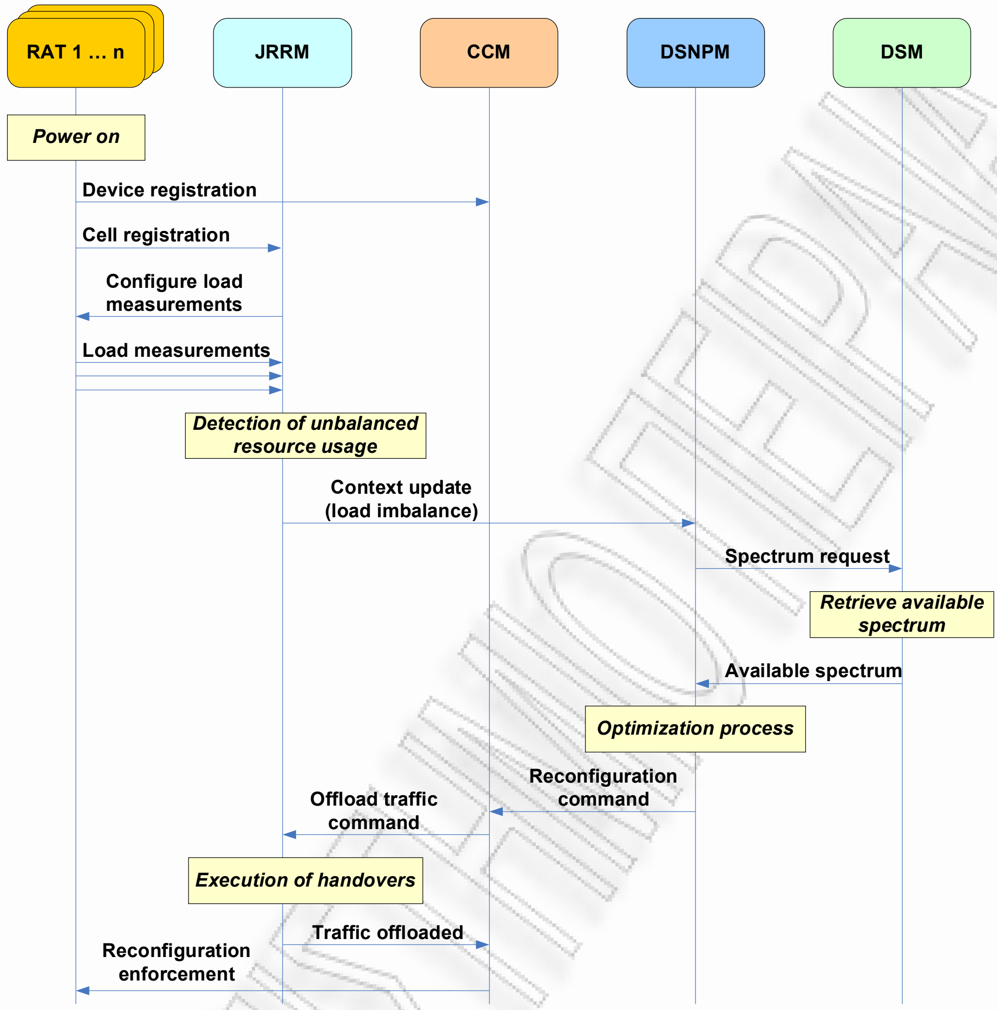


Figure 2-4: Indicative use case message sequence

In this case, JRRM informs DSNMP on the load imbalance with a context update, via interface MJ. DSNPM checks with the DSM the availability of additional (or different) spectrum (interface MS). After reception of the available spectrum framework (interface MS), DSNPM initiates the optimization process and decides on the reconfiguration of the cell in RAT 2. The DSNPM decision regarding a RAT 2 cell can be one of the following:

- Change spectrum parameters of RAT 2
- Change the operating RAT (e.g. from UMTS to WiMAX) while spectrum parameters remain the same
- Change both operating RAT and spectrum parameters

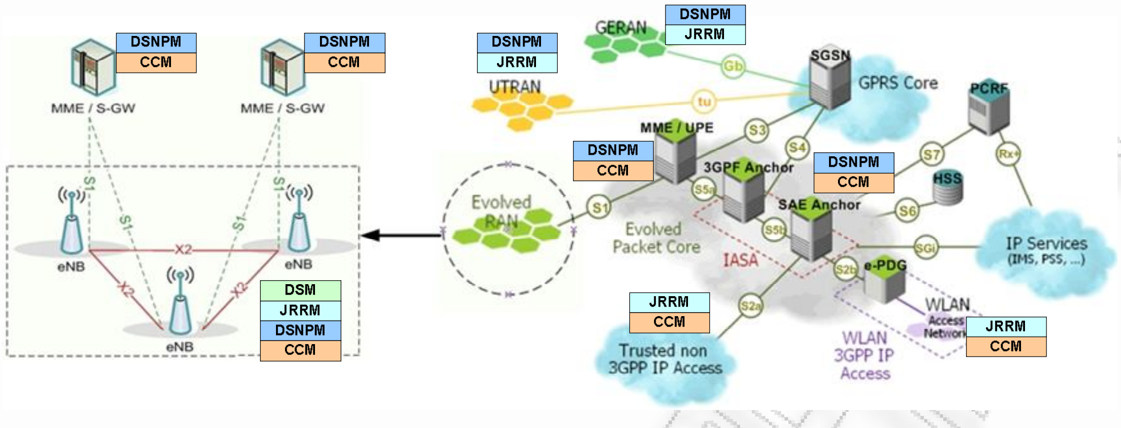
In the case of any of the above decisions, DSNPM will send the appropriate reconfiguration command to CCM (via interface MC), which should execute the reconfiguration for the selected cell in RAT 2. However, in order not to interrupt ongoing sessions, JRRM will be instructed to shift all traffic from the selected cell to other cells. After this is done, the reconfiguration will be executed.

Regarding the introduction of cognition in such cases, as described in sub-section 2.3.1, DSNPM operates on the basis of a well specified learning procedure, based on the abilities (i) to store information about past contexts and decisions and (ii) to identify whether a currently addressed context resembles a past one. Each time that DSNPM captures a context from JRRM, it tries to identify whether this context has already been addressed in the past. In case that there is a match, DSNPM will retrieve the solution that decided in the past skipping the - time consuming - optimization procedure. However, in case that there is no successful match, the optimization procedure will be triggered and the management and control system will wait until the decision is reached. In our use case, assuming that the context was captured by DSNPM for a first time, by the end of the optimization procedure the context along with its corresponding decision will be stored to DSNPM "memory". In case that the context is captured again in the future, DSNPM will identify that this context has already been addressed in the past and the corresponding decision will be retrieved directly from DSNPM "memory". Thus, the message sequence in this case will be the same as in Figure 2-4, however this time the optimization process part will be faster compared with the first time that the context was addressed.

## 2.6. FA mapping on LTE Architecture

An attempt to map the proposed FA to a new and promising system architecture is carried out in this sub-section. Figure 2-5(a) depicts the LTE network architecture [15].

The Evolved Universal Terrestrial Radio Access Network (E-UTRAN) consists of evolved Node-Bs (eNBs), while each eNB is connected to the Evolved Packet Core (EPC) network (parts of which are the Mobility Management Entity – MME and the Serving Gateway – S-GW).



(a) (b)

Figure 2-5: (a) LTE network architecture [15], (b) LTE system architecture [15],[16]

The target of MME is to monitor the mobility aspects that derive from the environment and provide them to management and control entities while the S-GW is responsible to provide access to the network services. Furthermore, LTE's eNB is responsible to host radio resource management functions (Radio Bearer Control, Admission Control, Connection Mobility Control, etc).

Figure 2-5(b) depicts the LTE system architecture [15], [16]. The Home Subscribing Server (HSS) stores the user profiles and it is also responsible for the user authentication procedure. The Policy and Charging Rules Function (PCRF) is responsible for network policies and user charging. The Packet Data Network Gateway (PDN GW) provides connectivity between the User Equipment (UE) and external packet data networks and is responsible to perform policy enforcement, packet filtering and charging support.

A possible FA's mapping on the LTE network and system architecture is shown also on Figure 2-5. More specifically:

- DSM is located on eNBs in order to be able to evaluate spectrum occupancy and system level parameters, detection of available spectrum etc
- DSNPM is located on eNBs and also in higher management level parts like MME, S-GW and Evolved Packet Core

- JRRM is typically located in the eNB, but parts of it can also be located more centrally. JRRM knows all cells and their resource status (e.g. cell load). Additionally, the terminal contains also JRRM functionality. This functionality performs the initial access selection in the idle state, monitors the link performance and makes the access selection in the connected state
- CCM is necessary on eNBs in order to perform the reconfiguration actions. Moreover, CCM is needed wherever management or control actions are decided from DSNPM and JRRM accordingly. Additionally, CCM is also located in the terminals, so as to enable them to implement reconfiguration decisions

## 2.7. Conclusions and Future Work

Wireless service offerings and capabilities constantly increase and the communication systems delivering them move towards CWNs, which can be efficiently realized by means of RRSs. However, this requires significant alterations in the way networks are managed and controlled. This chapter has presented a FA for the management and control of CWNs in the context of RRSs. The proposed FA will help to increase radio and spectrum resource efficiency by introducing a hybrid approach where different mechanisms cater for short, medium and long term radio and spectrum management and control in versatile geographical regions. In addition, the FA will need to support the implementation of various business models in order to make reconfiguration implementation mechanisms efficient. This last statement raises the need for standardization [9], constituting a promising step towards a holistic definition of such spectrum and radio resource optimization mechanisms.

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# 3. CONTEXT MATCHING FOR REALIZING COGNITIVE WIRELESS NETWORK SEGMENTS

Chapter Outline

Future wireless communication systems will be composed of different RATs in order to satisfy all user needs in services. The coexistence of many RATs in the same environment needs advanced network management systems in order to ensure efficient resources utilization while achieving the best possible QoS levels. Management functionality in the context of CWNs will have to solve complex problems, due to the existence of versatile options for satisfying stringent requirements, under difficult environment conditions. The introduction of cognitive systems in CWNs is a direction for addressing the complexity, as it will enable reaching decisions faster and more reliably, by considering also knowledge and experience derived from past interactions of the system with the network environment. This chapter presents an approach for identifying whether a context, encountered by the network segment, has also been dealt in the past. In this case context knowledge can be exploited for fast and cost efficient network reconfiguration and adaptation to the environment conditions.

Keywords: Cognitive networks, management functionality, pattern recognition, network adaptation

## 3.1. Introduction

As already stated in the previous chapters, the CWNs landscape will be comprised by a plethora of RATs like EDGE, UMTS, HSDPA, LTE, WLAN and WiMAX while the NOs will own heterogeneous infrastructures and rely on different RATs, in order to satisfy user and service requirements, often under difficult environment conditions [1].

One of the most important characteristics of a CWNs is the reconfiguration capabilities of the network resources in order to be properly adapted to the network environment conditions. BSs can be reconfigured through software enabled reconfigurations including changes like the operating RAT and/or frequency band. Furthermore, user equipment has also reconfiguration capabilities in order to be aligned with the allocated BS configuration. Figure 3-1 depicts a typical wireless network segment (i.e., subset of the overall infrastructure of CWNs) of a NO. It comprises several access points, respectively, which can operate a specific RAT or others with software-defined-radio capabilities. The latter have the ability to change the RAT operated on their transceivers, by activating the appropriate software on the hardware (one RAT can be operated at a time).

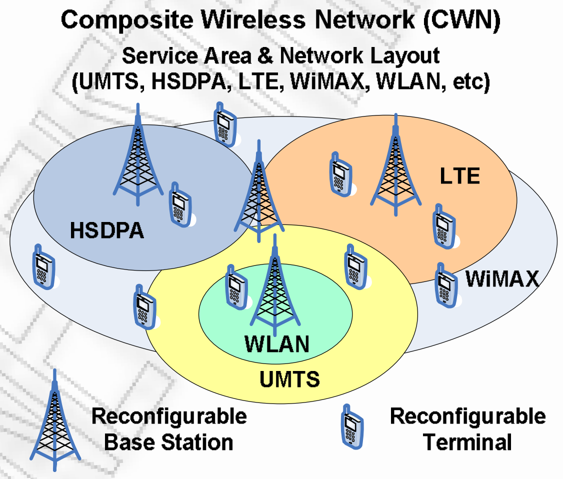


Figure 3-1: Wireless network segment of CWN infrastructure

The target of each NO is to provide network services to the users at the best possible QoS level in the most cost efficient manner [2] ,[3]. In order to achieve this target, advanced management functionality is more than necessary. The existence of different RATs in the same environment provides a great amount of network resources. However, while the environment conditions are continuously changing the network resources should be also reconfigured in order to adapt better to the traffic load and demand. Management functionalities, as introduced by DSNPM, should exploit all the available network and radio resources in the maximum possible level so as to satisfy user requirements regardless of the environment conditions. Network optimization, which is one of the most important targets of DSNPM, should find the most appropriate network configuration in terms of feasibility, effectiveness and cost. However, several efficient legacy management functionalities [4], [5], [6], [7], [8], suffer from time consuming procedures. The reason for that is twofold. The first one is the large number of potential solutions for the network and the second is the complexity introduced by checking each one of them.

An option for handling such complex situations is to introduce cognitive systems, as described in [9], [10], [11], [12], [13], for CWNs infrastructures. In general, cognitive systems determine their behaviour, in a reactive or proactive manner, based on the external stimuli (environment aspects), as well as their goals, principles, capabilities, experience and knowledge. In the case of cognitive networks, this definition can be translated as the ability to dynamically select the network's configuration, through self-management functionality that takes into account the context of operation (environment requirements and characteristics), goals and policies (corresponding to principles), profiles (capabilities), and machine learning [14] (for representing and managing knowledge and experience). Cognitive systems (the relevant self-management functionality) may be introduced at the level of the terminal, access point or network segment (set of access points).

This chapter contributes to the development of self-management functionality, in the context of DSNPM, for cognitive wireless network segments in CWNs infrastructures. In particular, an approach for the identification of whether the context currently encountered has also been addressed in the past is presented. In this way there can be exploitation of potential experience and knowledge on how the context was handled. The approach for this chapter is the following. First, there is a presentation of legacy optimization functionality targeted to wireless network segments ([8]). Then, there is a general presentation of directions for introducing cognition in the management functionalities of DSNPM. Finally, there is presentation of the mechanism for context identification. The problem is formally stated and solved by means of pattern matching techniques. Indicative results show the benefit from this scheme.

## 3.2. Why Cognitive Networks?

The advent of reconfigurable and adaptive networks in the context of CWN systems cannot guarantee lower cost and better QoS levels to the users without proper network management functionalities targeted to that scope. Furthermore, management functionalities except from technological constraints and capabilities, should also take into account NOs policies and strategies in order to provide optimized network configurations while respecting operator's business visions.

Considering the target of management functionalities of DSNPM (i.e. the provision of efficient, feasible and optimum network configurations exploiting available network resources while respecting user profiles and NO policies), it is quite easy to understand why this is a complex task introducing time consuming procedures. However, when a problem is addressed to the service area it should be solved the fastest possible in order to keep network Key Performance Indicators (KPIs) in acceptable levels and keep the users satisfied for the services they experience. Thus, fast network adaptation to the environment changes should be characterized from faster and less complex procedures. The introduction of cognitive wireless network segments tries to achieve this target.

The target of DSNPM for cognitive wireless networks is to exploit the knowledge obtained by the system from past interactions. The main idea behind cognitive management is twofold. The first is that the system is able to store information about problems and their solutions addressed in the past and second, is the ability to identify whether a problem currently addressed is similar to an older one that its solution is already available. In this way, the overall procedure is less complex due to the limited number of choices that should be checked and the network adaptation is performed faster. The subject of this chapter is to present this very procedure where a) the necessary information is stored to the system and translated to knowledge and b) the current network conditions captured from the service area can be matched with past conditions, using pattern matching techniques in order to decide whether a known solution can be applied or not.

The approach presented in this chapter contributes to the introduction of cognitive systems in the CWNs. The proposed scheme can inter-work with general context acquisition mechanisms presented in [15], [16] as well as discovery mechanisms introduced in [17], which can be sensing-based as described in [18] ,[19] and/or pilot channel based as in [20]. Context-acquisition and discovery mechanisms provide information on the available networks and on their QoS capabilities, which are input to the proposed scheme. Finally, the proposed scheme can readily complement network selection (decision-making) strategies, which can be general policy-based as described in [6], autonomic as presented in [21] ,[22] and/or collaborative as proposed in [23]. The complementary part of our scheme lies in the acquisition of knowledge from the basic information provided by the context-acquisition/discovery mechanisms, and in the exploitation of the knowledge in the decision making.

## 3.3. DSNPM Legacy Optimization Process

As already stated in sub-section 2.3.1, DSNPM optimization process includes the RDQ-A algorithm which is targeted for inter-RAT optimization [8]. It is of great importance to remind that the optimization procedure is responsible to produce a feasible network configuration after the information about context, profiles and policies, available to DSNPM, are taken into account. The solution of the RDQ-A algorithm consists in new reconfiguration actions, i.e. new allocations: (a) of available RATs to transceivers, (b) of demand (users) to transceivers and (c) of demand (users) to QoS levels. The solution method for obtaining the desired output takes part in four phases, each of which corresponds to one of the three aforementioned allocations (solution triplet) plus the final decision/selection phase.

In general, the strategy followed in RDQ-A algorithm is to find the best configuration (solution triplet) that maximise an objective function, which takes into account the user satisfaction, resulting from the allocation of applications to QoS levels, the cost at which QoS levels are offered and the cost of the reconfigurations.

The target of this procedure is to find the configuration that maximizes most the following objective function:

$$OF = \sum_{i \in U_t} \left[ u_{s_i,q_i} - c_{s_i,q_i}\left(l_i, r_{t_i}\right) \right] \tag{3.1}$$

where $u_{s_i,q_i}$ is the utility volume of user $i$ experiencing service $s_i$ at QoS level $q_i$ and $c_{s_i,q_i}\left(l_i, r_{t_i}\right)$ is the reconfiguration cost for user $i$ experiencing service $s_i$ at QoS level $q_i$ while being in location $l_i$ and served by transceiver $t$ through RAT $r_t$. The term "utility" borrowed from economics [24] presents the degree of user satisfaction gained from the consumptions of network resources. From this point, it is quite easy to understand that users are experiencing services at higher QoS levels along with the increment of the objective function while the overall reconfiguration cost is the minimum possible.

## 3.4. Introduction of Cognitive Mechanisms

The delay introduced from the optimization process lies on the fact that the number of all possible solutions that need to be checked, by calculating their objective function value, is quite large. In order to understand this better lets suppose that there is a need for optimization of a cell with $T$ reconfigurable transceivers supporting $R$ RATs like for example UMTS and WLAN. The total number of possible configurations that have to be checked is $R^T$. It is clear that as the resources of a cell are increased, like the number of available transceivers, the total number of possible configurations that need to be checked is increased exponentially. Furthermore, the total number will also be increased if the transceivers are able to support more RATs. Considering that this is what happens just for a cell, it is easy to understand why the optimization procedure is time consuming for a site containing a number of cells.

However, during a period of time, similar contexts are captured by the system and the optimization procedures provide near the same reconfiguration decisions as given in the past. This is the main idea where the cognitive features in the management functionalities are based. Figure 3-2 depicts the approach for introducing cognitive features in the management functionalities of DSNPM exploiting the characteristics of the repeated behavior of the network environment.

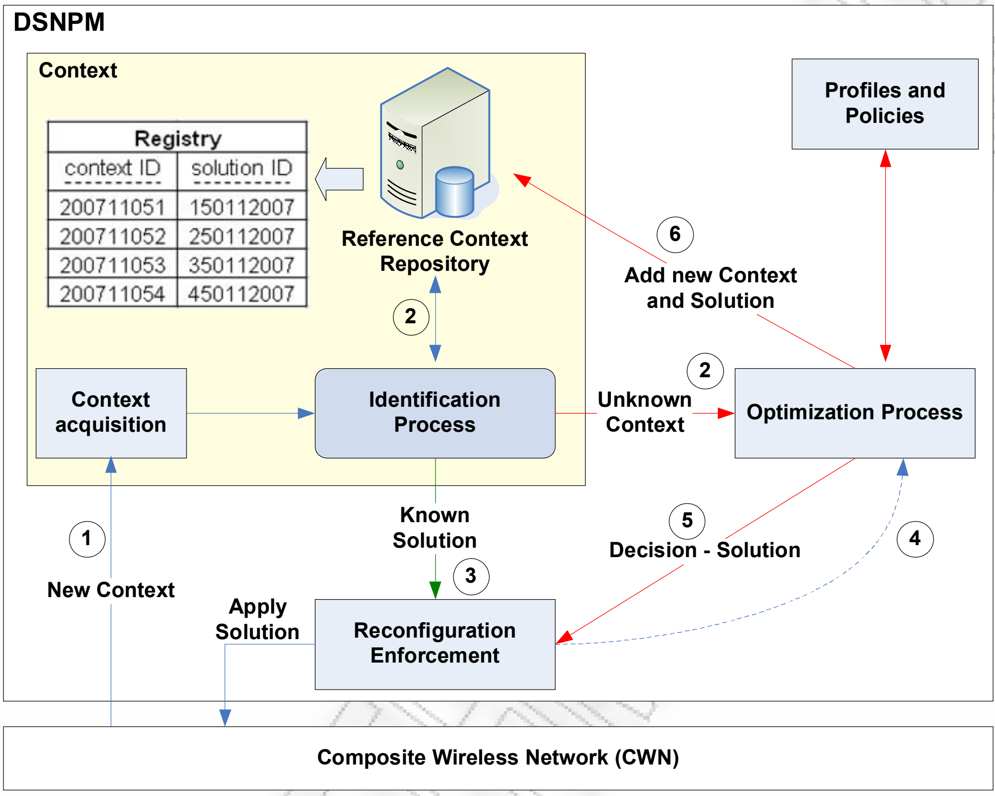


Figure 3-2: Identification process inside DSNPM

The starting point is context acquisition. The context of the service area contains information about its current status. The learning procedure proposed here adds knowledge to DSNPM regarding past interactions that can be exploited for proper network reconfiguration and adaptation in timely manner. The new DSNPM internal entities introduced here are Reference Context Repository and Identification Process.

**Reference Context Repository** It contains the information for each context addressed in the past. A registry table is used, in order to remember the solution for each context after the optimization procedure. In order to be clear on the difference between an arbitrary context derived from the network segment, and a context stored in the repository, the term "reference context" is used for the information stored in the repository.

**Identification Process** The target of this module is to find the closest reference context for the new captured context. The algorithm that is used is based on the k-Nearest Neighbour(s) (k-NN) algorithm [25], [26], [27] and it is going to be presented in the next paragraphs. The solution approach lays on the comparison of the current context information with past network conditions (reference contexts) in order to decide whether a known solution can be used instead of searching for a new one. The decision of the matching algorithm will be based on several threshold comparisons between the current context and reference contexts regarding the total number of users, the Euclidean and profile distance among users.

Figure 3-2 also shows the potential interactions during the overall operation of DSNPM. Interaction one, is the starting phase, in which Context Acquisition module entity retrieves all the relevant information from the network segment. Through interaction two, the Identification as well as Optimization processes are triggered. The Identification Process will utilize the repository data to find a reference context that is close to the current context. In parallel, the Optimization Process can be triggered to start processing the context, as a new situation, not encountered before.

Through interaction three, the Identification Process will pass the control to the Reconfiguration Enforcement entity or to the Optimization Process. The first is selected if match is found. The second is done if no reference context is close to the new context. The Reconfiguration Enforcement may also pass the control to the Optimization module, through interaction four, in case the solution proposed by the Identification Process cannot be applied. Through interaction five, the Optimization Process will ask the Reconfiguration Enforcement module to apply the derived configuration to the network segment. Moreover, through interaction six, the context and the solution are sent to the repository, in order to ensure that if the same context derives again in the future, the solution may be retrieved directly. In this way the management infrastructure has the ability to learn, apply known solutions, and therefore, reduce the time needed for context handling. This happens if the computations needed for the matching algorithm of Identification Process, are less than the computations needed for the optimization algorithm (RDQ-A). Such cases are shown in the results section. Prior there is discussion on the matching algorithm used.

## 3.5. Problem Formulation

This section presents the context identification problem formulation in terms of input and desired output. Furthermore, a proposed solution method will be presented.

### 3.5.1. Input

The input can be categorized as follows:

***Context*** We consider context $c$ with a set of $N$ active user sessions $U_c = \{u : u = 0,1,...N\}$ that comprise the demand in the service area. The location of each session in context $c$ is denoted as $l_{u,c}$ . The requested services (applications) available in the context $c$ service area are represented through set $S_c = \{s : s = 0,1,...|S|\}$. Each session $u$ in context $c$ requesting service $s$ is denoted as $u_{s,c}$. Set $P_c = \{p : p = 0,1,...|P|\}$ is considered to be the set of user profiles in context $c$. The user profile for each session $u$ in context $c$ experiencing service $s$ is denoted as $p_{u,s,c}$ $((u,s) \in (U_c \times S_c))$.

***Reference Contexts and Solutions*** Reference contexts of the service area are represented through set $RC = \{rc : rc = 0,1,...|RC|\}$ . The set of reference contexts solutions (decisions) is denoted as $D_{rc} = \{d : d = 0,1,...|D|\}$.

### 3.5.2. Output

The target is the decision $D_{rc}$ of the reference context which is closer to the current context to be provided. Thus, after the closest reference context is found, decision $D_{rc}$ is retrieved from Reference Context Repository and provided to the system in order to be implemented.

### 3.5.3. Solution Method

Given the current context $cc$ and the set of the reference contexts $RC$, the algorithm will check each reference context $rc$ in order to find the closest one to the $cc$ according to an overall distance. The overall distance is based on the following formulation:

***Total number of sessions distance*** The total number of sessions in current context $cc$ and reference context $rc$ are denoted as $|U_{cc}|$ and $|U_{rc}|$ respectively. The total number of sessions distance is: $\left||U_{cc}| - |U_{rc}|\right| = D_1$.

***Total number of sessions per service distance*** The total number of sessions in current context $cc$ and reference context $rc$ for service $s$ are denoted as $|U_{s,cc}|$ and $|U_{s,rc}|$ respectively. The total number of sessions per service distance is: $\sum_{s\in(S_{cc}\cup S_{rc})} \left\| U_{s,cc}| - |U_{s,rc} \right\| = D_2$.

***Sessions distribution distance*** The location of session $u$ in current context $cc$ is denoted as $l_{u,cc}$. Each session $u$ in $cc$ has a closest session $u'$ from $rc$ with the same service and profile attributes. The $u'$ from $rc$ can be found with k-NN algorithm execution in $rc$. The location of session $u'$ in $rc$ is denoted as $l_{u',rc}$. The sessions distribution distance is: $\sum_{u\in U_{cc}} |l_{u,cc} - l_{u',rc}| = D_3$.

Taking into account the above sub-distances $D_1$, $D_2$ and the normalized $D_3$, the overall distance for each $rc$ from $cc$ is formulated as follows:

$$\textit{Overall\_Distance} = \sum D_i$$

where $D_i$ denotes the distance calculated in phase *i* for $rc$.

The proposed solution method is the Context Matching Algorithm (CMA) which is implemented in four phases as depicted in Figure 3-3.

During the first phase all candidate reference contexts are retrieved from Context Repository and distance $D_1$ is calculated. For each $rc$ that $D_1$ is below than a certain threshold the lunch of a sub-problem is triggered. The resulting sub-problems are then processed in parallel.

In the second phase, for each of the sub-problems the algorithm checks the total number of sessions per service and distance $D_2$ is calculated. The $rc$ where its $D_2$ value is lower than a certain threshold it continues to next phase. Otherwise, this $rc$ is excluded from the rest phases and won't be further checked.

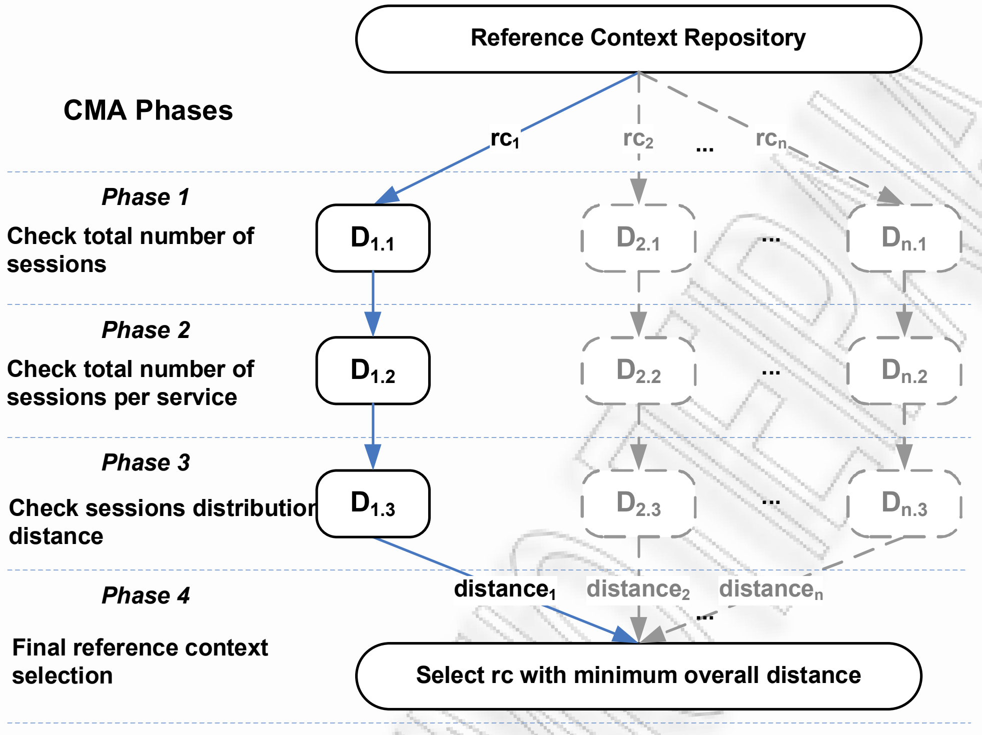


Figure 3-3: Phases of the solution method

In the third phase, the session's distribution in the service area is checked. The target of this phase is to find the Euclidean distance of the nearest sessions, by applying the k-NN algorithm, with the same attributes in terms of services and profiles. Distance $D_3$ will be calculated which reflects the sessions distribution correlation between $cc$ and $rc$. Each $rc$ that $D_3$ value is greater than a certain threshold will be excluded from the final phase.

Finally, the fourth phase contains the selection of the $rc$ with the minimum overall distance from $cc$. Eventually, the optimum selected $rc$ is translated into proper reconfiguration actions which derive from the solution of the $rc$ when it was addressed and solved in the past from the system for a first time. Figure 3-4 depicts how CMA is mapped onto DSNPM internal structure as part of the identification process.

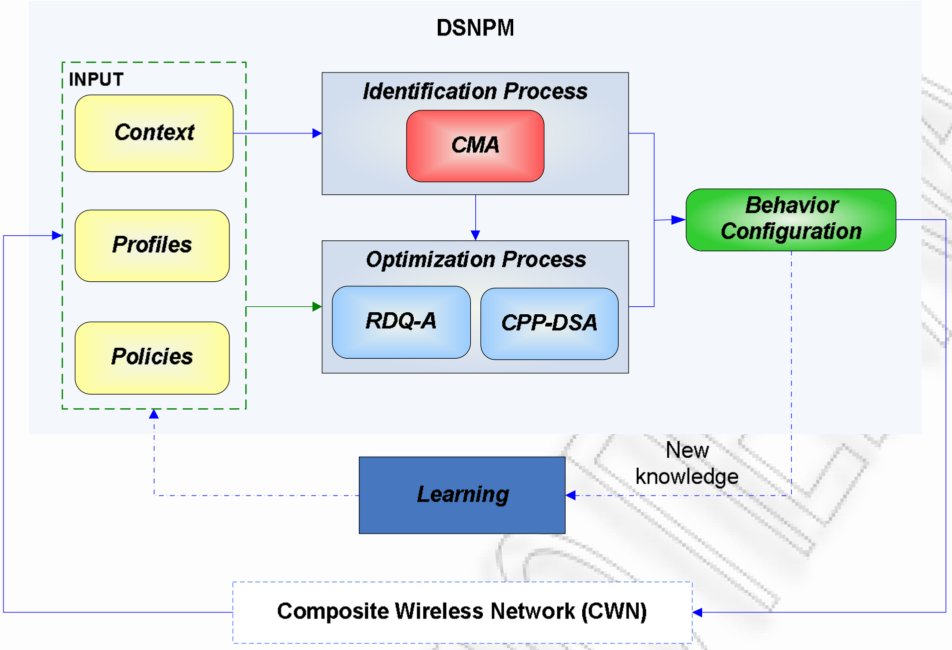


Figure 3-4: Mapping of CMA onto DSNPM

## 3.6. Detailed Phased Approach

CMA is based on a clustering procedure and k-NN algorithm in order to find the overall distance among the reference contexts (known contexts stored in Reference Context Repository) and the new context derived from the B3G infrastructure. The phases of CMA are thoroughly presented in the following sections.

### 3.6.1. Phase 1

Given the current context $cc$ and the set $RC$, this phase retrieves all available reference contexts and distance $D_1$ is calculated. Figure 3-5(a) depicts the algorithm steps for obtaining $D_1$ value for each $rc$ which are the following:

***Step 1.1*** *Retrieve $cc$ and $rc$ list*

The parameters of $cc$ as well as the list of all available $rc's$ from the Reference Context Repository are retrieved.

***Step 1.2*** *Find total number of cc sessions*

The total number of sessions is retrieved from *cc* parameters.

***Step 1.3*** *Find total number of rc sessions*

The total number of sessions is retrieved from the current *rc* parameters.

***Step 1.4*** *Calculate $D_1$ of cc and current rc*

Distance $D_1$ is calculated from the total number of sessions between *cc* and current *rc.*

***Step 1.5*** *Trigger $D_2$ with current rc*

Since current *rc* $D_1$ value is below a certain threshold the calculation of distance $D_2$ during phase 2 is triggered.

At the end of phase 1, parallel execution of phase 2 is triggered for each $rc$ which distance $D_1$ from the $cc$ is below a certain threshold.

### 3.6.2. Phase 2

In the beginning of phase 2 we have knowledge of the $cc$ and $rc$ parameters provided by phase 1 in order to calculate distance $D_2$ between $cc$ and $rc$. The algorithm for the calculation of $D_2$ value for the $rc$ is depicted in Figure 3-5(b) and takes steps as follows:

***Step 2.1*** *Sessions clustering per service for $cc$ and $rc$*

Clusters containing sessions of the same service type are extracted from $cc$ and $rc$. Thus, for each service there will be two clusters containing sessions of the same service type one for $cc$ and one for $rc$.

***Step 2.2*** *Find each cluster's total number of sessions*

For the current service find the total number of sessions in the corresponding clusters of $cc$ and $rc$.

***Step 2.3*** *Update $D_2$ of $cc$ and $rc$*

Distance $D_2$ is increased by the difference of the total number of sessions between $cc$ and $rc$ clusters of the same service.

***Step 2.4*** *Trigger phase 3 with* $rc$

Since $rc$ $D_2$ value is below a certain threshold the calculation of distance $D_3$ during phase 3 is triggered.

To this point, the $rc$ has been examined regarding the total number of sessions and the number of sessions of the same service clusters of $cc$.

### 3.6.3. Phase 3

In phase 3, the sessions distribution correlation between $cc$ and $rc$ will be checked. $D_3$ value will reflect the distance between $cc$ and $rc$ in terms of sessions distribution. Thus, the sessions distribution correlation is reversely proportional to $D_3$ value. The algorithm for the calculation of $D_3$ value for the $rc$ is depicted in Figure 3-6(a) and takes steps as follows:

***Step 3.1*** *Sessions clustering per service for* $cc$ *and* $rc$

Clusters containing sessions of the same service and profile are extracted from $cc$ and $rc$. Thus, for each combination of service and profile there will be two clusters, one for $cc$ and one for $rc$.

***Step 3.2*** *Find session's 1-Nearest Neighbor distance from* $rc$ *cluster*

For the current $cc$ session the nearest neighbor session is found from $rc$ cluster by implementing the k-NN pattern matching algorithm.

***Step 3.3*** *Update* $D_3$ *of* $cc$ *and* $rc$

Distance $D_3$ is increased by the Euclidean distance between the session in $cc$ and its nearest neighbor session in $rc$.

***Step 3.4*** *Trigger phase 4 with* $rc$

Since $rc$ final $D_3$ value is below a certain threshold phase 4 is triggered in order to select the $rc$ with the minimum possible overall distance.

### 3.6.4. Phase 4

After the completion of the three first phases of the solution method, the algorithm will decide which of the examined reference contexts is closer to the current context according to their overall distances. The algorithm for finding the minimum overall distance of the examined reference contexts is depicted in Figure 3-6(b) and takes steps as follows:

***Step 4.1*** *Create $rc$ list*

A list of all reference contexts that passed successfully through all the previous phases is created.

***Step 4.2*** *Find $rc's$ overall distance*

The overall distance for the current $rc$ is calculated.

***Step 4.3*** *Save $rc$ ID with minimum overall distance*

If the overall distance of the current $rc$ is the minimum compared to the distances of the reference contexts that have already been checked, the $rc$ *ID* is stored which reflects the result of the algorithm until that moment.

***Step 4.4*** *Provide $rc$ ID with minimum overall distance*

The result of the algorithm which is the $rc$ *ID* with the minimum overall distance from $cc$ is provided to the management system.

After the end of the CMA phases, the solution $D_{rc}$ to be implemented to the service area is retrieved from the Reference Context Repository since the $rc$ *ID* with the minimum overall distance from $cc$ is now available. After the decision is applied to the service area, the KPIs are monitored in order to check whether the performance of the network has been improved as expected or not.

Despite the fact that decision $D_{rc}$ of the $rc$ with the minimum overall distance was applied, there could be contexts that the second best solution or later may address them in a better way. Another interesting approach for phase 4 could be to find the overall distance for each $rc$ and create an ascending sorted list containing the corresponding decisions $D_{rc}$. In this way, phase 4 will provide a set of possible solutions in order the system to choose the most appropriate among them considering also the feedback taken from the service area in terms of KPIs after the decision was applied. However, it is expected that the first decision of the list will be the appropriate for the majority of the contexts.

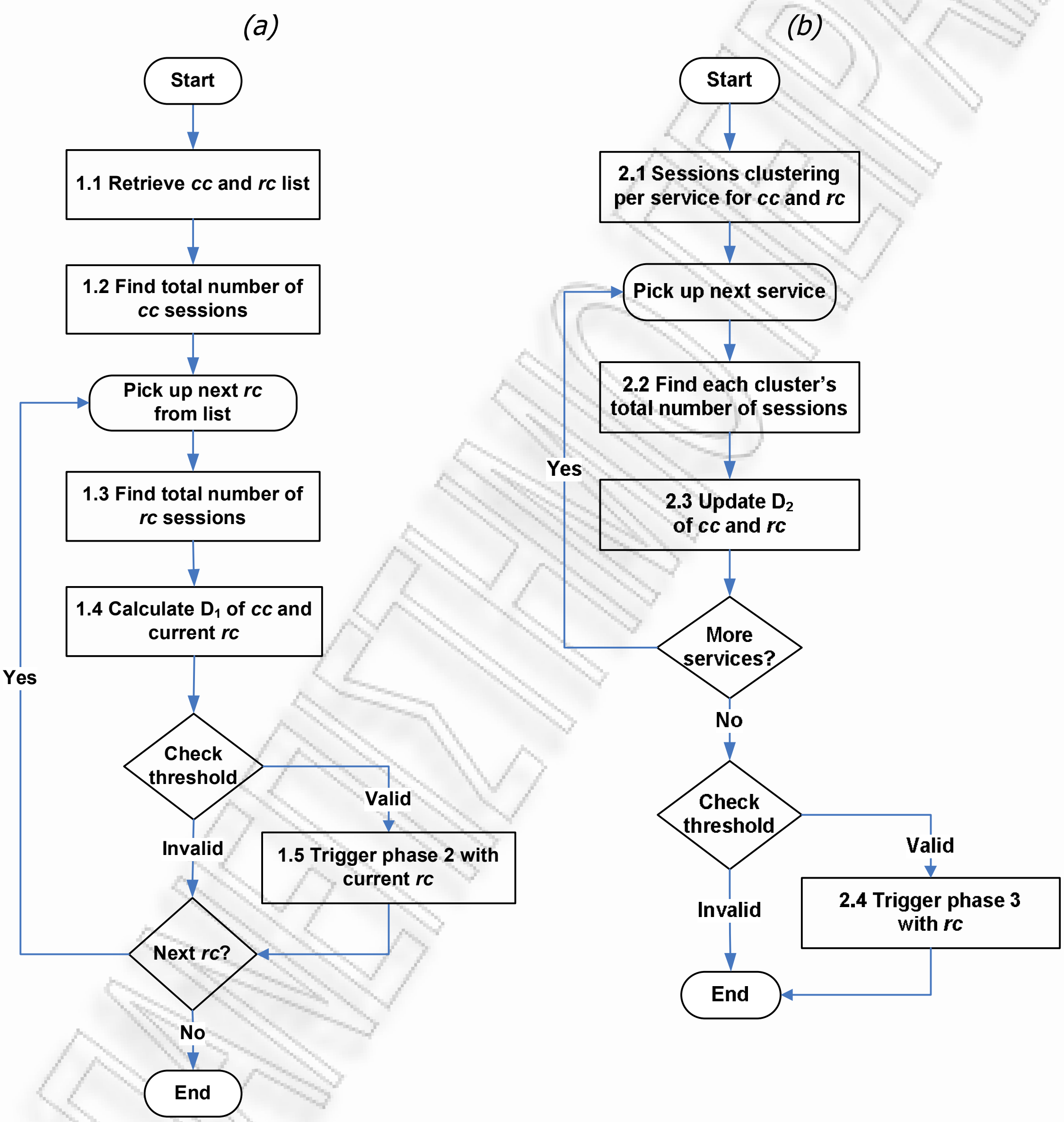


Figure 3-5: Solution algorithm – (a) Phase 1, (b) Phase 2

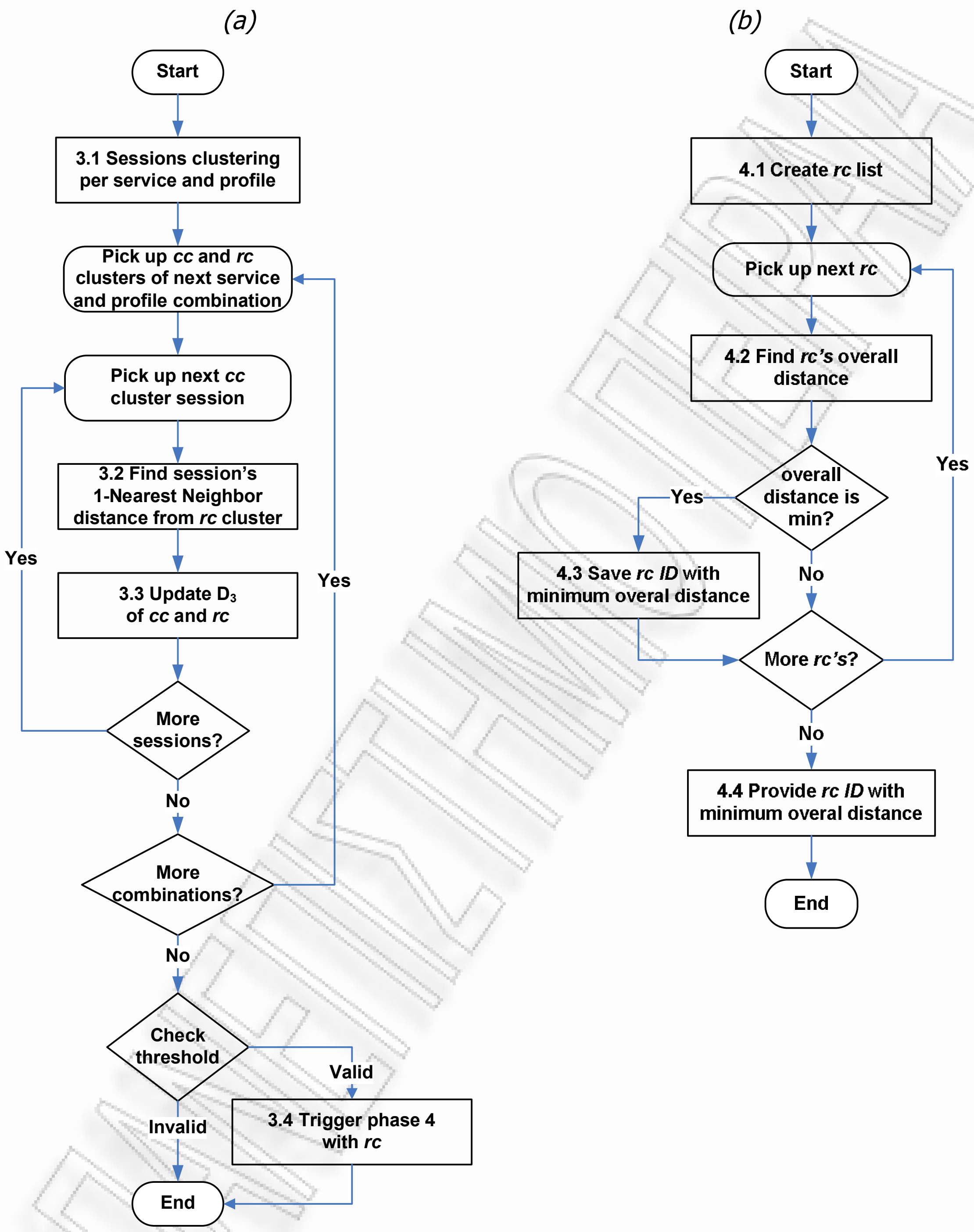


Figure 3-6: Solution algorithm – (a) Phase 3, (b) Phase 4

### 3.6.5. On the Complexity

The algorithm complexity depends on the number of comparisons needed during the four phases described above. This is explained below for the different phases of CMA.

***Phase 1*** For each $rc$, distance $D_1$ is calculated. The total number of comparisons is $|RC|$.

***Phase 2*** For each service $s$ the distance $D_2$ is calculated. The total number of comparisons is $|S|$.

***Phase 3*** For each combination of service and profile, distance $D_3$ is calculated by executing k-NN algorithm. The total number of comparisons is $(|S| \times |P|) \times O(N^2)$, where $O(N^2)$ is the complexity of k-NN algorithm considering the worst case scenario in which the two sets to be compared contain $N$ sessions both of them.

***Phase 4*** For each $rc$ arrived, the overall distance is calculated. In the worst case scenario where all available reference contexts arrived in phase 4, the total number of comparisons is $|RC|$.

## 3.7. Results

This section presents the scenarios and contains also some simulation results, in order to test the efficiency of the cognitive management functionalities of DSNPM as enhanced by utilizing CMA. Comprehensive results from indicative cases will be shown from legacy optimization, as well as results after the implementation of CMA. More specifically, the behaviour of a network segment will be presented during its learning procedure as well as a system of 36 cells by implementing the learning procedure for each one of its cells.

### 3.7.1. Scenarios

Two scenarios are considered with two phases for each one of them. In the first phase legacy optimization is applied for the proper network adaptation to a set of four traffic cases. In the second phase, CMA is applied in order to check whether the contexts of the new set are close enough to the old ones and apply known solutions. The scenarios are differentiated with respect to the number of the available RATs in the network segment. For the first scenario two RATs are considered, i.e. HSDPA and WLAN, and for the second there are three RATs, i.e. HSDPA, WLAN and WiMAX. The following network segment conditions are the same for both scenarios:

- Three reconfigurable transceivers of same capabilities
- Two kind of services, audio and video streaming
- Same kinds of user profiles (preferences)
- Same contexts, each of which is associated with a certain demand percentage of audio call and video streaming sessions

User preferences are reflected through utility volume [24], that the optimization algorithm's OF takes into account in order to decide whether a configuration satisfies the most the user preferences. The utility volume depends on the throughput (Kbps) that the user experiences the requested service. In our scenarios, the utility volumes according to the throughput are depicted in Table 3-I below.

Table 3-I: Utility volumes per QoS levels in scenarios

| **Throughput (kbps)** | **Utility volume** |
|---|---|
| *64* | *2* |
| *128* | *3* |
| *256* | *4* |
| *384* | *5* |
| *512* | *6* |
| *1024* | *10* |

Beginning with the first phase of the scenarios, four contexts are considered. The first one begins with 140 audio calls. Gradually audio call sessions are reduced to 90 in context 2, 60 in context 3 and 30 in context 4. On the other hand, video streaming sessions are increased to 25 in context 2, 40 in context 3 and 70 in context 4. Table 3-II summarizes the context sessions parameters.

Table 3-II: Number of sessions in each contextual situation

| **Context** | **Audio call sessions** | **Video streaming sessions** |
|---|---|---|
| *1* | *140* | *0* |
| *2* | *90* | *25* |
| *3* | *60* | *40* |
| *4* | *30* | *70* |

For each context the optimization process, based on RDQ-A algorithm described in sub-section 3.3, finds all possible network configurations and selects the best one according to its objective function value. Figure 3-7(a) and (b) depict the OF evolution, for both scenarios of the best configurations for the examined context cases.

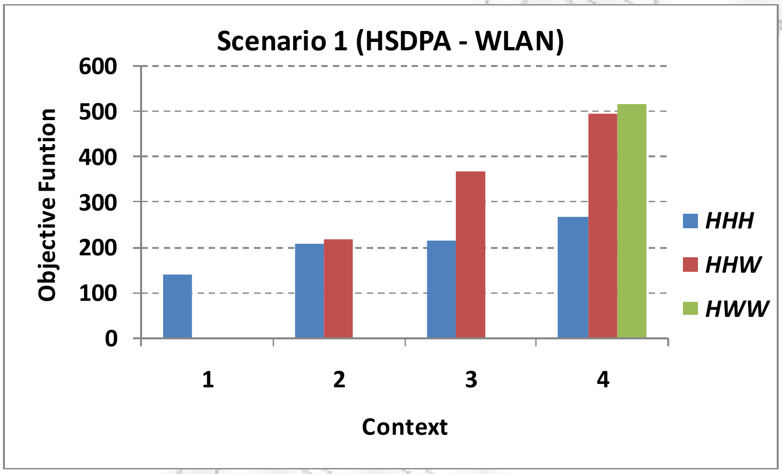
An indicative case will be explained as an example. In context case 3 the network segments has 60 active video streaming sessions and 40 active audio call sessions. The results for this case are summarized in Table 3-III.

Table 3-III: Optimization results in context case 3

| **Service** | **Sessions percentage** | **Throughput (kbps)** |
|---|---|---|
| *Audio call* | *100%* | *64* |
| *Video streaming* | *17%* | *128* |
| *Video streaming* | *1%* | *512* |
| *Video streaming* | *22%* | *1024* |

After the optimization algorithm executed, two configurations selected out of four, HHH and HHW where "H" denotes an HSDPA activated transceiver, "W" denotes a WLAN activated transceiver and "Wi" denotes a WiMAX activated transceiver. Configurations HWW and WWW were discarded for capacity and coverage reasons accordingly. The optimization algorithm chose the configuration with the maximum objective function value (369), which in this context case is HHW, according to the best possible user to throughput allocation considering capacity, coverage and user profile limitations. The objective function values for the rest of the scenarios contexts are calculated in the same way.

*(a)*



*(b)*

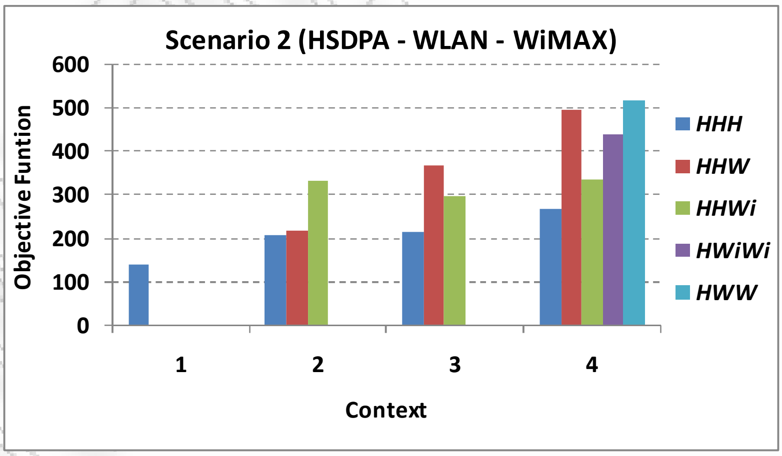


Figure 3-7: (a) Objective function evolution for scenario 1, (b) Objective function evolution for scenario 2

The video streaming sessions can be served with the maximum possible QoS level and thus user satisfaction which is reflected by the objective function value is constantly increasing, as long as the number of these sessions rises. Furthermore, there is only one best solution for each context according to it's objective function value. However, for many contexts there can be two or even three candidate solutions which their objective function values are close to the best one. The advantage of this is that DSNPM has the capability to select the most appropriate not only by taking into account technological aspects, restrictions and policies but also knowledge derived from past interactions.

The knowledge that DSNPM will obtain is the association of each context with its solution as derived from the optimization procedure. This pair of context and solution will be stored to the registry tables of Reference Context Repository. That means that if the same or close enough contexts derive again in the future, the identification process of DSNPM will apply the known solutions executing the CMA instead of the time consuming optimization algorithm. In our case there is only one configuration for each context case with the maximum possible objective function value. For example, in case 3, where there are 40 video streaming sessions and 60 audio call sessions, the best configuration for each one of the three transceivers is two of them to operate in HSDPA and the last one in WLAN (HHW). Based on these optimization results derived from the legacy optimization process, the registry tables for each one of the scenarios are created in Reference Context Repository as depicted in Table 3-IV and Table 3-V.

Table 3-IV: Registry table in scenario 1

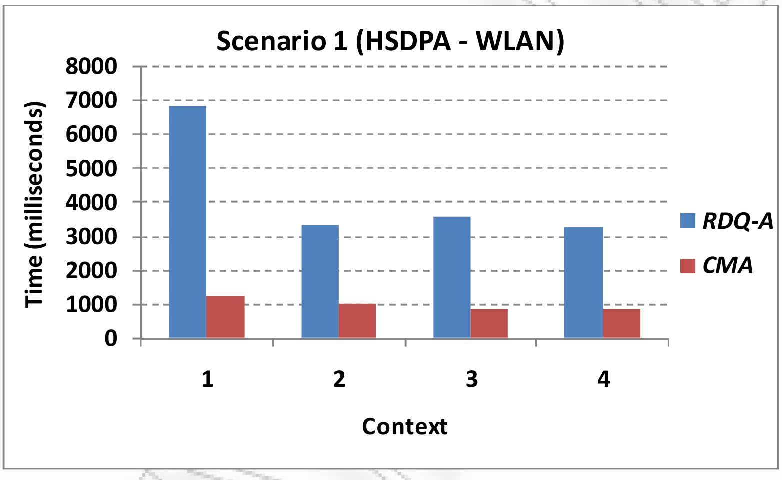
| Context | Decision |
|---|---|
| 1 | HHH |
| 2 | HHW |
| 3 | HHW |
| 4 | HWW |

Table 3-V: Registry table in scenario 2

| Context | Decision |
|---|---|
| 1 | HHH |
| 2 | HHWi |
| 3 | HHW |
| 4 | HWW |

According to phase two of the scenarios, a set of four new contexts is captured by DSNPM and each one of them is similar to a reference context in terms of a) total number of users, b) random user distribution around the reference context topologies and c) user profiles and services. The registry tables provide the option to check the "memory" of DSNPM and provide known solutions. The CMA tries to find how close to the above reference contexts is the new captured context and retrieve the solution of the closest one. The result at the end of the matching algorithm for each one of the new contexts is the association with a reference context. Figure 3-8(a) and (b) make a comparison of the time needed in order the proper configuration to be retrieved either using the CMA or the legacy optimization algorithm for both scenarios.

*(a)*



*(b)*

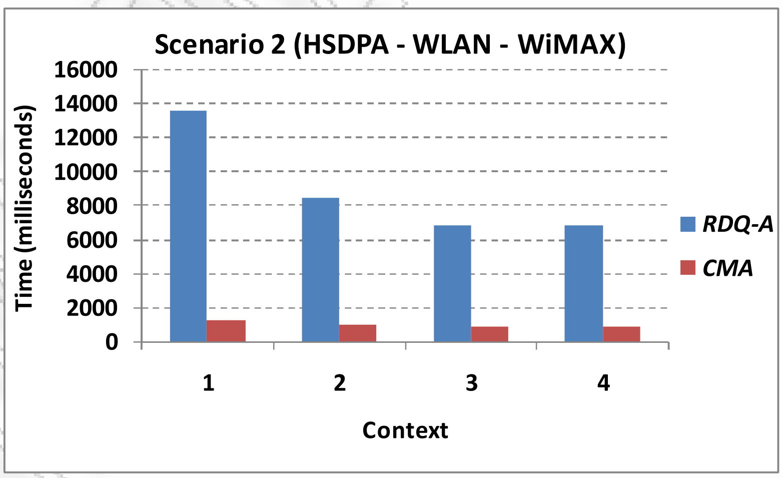


Figure 3-8: Efficiency of context matching and legacy optimization algorithms – (a) Scenario 1, (b) Scenario 2

Figure 3-8(a) and (b) provide useful insight regarding the efficiency of the cognitive capabilities of DSNPM. The first time that the contexts were captured, the only possible solution was to execute the optimization algorithm since no similar past contexts found or there were no past context at all in the Reference Context Repository. When the set of near contexts captured, CMA allocated them to the corresponding reference contexts and their solutions were retrieved and applied without the need of executing the optimization algorithm again. Furthermore, the overall time the matching algorithm needs, depends only on the total number users. Thus, the time needed for the context matching algorithm is the same for all contexts between the scenarios, while the optimization algorithm needed a great amount of time. The complexity and the optimization time depend on the number of possible solutions which is $R^T$, where set $R$ denotes the set of RATs and set $T$ denotes the set of transceivers. According to this, the possible configurations that the optimization algorithm checked at the first scenario are $R^T = 2^3 = 8$ and for the second scenario are $R^T = 3^3 = 27$. On the other hand, the matching algorithm complexity and time depend only on the number of users, which is the same in the corresponding cases for both scenarios. Further analysis from the simulation results is provided in the next section on the context matching success probability and the overall time needed in order the CMA to identify and provide the best possible decisions.

### 3.7.2. Simulations

Several simulations where performed in order to study the success probability and the time needed from CMA to provide the appropriate decisions. The algorithm was developed with Java programming language and run on a Pentium-4 3.0 GHz with 1.5 GB of RAM. During our simulations, each one of the four contexts was captured several times in order to study the behaviour of the cognitive management system. The first three simulations differentiate at the occurrence probability for each context. In the fourth and fifth simulation emergency cases will be studied, after the system is quite experienced, which caused by an unknown context and several unknown contexts respectively. Taking into account the aforementioned contexts, the following simulation cases are considered.

**Simulation 1** The occurrence probability is the same for all contexts

**Simulation 2** The occurrence probability of context 2 is greater compared to the other three

**Simulation 3** The occurrence probability of context 3 is greater compared to the other three

**Simulation 4** An emergency case will be studied where a totally unknown context is captured by an experienced system

**Simulation 5** An emergency case will be studied where several successive unknown contexts are captured by an experienced system

#### 3.7.2.1 Simulation 1

Figure 3-9 depicts the contexts occurrence probability during the simulation time for scenario 1 where there are two available RATs to the service area, HSDPA and WLAN.

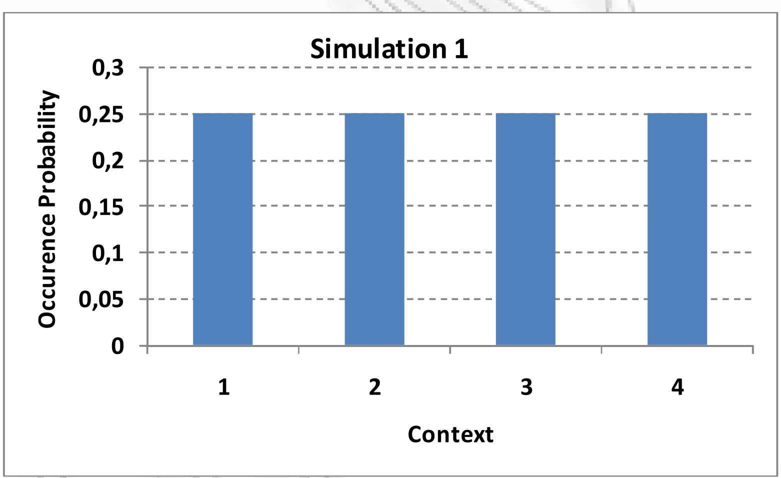


Figure 3-9: Simulation 1 - Context occurrence probability

During the first contexts that captured by the cognitive management system there was no successful matching because they were unknown to DSNPM. Thus, as it is depicted in Figure 3-10, the context matching success probability is decreasing during the first four contexts (4, 4, 3, 1). However, the contexts parameters and the corresponding solutions were stored and during the next 3 contexts (3, 3, 1) the successful matching probability was increased due to the fact that these contexts were already addressed in the past and CMA was able to identify them. The next context captured by DSNPM was context 2 which was totally unknown and the success probability was decreased once more. The success probability of the system was decreased four times which is the total number of the contexts considered during the simulation. However, since DSNPM has now obtained knowledge for all possible contexts in the service area, the success probability is constantly increasing throughout the rest simulation time.

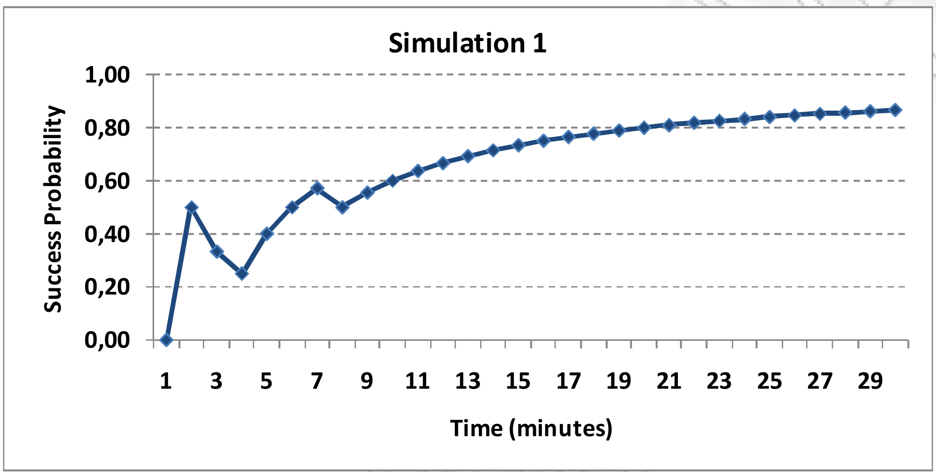


Figure 3-10: Simulation 1 - Context matching probability

Figure 3-11 depicts the average DSNPM response time for each context captured throughout the simulation.

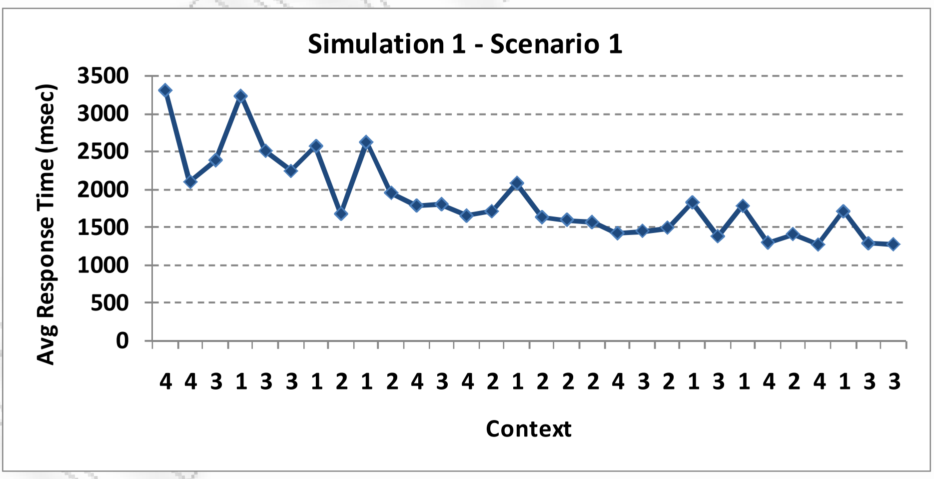


Figure 3-11: Simulation 1 - Evolution versus DSNPM response time in scenario 1 (x-axis shows also the contextual situation occurring in each time instant)

For each context that CMA isn't able to provide decisions, since there is no identification, the optimization procedure is necessary to be executed in order the appropriate decisions to be provided. On the other hand, when the system identifies successfully each context the decision is retrieved from the Reference Context Repository and provided directly to the service area to be implemented, skipping the optimization procedure. Thus, the average system response time is constantly decreasing for each context while the simulation continues.

The contexts occurrence probability in simulation 1 is the same for both scenarios (Figure 3-9). Thus, the corresponding context matching probability will be also the same in scenario 2 (Figure 3-10). However, in scenario 2 there are three available RATs to the service area, HSDPA, WLAN and WiMAX. Since a new RAT is added to the service area, there are more possible solutions needed to be checked by the optimization algorithm in order to select the best among them. Thus, the overall optimization time needed will be increased. On the other hand, the overall time needed by CMA is the same since the number of the comparisons depends only on the total number of sessions in each context, which remains the same. As a result of that, CMA is capable to provide solutions faster and better since there is also available a better solution including more network resources.

Figure 3-12 provides useful information about the time needed in order the system to optimize the contexts which derive for a first time.

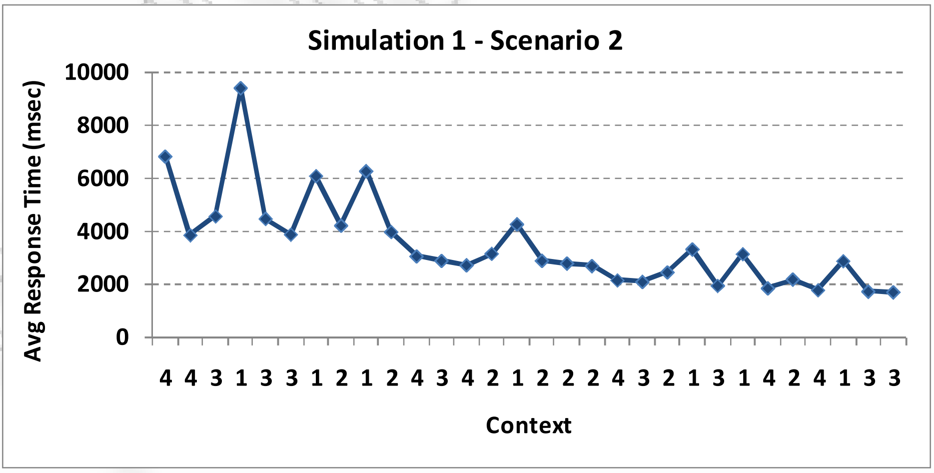


Figure 3-12: Simulation 1 - Evolution versus DSNPM response time in scenario 2 (x-axis shows also the contextual situation occurring in each time instant)

Also, the comparison of Figure 3-12 and Figure 3-11 provide useful insight regarding the efficiency of DSNPM. It is quite clear that the overall optimization time needed in scenario 2, where there are three available RATs, is greater compared to the time needed in scenario 1. However, during the simulation DSNPM is constantly learning new contexts and their corresponding solutions and the average time needed in order the appropriate solution to be provided tends to coincide regardless the total amount of available resources.

#### 3.7.2.2 Simulation 2

In simulation 1 it was assumed that the occurrence probability for all contexts was equal. In order the simulations to be better aligned with real traffic conditions, in simulation 2 scenarios the occurrence probability of context 2 will be greater compared to the other three. This is depicted in Figure 3-13.

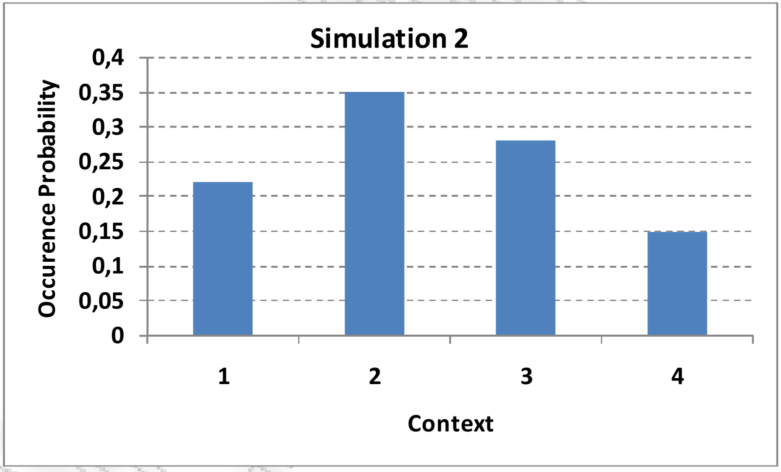


Figure 3-13: Simulation 2 - Context occurrence probability

The successful context matching probability for both scenarios is depicted in Figure 3-14.

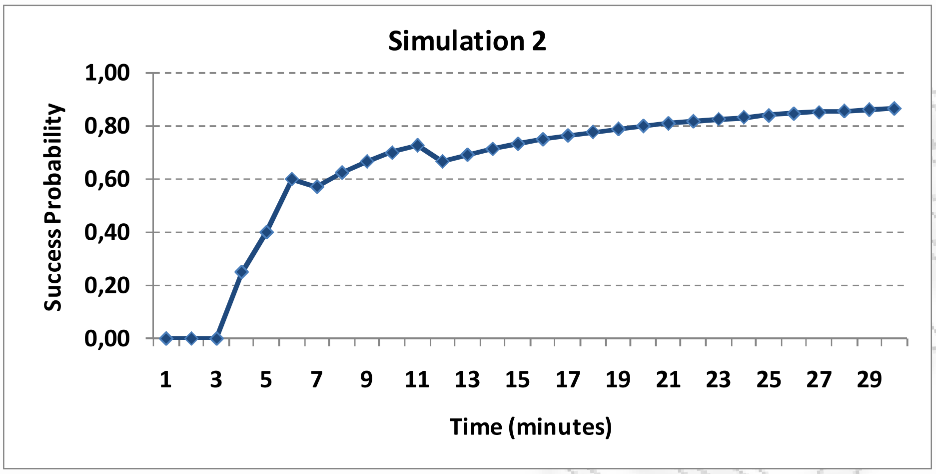


Figure 3-14: Simulation 2 - Context matching probability

The system response time in this case is depicted in Figure 3-15 and Figure 3-16 for scenario 1 and 2 respectively.

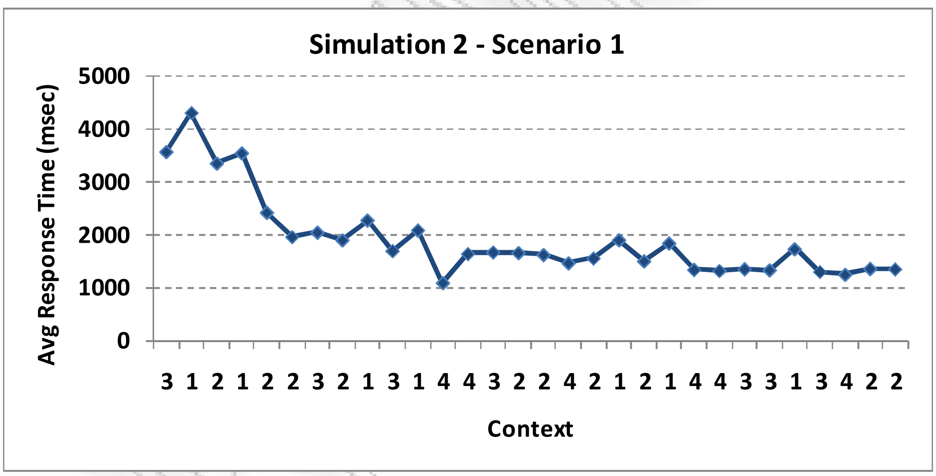


Figure 3-15: Simulation 2 - Evolution versus DSNPM response time in scenario 1 (x-axis shows also the contextual situation occurring in each time instant)

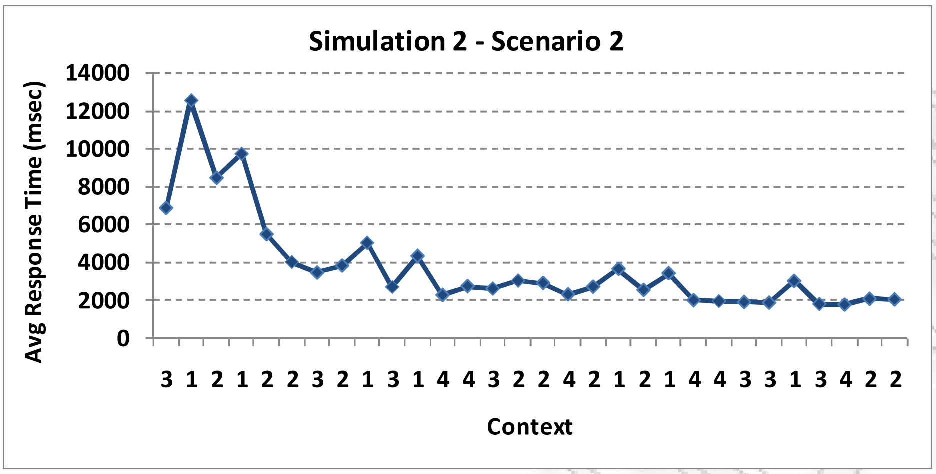


Figure 3-16: Simulation 2 - Evolution versus DSNPM response time in scenario 2 (x-axis shows also the contextual situation occurring in each time instant)

As in simulation 1, the time difference between the scenarios is continuously decreasing as long as the system experiences the learning procedure.

#### 3.7.2.3 Simulation 3

The last test case for the context occurrence probability trying to address real traffic conditions is depicted in Figure 3-17.

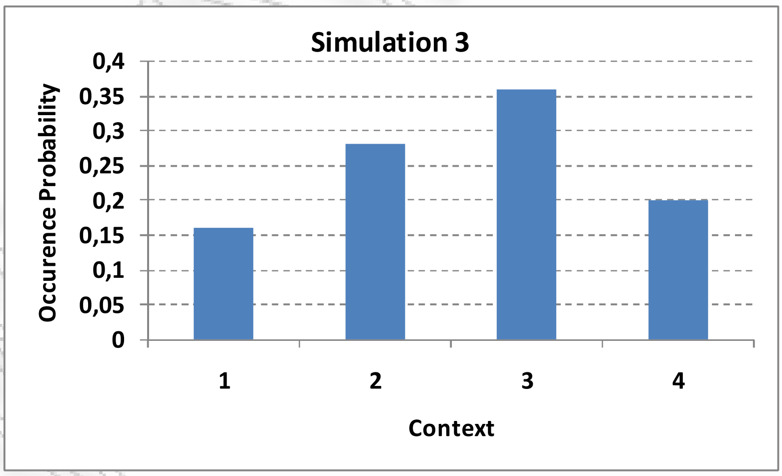


Figure 3-17: Simulation 3 - Context occurrence probability

Figure 3-18 depicts the successful context matching probability while Figure 3-19 and Figure 3-20 depict the system response time in both scenarios.

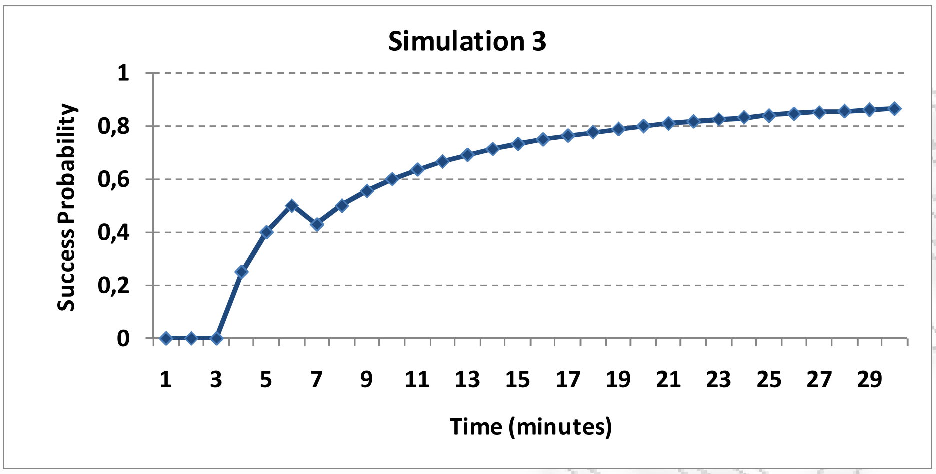


Figure 3-18: Simulation 3 - Context matching probability

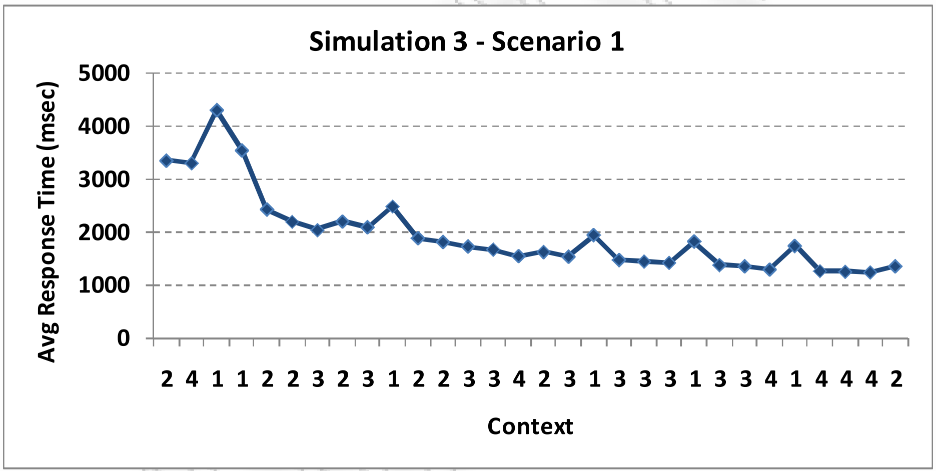


Figure 3-19: Simulation 3 - Evolution versus DSNPM response time in scenario 1 (x-axis shows also the contextual situation occurring in each time instant)

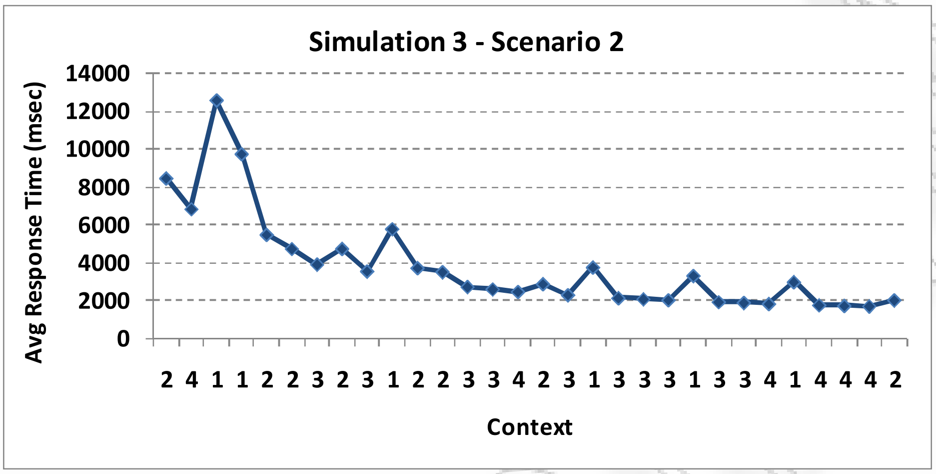


Figure 3-20: Simulation 3 - Evolution versus DSNPM response time in scenario 2 (x-axis shows also the contextual situation occurring in each time instant)

The time difference between the scenarios is also decreasing as long as the system experiences the learning procedure.

#### 3.7.2.4 Simulation 4

In this simulation the behaviour of DSNPM will be studied when it captures an unknown context of an emergency situation which may derive either due to high traffic demand in the service area or due to malfunction of one or more transceivers. It is assumed that DSNPM is quite experienced (eg. as in Simulation 3) since it captured several contexts in the past and identified them in the future providing directly the corresponding decisions.

Considering that context 5 is unknown and reflects the characteristics of the emergency situation, Figure 3-21 depicts the evolution of successful matching probability of the system both for the known contexts (provided by simulation 3) as well as after context 5 is captured for the very first time.

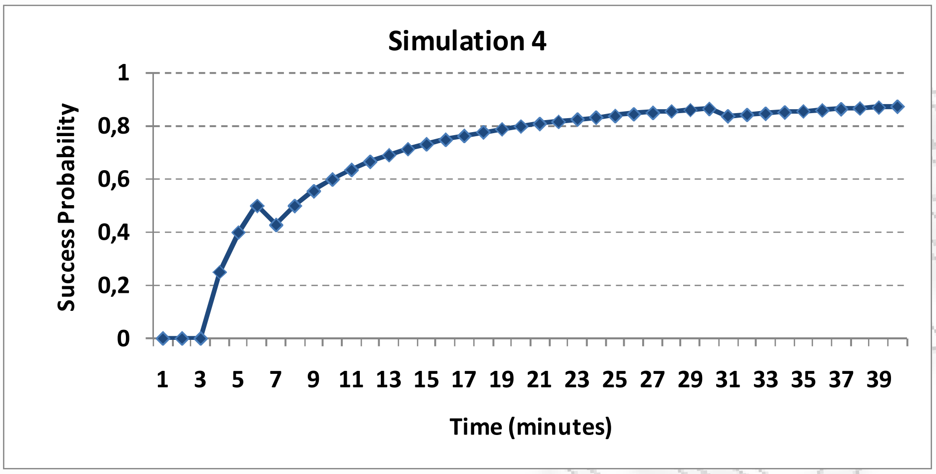


Figure 3-21: Simulation 4 – Context matching probability

It is obvious that as long as the system was capturing known contexts for a great amount of simulation time (8-30) the successful matching probability was constantly increasing. However, when the unknown context 5 was captured the successful matching probability was dropped due to the fact that this context wasn't identified by CMA to be similar to any of the previously captured and optimized contexts of Reference Context Repository module. Following the procedure described in Figure 3-2, the optimization process will provide the most appropriate solution for context 5 which will be sent to be applied to the service area. Moreover, the characteristics of context 5 as well as its solution were stored in order to be available in the future.

The optimization process that was triggered for the unknown context 5, in the first time that was captured, delayed DSNPM to provide the appropriate decision. This is depicted in Figure 3-22.

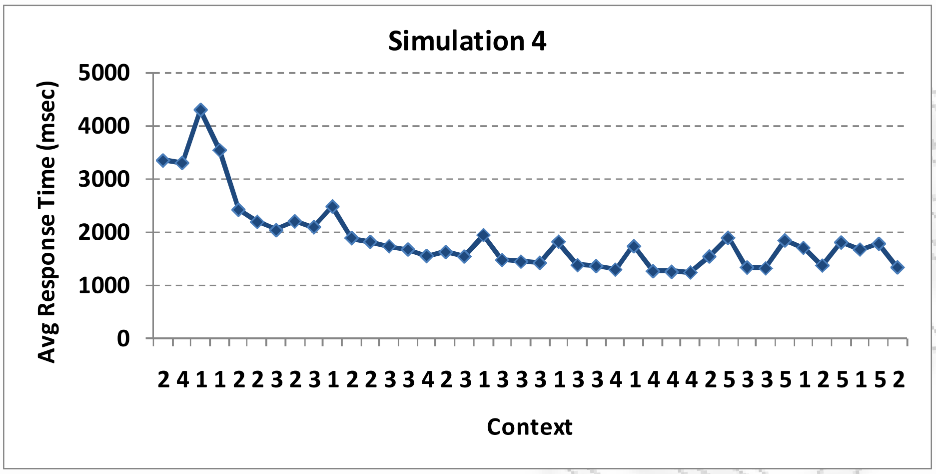


Figure 3-22: Simulation 4 - Evolution versus DSNPM response time (x-axis shows also the contextual situation occurring in each time instant)

When context 5 was captured for a first time the system was delayed almost 2 seconds for providing the optimum decision. However, since the context's characteristics were stored as well as the corresponding solution, each time that this context was captured after its first occurrence the system delay was constantly decreasing.

#### 3.7.2.5 Simulation 5

In simulation 4 it was assumed that the emergency case was caused due to a new context (context 5) in the service area that the experienced management system wasn't aware of it, since it had never been captured in the past. In this simulation it is assumed that the emergency case is caused by several successive unknown contexts which are captured by the experienced system (eg. as in Simulation 3). In addition to context 5 that was supposed to be the unknown context in simulation 4, it is also assumed that successive contexts 6, 7 and 8 are also unknown.

Figure 3-23 depicts the evolution of successful matching probability of the system both for the known contexts (provided by simulation 3) as well as for the unknown contexts 5, 6, 7 and 8 which are captured for the very first time.

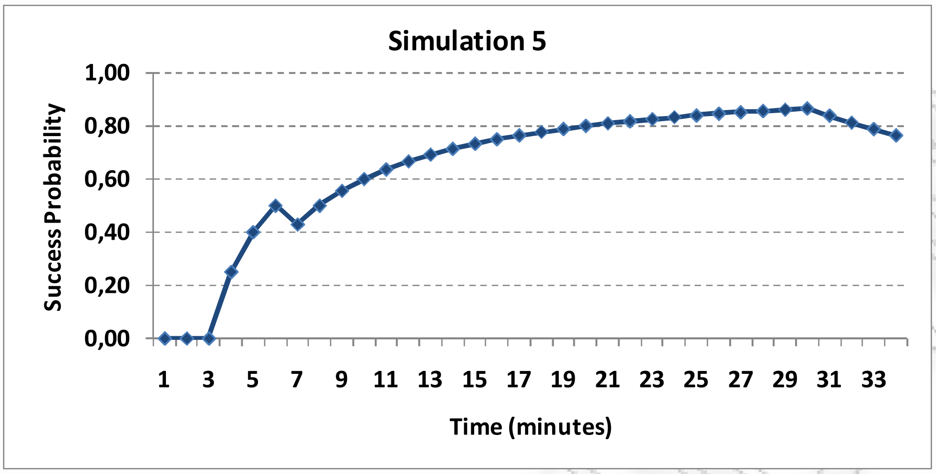


Figure 3-23: Simulation 5 – Context matching probability

When the unknown context 5 was captured the successful matching probability was dropped, since it wasn't successfully identified by CMA. On the other hand, its characteristics were stored as well as the corresponding decision provided from the optimization procedure in order to be available in the future. However, none of the known contexts (1-4 as well as context 5) is captured again. Due to the emergency case DSNPM captured also three unknown contexts 6, 7 and 8. Similar on what happened when context 5 was captured for a first time, the unknown contexts caused the successful matching probability to be dropped since it wasn't possible for CMA to identify any of these contexts.

Since DSNPM captured successive unknown contexts it was necessary to trigger the time consuming optimization procedure given that there were no past decisions available for similar contexts in the Reference Context Repository module. Figure 3-24 depicts the evolution of the time needed by the system to provide the corresponding decisions.

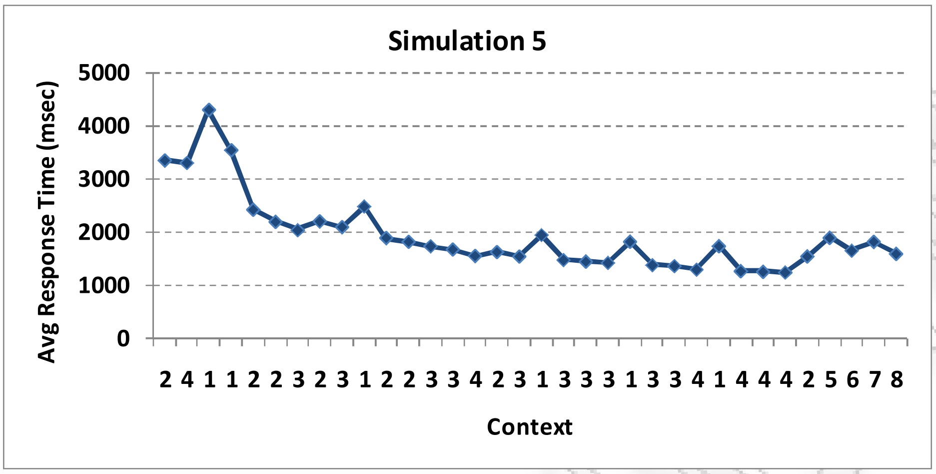


Figure 3-24: Simulation 5 - Evolution versus DSNPM response time (x-axis shows also the contextual situation occurring in each time instant)

It is clear that the time needed by the system to provide the appropriate decisions before the emergency case (before the occurrence of contexts 5, 6, 7 and 8) was constantly decreasing. However, due to the occurrence of the successive unknown contexts, the response time was increasing since, as already described, the necessary decision for each context provided by the time consuming optimization procedure.

#### 3.7.2.6 Test case of a city service area covered by 37 cells

In the previous section presented the capability of CMA, as part of the identification process of DSNPM, to identify whether a context was captured in the past and provide the already known solution skipping the time consuming optimization procedure. This section presents how DSNPM is able to provide solutions in a city service area test case covered by 37 cells and study the behaviour of the system during a significant amount of time where the network conditions are changing according to user movement and location [28].

The city service area is divided into specific zones in order to denote the areas where the users are moving. Figure 3-25(a), Figure 3-25(b), and Figure 3-25(c) depict the edge zone (suburb of the city), intermediate zone and centre zone (city centre) of the city service area respectively.

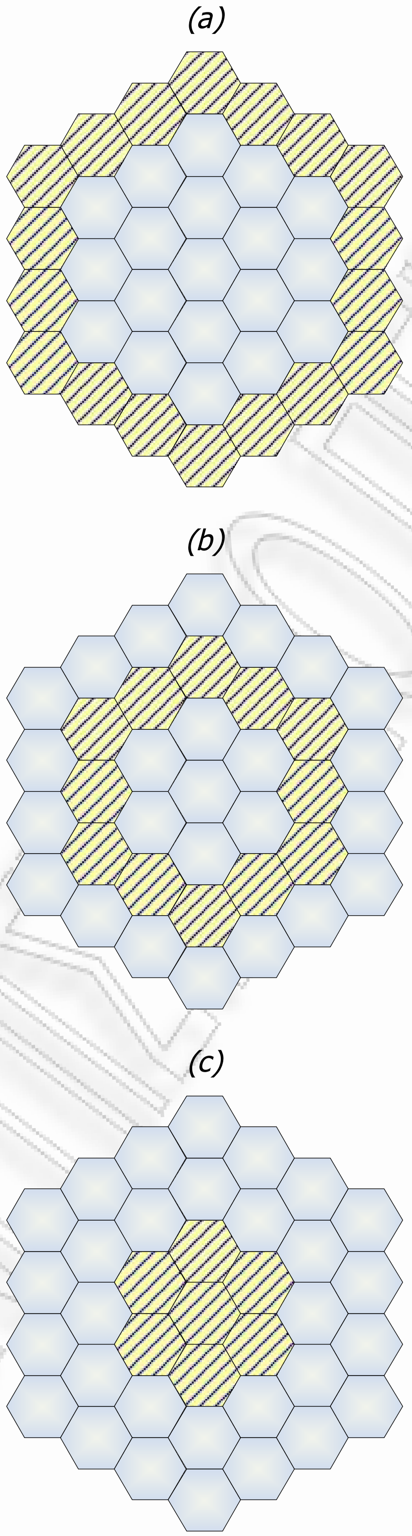


Figure 3-25: A cell layout serving an arbitrary city area – (a) Edge zone, (b) Intermediate zone, (c) Center zone

Assuming that the service area is monitored during a daytime, the system will retrieve contexts from five phases. The first context will be captured during phase 1 where most of the users are located in their houses in the suburb. The most important characteristics of phase 1 contexts are the following:

- The mobility levels of the users are low
- The percentage of data service sessions are greater compared to voice service sessions percentage
- The contexts are addressed at the edge zone of the city service area

Contexts 2 and 3 from Table 3-II usually appear at the edge zone of the city service area during phase 1. For each one of the cells the system will execute the optimization procedure since it is the first time that this context is retrieved. The system will store the context and its solution in order to be able to identify it in the future and apply directly the solution, as described in scenarios simulations in the previous section.

In phase 2 the mobility levels of the users will be increased as well as the voice service sessions. The general characteristics of phase 2 are the following:

- The mobility levels of the users will be increased
- The voice service sessions will be increased
- The contexts are addressed at the intermediate zone of the city service area
- Due to the fact that the mobility levels are increased solutions should derive and be applied as soon as possible in order to avoid high blocking rates and low QoS levels

Contexts 1 and 2 from Table 3-II are more likely to appear at the intermediate zone of the city service area during phase 2. Again, since this is the first time that the contexts captured to this zone the pairs of context and solution for each cell will be stored in order to be available in the future for identification and direct application respectively.

The next phase is phase 3. The mobility levels are low again as in phase 1, however the contexts are addressed in centre zone of the city service area.

The major characteristics of phase 3 contexts are:

- The mobility levels of the users are low
- The percentage of data service sessions are greater compared with voice service sessions percentage
- The contexts are addressed at the centre zone of the city service area

Contexts 3 and 4 from Table 3-II will be captured by the DSNPM during phase 3. The centre zone cells are expected to be overloaded due to the large number of users in this area and the high QoS levels they request. Thus, the need for larger capacity RATs will be raised in order to adapt better to the changing environment. Since this is the first time DSNPM captures contexts at this zone, the contexts and solutions pairs will be stored according to the learning procedure.

Following the reverse direction, from centre zone to edge zone, contexts from phases 4 and 5 will be captured by the DSNPM. Contexts of phase 4 are located in intermediate zone as in phase 2. However, due to the different time zone, the context characteristics are slightly different compared with contexts 1 and 2 from Table 3-II (eg. less number of parallel active users and corresponding sessions). Despite the fact that there is a context in the same zone that should be solved, past solutions from phase 2 contexts are not valid because, for example, the total capacity should be shared to less users and each of them will then receive higher QoS level. Thus, the optimization algorithm will be executed also for this case and the Reference Context Repository will be updated by adding new records describing the context characteristics and of course the decision taken. In this way, for the cells of the intermediate zone, the Reference Context Repository will have two potential solutions. CMA will be responsible to select the most appropriate solution by identifying the closest reference context to the current context. It is quite easy to understand that as long as the system becomes more and more experienced through learning procedure, more appropriate solutions will be provided.

Phase 5 is the final one. Contexts of phase 5 are located in edge zone as in phase 1. Similar to phase 4, different context characteristics are captured compared with phase 1 contexts. Thus, the optimization procedure will be triggered and new solution will be provided for the cells of edge zone. In future contexts, CMA will identify the closest reference context and the corresponding solution will be provided.

Considering that the behaviour as described above is periodical during a certain amount of time (e.g. daily) it is quite easy to understand that the same contexts will be captured and the same solutions would be necessary to be implemented for proper network adaptation. Thus, the exploitation of capabilities in periodical cases will save great amount of time and the network will adapt faster to the environment conditions. Furthermore, as long as the new contexts are captures, DSNPM becomes more and more experienced and it is capable to propose the most appropriate solution or a set of appropriate solutions.

Assuming that the above test case is periodical the behaviour of DSNPM will be studied, now that the problem characteristics and their corresponding solutions are available. Beginning with phase 1 CMA identifies that the same context characteristics are captured again compared with the available contexts in Context Reference Repository. CMA provides directly the corresponding solution without any further delay. Thus, in this case the overall time the system will need in order to adapt to the environment conditions will be less compared with the time needed during the optimization procedure, as described in the simulations of the previous sub-sections. Moving towards phase 2, the DSNPM is also aware of the characteristics of past contexts addressed in this phase and their solutions are available. As in phase 1, CMA provides directly the solution of the closest past phase 2 context. This also continues for all the rest phases. Thus, the context matching success probability continues to increase as long as DSNPM addresses contexts that have been already solved and their solutions are retrieved instead of deciding them again using the optimization procedure.

Figure 3-26 depicts the context matching success probability of the system for the city service area covered by 37 cells. As already described above, the first time the system addresses the contexts during phases 1-5 the optimization procedure should be triggered since there is no successful matching either because there wasn't any previous context available to check or all the previous contexts weren't close enough to the current context.

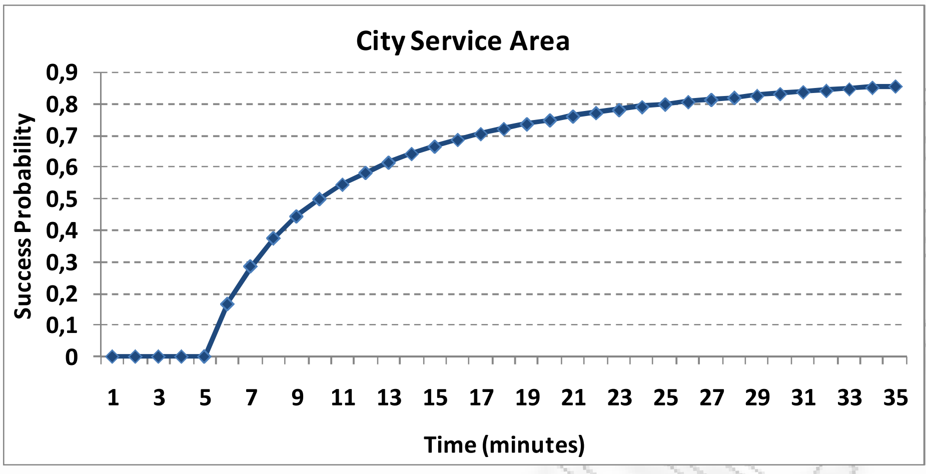


Figure 3-26: City service area – Context matching probability

Thus, in Figure 3-26 the context matching success probability begins to increase after the system has already optimized past contexts and their solutions are now available to be provided by CMA. Each time that CMA identifies the same context characteristics and the corresponding solution is provided, the successful matching probability increases. Furthermore, Figure 3-27 depicts the evolution of the average response time for indicative cells of the same zone.

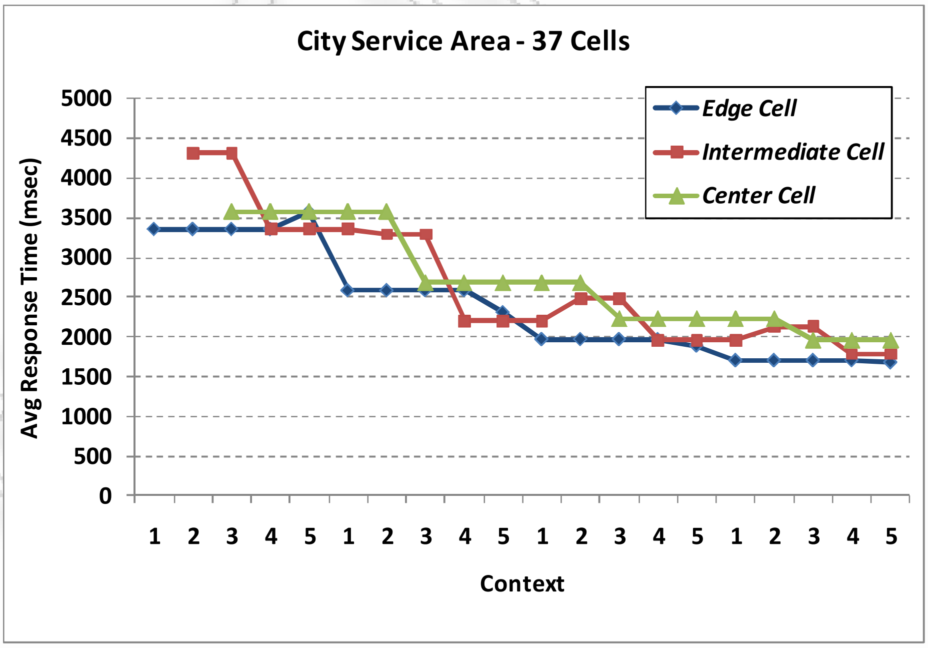


Figure 3-27: City service area - Evolution versus DSNPM response time (x-axis shows also the contextual situation occurring in each time instant)

The cell at the edge zone is the first that will be optimized. Then optimization in intermediate zone cell and centre zone cell will follow during phases 1-3. During phases 4 and 5 different contexts in intermediate zone cell and centre zone cell will be captured and the optimization will provide the appropriate solutions. From this point, the system knows the solutions of the contexts and each time the same context is captured, from the corresponding phases, the system provides faster the solution of the closest past contexts. It is clear that as long as the phases are repeated and DSNPM becomes more and more experienced the response time is decreasing approaching the time that only CMA needs.

## 3.8. Conclusions and Future Work

In this chapter, the rapid evolution of the CWNs was addressed as well as the need for efficient solutions for complex problems deriving from the parallel operation of heterogeneous RATs. Wireless network segments are spreading fast and while the problems become more complex the network adaptation to the environment is getting time consuming and more resources are needed. Cognitive capabilities are promising for the proper network adaptation in a cost efficient manner, in terms of time and resources, using their ability to remember pairs of contexts and their corresponding solutions.

A learning procedure enhanced with a matching algorithm was presented in this chapter for management infrastructures enabling them to retrieve knowledge from past interactions with the network segments and overcome problems by applying already known solutions comprising cognitive management systems. The Context Matching Algorithm (CMA) was presented which is responsible for the context identification whether it is similar or not with any of the available reference contexts captured in the past. Indicative results from several scenarios simulations were presented showing that as the cognitive management system becomes more and more experienced the successful context matching probability is continuously increasing while the system delay for providing solutions is decreasing, regardless the amount of the available resources. Thus, the network is capable to adapt better and faster to the environment conditions. Further research in this area will introduce time dimension for network problems in order to enable us to predict traffic conditions and potential problems so as to apply proactively the corresponding solutions before the problem occurs.

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# 4. EXPLOITING CONTEXT, PROFILES AND POLICIES IN DYNAMIC SUB-CARRIER ASSIGNMENT ALGORITHMS FOR EFFICIENT RADIO RESOURCE MANAGEMENT IN OFDMA NETWORKS

Chapter Outline

Dynamic Sub-carrier Assignment (DSA) is considered as one of the most important aspects for achieving efficient spectrum utilization in Orthogonal Frequency Division Multiple Access (OFDMA) based networks. Most of well known DSA algorithms operate in a best effort manner, where the full set of sub-carriers is used in order to achieve the maximum possible QoS level per user. However, in a real network environment there are several management aspects to be considered such as context information (users, services, and radio environment conditions), user profiles and NO policies. In the context of OFDMA networks management, DSA algorithms should be extended incorporating such aspects in order to introduce fairness in the assignment of sub-carriers as well as to improve the overall system performance. In this chapter a new DSA algorithm which exploits also management information of DSNPM, namely Context, Profiles and Policies, is presented. Results showcase the benefits that the proposed approach brings in terms of fairness on sub-carriers assignment and overall system performance.

Keywords: Orthogonal Frequency Division Multiple Access (OFDMA), Dynamic Sub-carrier Assignment (DSA), Context, Profiles, Policies.

## 4.1. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) is today adopted as the multiple access technology from many RATs including e.g. WLANs (802.11 a/g), WiMAX and 3GPP LTE. OFDMA actually extends the Orthogonal Frequency Division Multiplexing (OFDM) transmission scheme for supporting multi-user applications. At the same time, OFDM has been proven to comprise a powerful and spectrum-efficient transmission scheme based on the principle of transmitting simultaneously many narrow-band frequencies (subcarriers), which are orthogonal to each other thus eliminating the interference between channels [1]. Apart from such an inherently robust physical layer-related technique, proper Radio Resource Management (RRM) mechanisms are needed in order to increase performance in terms of spectral efficiency. In the context of RRM in OFDMA-based systems several techniques are provided and aim at addressing the problems of the versatile and highly varying, modern service area in a dynamic manner and by utilizing solutions for radio network adaptation namely, Dynamic Sub-carrier Assignment (DSA), Adaptive Power Allocation (APA) and Adaptive Modulation (AM), capable to address problems of the service area and provide solutions for proper network adaptation [1], [2], [3]. The target of DSA is to find the optimum number of sub-carriers to assign to each user so as they can be served with the maximum possible QoS level. APA is responsible to find the optimum power allocation for the users' sub-carriers in order to address issues of efficient frequency reuse and interference minimization. Finally, the transmitter can utilize AM in order to be able to transmit at higher data rates over the sub-carriers which exhibit better channel conditions, thus ensuring an acceptable Bit Error Rate (BER) in all sub-carriers. In this chapter, we will focus on DSA algorithms and try to exploit their results towards enhancing DSNPM with efficient management for OFDMA-based wireless networks.

Furthermore, NO aim at providing network services to the users at the best possible QoS level and in the most cost-efficient manner [4], [5]. In order to achieve this target, DSNPM optimization functionalities which are responsible to find the most appropriate decisions in terms of feasibility, effectiveness and cost of radio resource usage must be also aware of other higher-level, but still critical information, like user requested services, user profiles and NOs policies. Framed within the above, this chapter introduces an approach for incorporating DSA algorithm inside DSNPM, that consider at the same time all the available management information, namely Context, Profiles and Policies in order to introduce fairness in the way that the sub-carriers are assigned to users, as well as to increase the overall system performance by utilizing the available spectrum only where and when it is necessary. The new algorithm is called CPP-DSA and Figure 4-1 depicts how it is mapped onto DSNPM as part of the optimization process.

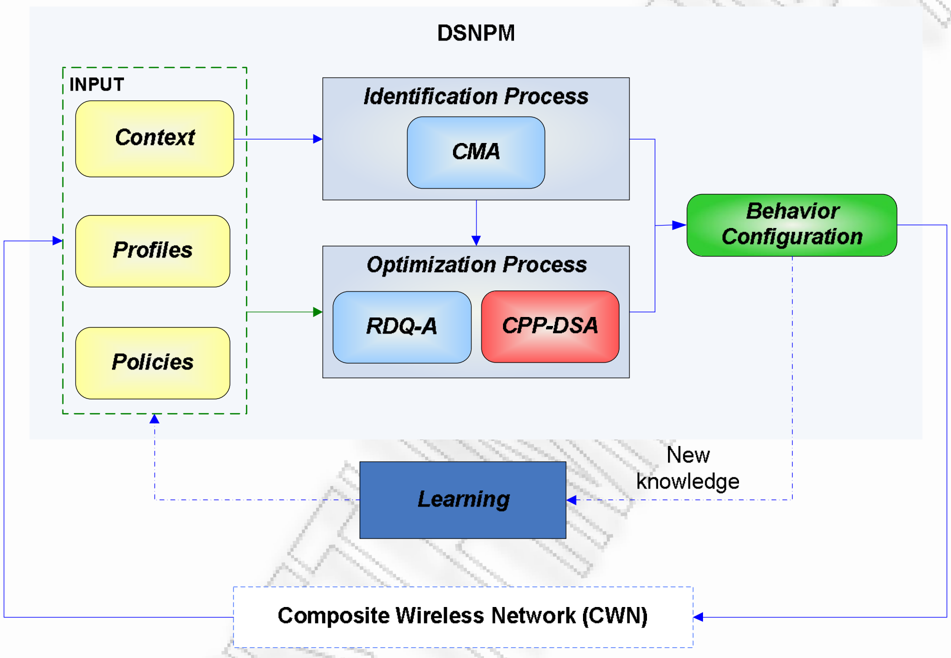

Figure 4-1: Mapping of CPP-DSA algorithm onto DSNPM

The rest of this chapter is structured as follows. The necessary enhancements of DSNPM for incorporating DSA technique for OFDMA-based networks are presented first. Then, a high level description of the assignment problem that DSA technique is applied to is presented, while in section 4.4 several DSA algorithms are presented and described. Section 4.5 provides simulation results showcasing the efficiency of DSNPM with the proposed DSA algorithm. Finally, the chapter is concluded in section 4.7.

## 4.2. Enhancing DSNPM with DSA Technique

Beyond the management information that DSNPM is capable to provide, the input that DSA algorithms require which is related to channel state information should also be provided by DSNPM via context information. Furthermore, the optimization process will provide the best possible sub-carriers assignment sets to user's sessions while the behaviour configuration should also include the corresponding actions targeted to apply the DSA algorithm's decisions. The necessary enhancements of DSNPM entities are described below.

**Context** Monitoring procedures provide, for each network element of the segment, and for a specific time period, the traffic requirements, the mobility conditions, the current configuration in terms operating parameters (eg. spectrum assignment, power level etc) and the QoS levels offered. Furthermore, it includes procedures for capturing the channel state information which is reflected by the estimation of the mean SNR value for each sub-carrier.

**Optimization Process** Part of the optimization procedure is the DSA technique which is expressed by the corresponding DSA algorithms. DSA algorithms try to find the best possible sub-carriers assignment in order to serve users with the highest possible QoS level. However, an efficient RRM scheme will try to exploit also all the available management information in order to guarantee acceptable QoS levels to the users as well as to introduce fairness.

Figure 4-2 depicts how the DSA algorithm is encompassed inside an abstract view of DSNPM.

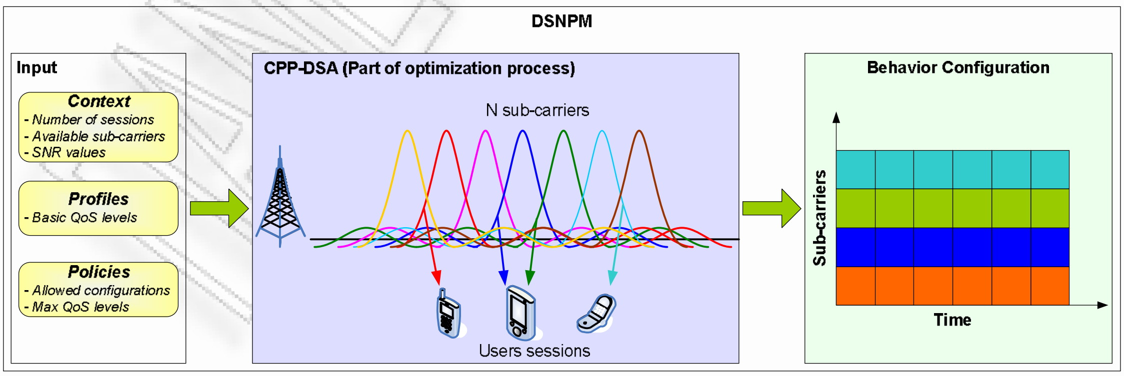

Figure 4-2: DSNPM incorporating CPP-DSA algorithm

Assuming that there are several users in the service area where each one of them is allowed to request multiple sessions, the *Context* input entity will be responsible to provide the traffic and network conditions in terms of the number of active sessions, the requested service for each session, the available sub-carriers as well as their channel information in terms of their mean Signal to Noise Ratio (SNR) values. The *Profiles* input entity will be responsible to provide the user preferences in terms of the QoS level that must be achieved according to the requested service, based on what the users are willing to pay. The impact of this information to the DSA algorithm's decision will be twofold. First, DSNPM will be capable to guarantee that the users will be served with the QoS level that they prefer. Second, fairness will be introduced since in cases where unassigned sub-carriers are available, they will be utilized only for sessions that are still below their preferred QoS level and won't be equally distributed among the sessions regardless of whether their preferred QoS level is achieved or not. Finally, the input from *Policies* entity will be considered as being complementary to the above. The NO's policies can specify, for example, the thresholds for the minimum and maximum allowed QoS levels for each offered service. Thus, it will be guaranteed that all sessions will be served with an acceptable QoS level for each service and also that the system will be capable of serving new potential sessions.

**Behaviour Configuration** In general, decisions are targeted at producing feasible network configurations in terms of a) sub-carriers assignment to users' sessions and b) modulation rate assignment for each sub-carrier based on its mean SNR value. Thus, the decision basically affects the application layer since its target is to guarantee fair QoS levels assignment as well as lower MAC/PHY layers due to changes to the number of assigned subcarriers and their modulation type. Furthermore, in cases of high traffic demand the decision may impose efficient traffic distribution to nearby cells by exploiting potentially free sub-carriers. Framed within the above the role of this entity is twofold. First, it is responsible to translate accordingly the optimization decision to the necessary configuration actions, considering the network elements reconfiguration capabilities. Thus, each network element's capabilities will be fully exploited so as the corresponding configuration actions to be applied with the minimum possible overhead, delay and cost. Second, all the necessary information targeted for learning purposes in terms of currently addressed network and radio environment conditions as well as the corresponding optimum decisions will be provided to Learning functional block in order to be further analysed and processed.

## 4.3. The Assignment Problem of DSA Technique

In this section, a description of the assignment problem that DSA algorithms are applied to will be provided as well as the corresponding formulation framed in the context of DSNPM.

### 4.3.1. Overall Description

As already stated, in an OFDMA-based system the available spectrum is divided into multiple narrowband, interference-free sub-carriers. The target of DSA algorithms is then to find the most appropriate assignment of those sub-carriers to the users, by taking into account their channel state information and resulting in an efficient multiple access scheme that increases the overall system performance as much as possible. As it is depicted in Figure 4-3, multiple sub-carriers are allowed to be assigned to a single user.

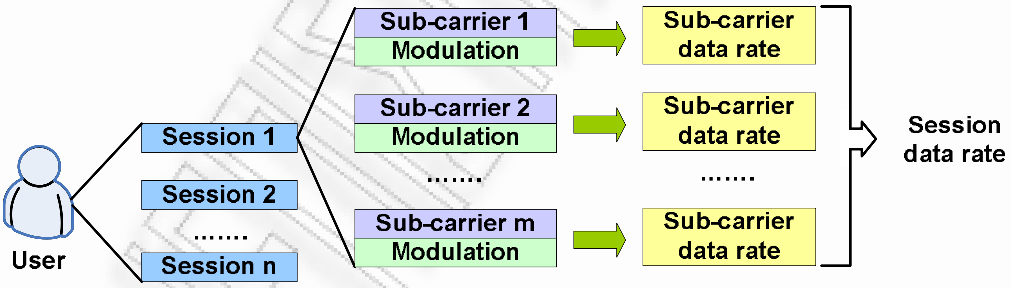

Figure 4-3: Sub-carrier assignment to user sessions

The number of sub-carriers needed to be assigned to a user may depend on several parameters like user location, requested service, user profile and NO's policies. Moreover, information on the channel state, as seen by a specific user on each sub-carrier is also considered in order to select the most appropriate modulation scheme in an adaptive manner.

## 4.3.2. Problem Formulation

### 4.3.2.1 Context

We consider a set of *N* active user sessions $S = \{s : s = 0,1,...N\}$ that comprise the demand in the service area. Set $SC = \{j : j = 0,1,...,K\}$ is the set of available sub-carriers to be assigned to user sessions. The DSA algorithms that will be studied here need channel information which is assumed to be reflected by the mean SNR value for each sub-carrier $j$ $(j \in SC)$ and session $s$ $(s \in S)$. We consider a set of $N \times K$ SNR values $SNR = \{snr_{s,j} : snr_{s,j} \in R\}$ that reflect this channel information for each sub-carrier $j$ $(j \in SC)$ and session $s$ $(s \in S)$ [6], [7].

The bit rate that can be achieved for each sub-carrier $j$ $(j \in SC)$ assigned to session $s$ $(s \in S)$ depends on the SNR value $snr_{s,j}$ [8], [9]. We consider the following Modulation Rates (*MRs*) that will be selected for each sub-carrier based on the $snr_{s,j}$ SNR value.

$$MR(snr_{s,j}) = \begin{Bmatrix} k \;\; bits/symbol & a \le snr_{s,j} < b \\ l \;\; bits/symbol & b \le snr_{s,j} < c \\ m \;\; bits/symbol & c \le snr_{s,j} < d \end{Bmatrix} \tag{4.1}$$

where $k, l, m$ denote the number of bits transmitted per symbol and holds that $k < l < m$. Considering the above, the bit rate for the sub-carrier $j$ assigned to session $s$ is

$$br(s,j) = SR \times MR(snr_{s,j})$$

where $SR$ is the Symbol Rate (symbols per second) and $MR(snr_{s,j})$ is the number of bits to be transmitted per symbol based on the SNR value $snr_{s,j}$ of sub-carrier $j$ $(j \in SC)$ which is assigned to session $s$ $(s \in S)$. The session data rate is

$$B_s = \sum_j \left[ x_{s,j} \cdot br(s,j) \right] \tag{4.2}$$

where $x_{s,j} \in \{0,1\}, \forall s, j$ is a decision variable used to denote whether sub-carrier $j$ is assigned to session $s$ (1) or not (0). The total capacity achieved in the service area is

$$\sum_s B_s = \sum_s \sum_j \left[ x_{s,j} \cdot br(s,j) \right] \tag{4.3}$$

It also holds that for each sub-carrier $j$

$$\sum_s x_{s,j} \le 1, (s,j) \in (S \times SC) \tag{4.4}$$

since each sub-carrier is allowed to be assigned to only one session [9], [10].

#### 4.3.2.2 Profiles

The input from profiles management entity is considered in the form of a set of *M* user profiles $P = \{p : p = 0,1,...M\}$. In our case, each profile imposes a specific target bit rate $p_s\ (s \in S)$ that must be achieved for each session. Thus, the total achieved bit rate for each session, as given by (4.2), will be equal to $p_s$ when the necessary sub-carriers are available or less otherwise, but still the maximum possible. Thus, the following constraint should always be satisfied:

$$\sum_j \left[ x_{s,j} \cdot br(s,j) \right] \le p_s \tag{4.5}$$

#### 4.3.2.3 Policies

We consider a set of *Q* policies $NP = \{np : np = 0,1,...Q\}$ provided by the policies derivation entity. Each policy simply corresponds to the maximum allowed bit rate based on the network and radio environment conditions. Considering that the policy for each session $s$ is denoted as $np_s\ (s \in S)$, the total achieved bit rate for each session (as given in relation (4.2)) should be less or equal to the session's policy. Thus, the following restriction should always be satisfied:

$$\sum_j \left[ x_{s,j} \cdot br(s,j) \right] \le np_s \tag{4.6}$$

It also holds that a session policy $np_s$ can be greater or equal with the session's user profile $p_s\ (p_s \le np_s)$ in cases where either there are several network resources available and the NO wants to provide the maximum possible bit rate or the user profile targets at low bit rates. However, in cases where the traffic in the service area is increased the

NO's policies can be configured to act as the upper limit for the bit rate to be achieved, regardless of the users' profiles target bit rates. In these cases it holds that $np_s \leq p_s$.

## 4.4. Algorithms Description

In the following sub-sections, we present five DSA algorithms for the solution of the optimization problem described by relationships (4.1)-(4.6). The first four sub-sections describe algorithms that take into account only the context information while the last sub-section (4.4.5) presents the proposed DSA algorithm which considers Context, Profiles and Policies (CPP) information and is called CPP-DSA algorithm.

### 4.4.1. The Hungarian based algorithm

The first presented DSA algorithm is based on the well known Hungarian method [11], [12]. The Hungarian method is targeted to the solution of the general assignment problem [13]. In particular, it manages to optimally solve the problem of assigning *n* jobs to *n* workers in polynomial time. To do so, it performs matrix manipulations upon a nonnegative *n* × *n* matrix, where the element in the *i-th* row and *j-th* column represents the cost (/performance score) of assigning the *j-th* job to the *i-th* worker, respectively. The goal is to find an assignment of the jobs to the workers, which has minimum (/maximum) cost (/performance score). A detailed description of Hungarian method is out of the scope of this paper and can be found in [11].

The Hungarian algorithm can be applied also for providing the optimum solutions for the assignment of sub-carriers to sessions. Correspondingly, the input is considered in the form of a $N \times K$ *(i.e. number of sessions* × *number of sub-carriers*) matrix, where each matrix element corresponds to the estimated mean SNR value for each session (row) and sub-carrier (column), respectively. The Hungarian-based algorithm considered in this paper aims at finding the best possible assignment of sub-carriers to sessions and specifically the one that maximizes the total sum of the mean SNR values. The complexity of this algorithm is $O\left(K^3\right)$ where $K$ denotes the total number of available sub-carriers. It should be also noted that for compliance to the originally defined method the following relation holds, $N = K$. The optimal assignment produced by the

Hungarian-based algorithm will be used as a reference to the sub-optimal algorithms presented in the sequel.

### 4.4.2. The advanced Dynamic Algorithm

The second algorithm is the advanced Dynamic Algorithm (aDA) available in [6]. This sub-optimal algorithm is based on priorities and weights for selecting the next wireless terminal to assign the sub-carriers. In particular, aDA assigns sub-carriers with a better quality to the wireless terminals with the highest priority. The weight of a sub-carrier expresses how well it might be used by all other terminals with a lower priority than the currently considered one. The algorithm will finish after all sessions have been assigned with a sub-carrier. The complexity of this algorithm is $O(K \times N \times \log(N))$ since the complexity of sorting $N$ sessions is $N \times \log(N)$ and it will be performed for $K$ sub-carriers. aDA is depicted in Figure 4-4(a) and takes steps as follows:

***Step 1*** *Random generation of sessions' priorities*

For each session a random priority is generated. In this way the session with priority equal to 1 has the highest possible priority while the session with priority equal to 0 has the lowest possible one.

***Step 2*** *Sort sessions in increment order based on priorities*

The sessions are sorted in increment order based on their current priorities. The first session will the one with the highest possible priority compared to the others.

***Step 3*** *Sub-carriers' weight estimation*

A weight of a sub-carrier $j$ of session $s$ i.e. $\left(weight_{j,s}\right)$, is given by the sum of all Channel to Noise Ratio (CNR) values of this sub-carrier regarding all sessions with lower priority than the priority of session $s$. In this way the weight for each sub-carrier for the selected session $s$ is estimated.

***Step 4*** *Weight ratio estimation*

The weight ratio for sub-carrier $j$ of session $s$ is defined as $CNR_{j,s} / weight_{j,s}$. The weight ratio of each sub-carrier of the selected session $s$ is estimated.

***Step 5*** *Select the sub-carrier with maximum weight ratio and assign it to current session*

The sub-carrier with the highest possible weight ratio is selected to be assigned to the selected session $s$.

***Step 6*** *Priorities switching*

This algorithm assigns the sessions of high priorities with sub-carriers of better quality than it assigns the sessions with the lowest priority. To balance this unfairness the priorities are switched after each assignment. In this way, the priority of each session is decreased by one and thus the session with the highest priority will receive for the next assignment the lowest priority.

### 4.4.3. Basic-CPP-DSA algorithm

The Basic-CPP-DSA (B-CPP-DSA) algorithm considers only the input of context information. The selection of the next session to assign a sub-carrier to is based on the session's mean SNR value for all the available sub-carriers to this session. The algorithm selects the session with the minimum mean SNR value in order to guarantee that sessions with few or less available sub-carriers will be selected for sub-carrier assignment first, compared to the other sessions. After selecting the next session, B-CPP-DSA will select the most appropriate sub-carrier among the available sub-carriers for this session. Once more, the selection will be based on the minimum mean SNR value but in this case it will be estimated from all sessions' SNR values of the sub-carriers capable of achieving the maximum possible bit rate. Thus, the sub-carrier mean SNR value won't be estimated for all the sub-carriers of the selected session but only for the sub-carriers where the maximum data rate can be achieved. Each session which is assigned with a sub-carrier is never checked again, and the algorithm will finish after all sessions are assigned. The steps of B-CPP-DSA algorithm are depicted in Figure 4-4(b) and can be described as follows:

***Step 1*** *Sessions' mean SNR values calculation*

For each unassigned session $s$ the mean SNR value will be calculated from the SNR values of the available, unassigned sub-carriers to this session i.e. $K_s^{un} \subseteq SC$ . It is assumed that sessions with low mean SNR value are experiencing bad conditions in terms of the total number and the quality of their available sub-carriers. Thus, the session $s^*$ that will be selected for being assigned with a sub-carrier first will be the one with the minimum mean SNR value estimated for each of the unassigned sub-carriers $j$ that it can sense. This can be formulated as follows:

$$s^* = \arg\min_s \left( \frac{\sum_j snr_{s,j}}{K_s^{un}} \right), \qquad j \in K_s^{un}$$

where it is recalled that a) function $\arg\min_x f(x)$ returns the value of the argument i.e., *x*, for which the value of the given expression i.e., *f(x)*, attains its minimum value and b) $K_s^{un} \subseteq SC$ contains the total number of unassigned sub-carriers of session $s$.

***Step 2*** *Find sub-carriers sub-set with the highest modulation rate*

As long as the next session to be assigned with a sub-carrier is already selected in step 1, the algorithm will then select a sub-carrier that is capable to provide high bit rates. Based on the SNR values of the session's sub-carriers, a sub-set, $\widehat{SC} \subseteq SC$ containing sub-carriers capable to achieve the highest possible modulation rate (as given in relation (4.1)), is created, namely:

$$\widehat{SC} = \left\{ j \mid MR\left(snr_{s^*,j}\right) = m \right\}$$

***Step 3*** *Mean SNR values estimation for sub-carriers in sub-set*

Given the sub-set $\widehat{SC}$ (which contains the sub-carriers that are capable to provide the highest possible bit rate for the selected session), the algorithm will estimate the mean SNR value for each one of the sub-carriers that it contains. The mean SNR value for a sub-carrier $j$ in $\widehat{SC}$, be it $\overline{snr}_j$, is estimated from the SNR values of this sub-carrier for all the other unassigned sessions, namely:

$$\overline{snr}_j = \frac{\sum_s snr_{s,j}}{N_j^{un}}, \qquad j \in \widehat{SC},\ s \in N_j^{un}$$

where $N_j^{un} \subseteq S$ stands for the set containing the total number of unassigned sessions that can also sense sub-carrier $j$.

***Step 4*** *Select the sub-carrier with the minimum mean SNR value and assign it to current session*

The sub-carrier $j^*$ with the minimum mean SNR value is considered to be the sub-carrier the capabilities of which will be exploited in the best way by the selected session, in comparison to the other unassigned sessions. The $j^*$ is selected as follows:

$$j^* = \arg\min_j \left( \frac{\sum_s snr_{s,j}}{N_j^{un}} \right) \Leftrightarrow j^* = \arg\min_j \left( \overline{snr_j} \right), \qquad j \in \widehat{SC},\ s \in N_j^{un}$$

The result of the described process is the assignment, $x_{s^*,j^*} = 1$, i.e. $s^*$ is assigned with sub-carrier $j^*$. The 4 steps of the algorithm are repeated until all sessions are assigned with a sub-carrier.

In order to give some evidence on the algorithm's complexity, we estimate the number of performed comparisons that dominate each step. First in step 1, each session's mean SNR should be compared with the minimum value found, in order to determine whether it is the minimum or not. The number of comparisons at the first time that step 1 is executed is $N-1$, which is actually the total number of comparisons needed in order to find the minimum in a set of $N$ elements. Each time step 1 is executed, the total number of unassigned sessions is decreased by one i.e. going from $N$ to $N-1$, then to $N-2$ and so on, while the number of comparisons will be accordingly decreased from $N-1$, to $N-2$, then to $N-3$ and so on. Summing up all the comparisons needed for step 1, the algorithm's complexity can be easily extracted to be in the order of $O(N^2)$. In step 2, each sub-carrier of the selected session should be checked whether it belongs to the high modulation rate sub-set or not. Considering the worst case, in which the selected session senses all the sub-carriers, there are $K$ comparisons. The complexity in this case will be $O(K \times N)$. In step 3 the mean SNR values for each sub-carrier in the sub-set is estimated, but no comparisons are needed. Finally in the last step, the number of comparisons needed in order to determine the sub-carrier with the minimum mean SNR value, is $K$, considering the worst case where all the available sub-carriers belong to the high modulation rate sub-set. Thus, the complexity in step 4 is in the order of $O(K \times N)$.

### 4.4.4. Assignment based on Max SNR values

The last sub-optimization algorithm is based on the simple criterion of selecting the sub-carrier and the corresponding session with the maximum mean SNR value. Each session will be assigned with a sub-carrier and the algorithm will finish after all sub-carriers are assigned to sessions. The complexity of this algorithm (Max-SNR) is $O(K \times N)$ because we need to know for each session the sub-carrier with the maximum SNR value. Max-SNR algorithm is depicted in Figure 4-5(a) and takes the following steps:

***Step 1*** *Find session with the maximum SNR value*

The sub-carrier with the maximum SNR value is found. The session of which the sub-carrier has the maximum SNR value is selected.

***Step 2*** *Assign this sub-carrier to session*

The new assignment will be the pair of session and sub-carrier where the sub-carrier has the maximum SNR value.

The target of Max-SNR algorithm is to assign each sub-carrier to the session that its quality will be exploited the most. Despite the fact that this statement seems to be logical, it introduces unfairness in the way that the sub-carriers are assigned to sessions. In particular, let's suppose that session $s_1$ can be served by low quality sub-carriers as well as by sub-carrier *A* which is sensed in medium quality. Furthermore, session $s_2$ is sensing several sub-carriers of high quality as well as sub-carrier *A* which is sensed in the maximum mean SNR value for this session. In such cases, Max-SNR algorithm will choose to assign sub-carrier *A* to session $s_2$, instead of $s_1$, despite the fact that a) session $s_2$ can be served also by other high quality sub-carriers and b) sub-carrier *A* is the only option for session $s_1$ to receive the maximum possible QoS level.

### 4.4.5. CPP-DSA algorithm

The target and the concept of the CPP-DSA algorithm is the same as its basic version (B-CPP-DSA) however, it considers greater number of available sub-carriers compared to the number of active sessions and additional information from *Profiles* and *Policies* entities so as to estimate the target bit rate for each session that must be achieved. Thus, each session can be assigned with one or more sub-carriers. The algorithm will finish either when all sub-carriers are assigned to sessions or there are no more sessions to be further assigned with the remaining sub-carriers. In order for all the above to be considered, the extended CPP-DSA algorithm incorporates further steps for the comparison of the currently achieved bit rate per session and the target one. The algorithm is depicted in Figure 4-5(b) and takes steps as follows:

***Step 1*** *Sessions' mean SNR values calculation*

For each session the mean SNR value will be calculated from the SNR values of the available sub-carriers to this session. It is assumed that sessions with low mean SNR value are experiencing bad conditions in terms of the total number and the quality of their available sub-carriers. Thus, the session that will be assigned first will be the one with the minimum mean SNR value.

***Step 2*** *Find sub-carriers sub-set with the highest modulation rate*

Since the next session to assign a sub-carrier to is already selected, the algorithm will select a sub-carrier that is capable to provide high bit rates. Based on the SNR values of the session's sub-carriers, a sub-set containing the sub-carriers of the highest possible modulation rate is created.

***Step 3*** *Mean SNR values estimation for sub-carriers in sub-set*

Given the sub-set which contains the sub-carriers capable to provide the highest possible bit rate for the selected session, the algorithm will estimate the mean SNR value for each one of the sub-set sub-carriers. The mean SNR value for a sub-carrier is estimated from the SNR values of this sub-carrier for all the other unassigned sessions.

***Step 4*** *Select the sub-carrier with the minimum mean SNR value*

The sub-carrier with the minimum mean SNR value is considered to be the sub-carrier that the selected session will exploit its capabilities better compared to the other unassigned sessions. This sub-carrier is candidate for assignment to the selected session.

***Step 5*** *Target bit rate achieved?*

Taking into account all the previous assigned sub-carriers for the selected session as well as the candidate one, the bit rate for this session is estimated. In case that the estimated bit rate is above the target bit rate for this session the algorithm proceeds to step 6, otherwise to step 7.

***Step 6*** *Assign sub-carrier to current session and remove session for list*

Since the estimated bit rate for this session is above the target one, the candidate sub-carrier should be permanently assigned to the current session. Furthermore, this session should not be checked again for further assignment so it is removed from sessions list.

***Step 7*** *Assign sub-carrier to current session*

Since the estimated bit rate for this session is below the target one a) the candidate sub-carrier should be permanently assigned to the current session and b) this session should be checked again for further assignment until the target bit rate is reached.

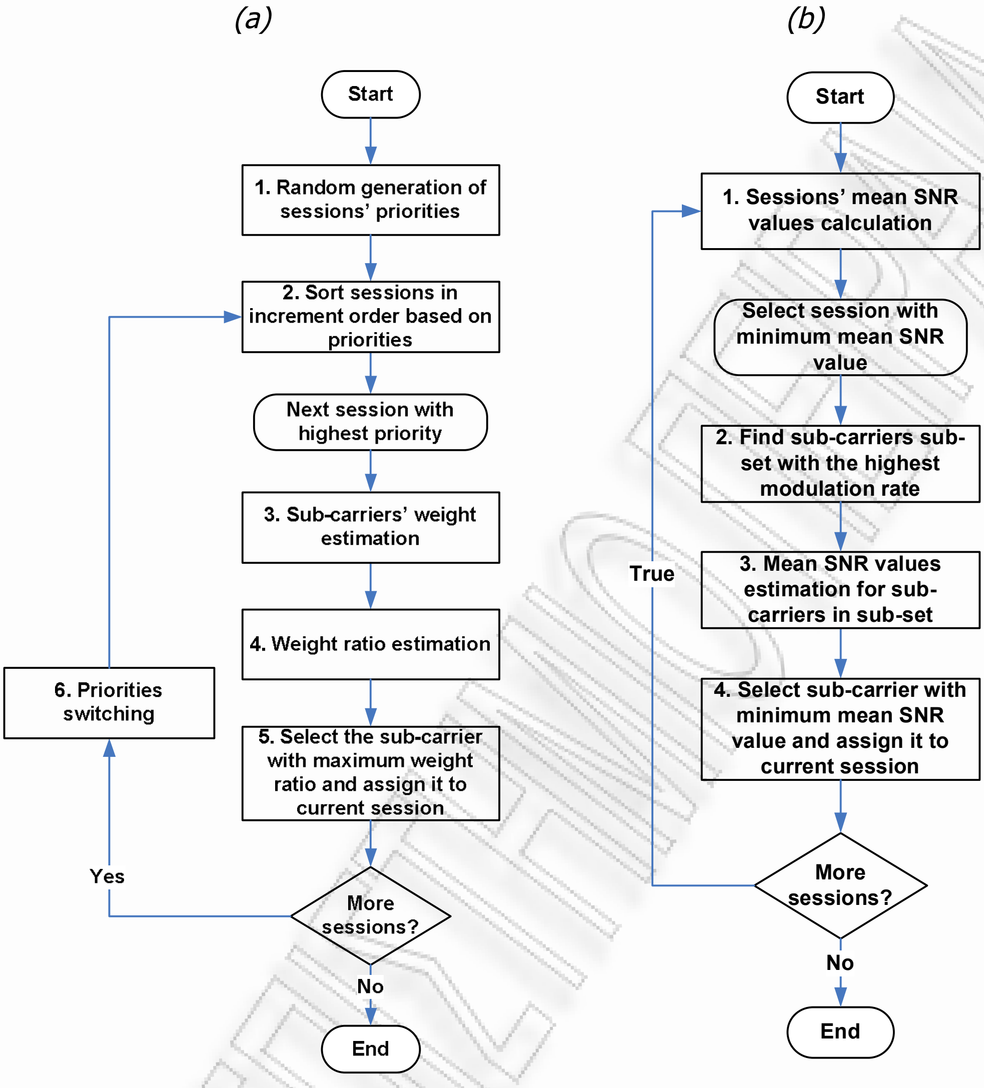

Figure 4-4: (a) Flowchart for the aDA algorithm, (b) Flowchart for the Basic-CPP-DSA algorithm

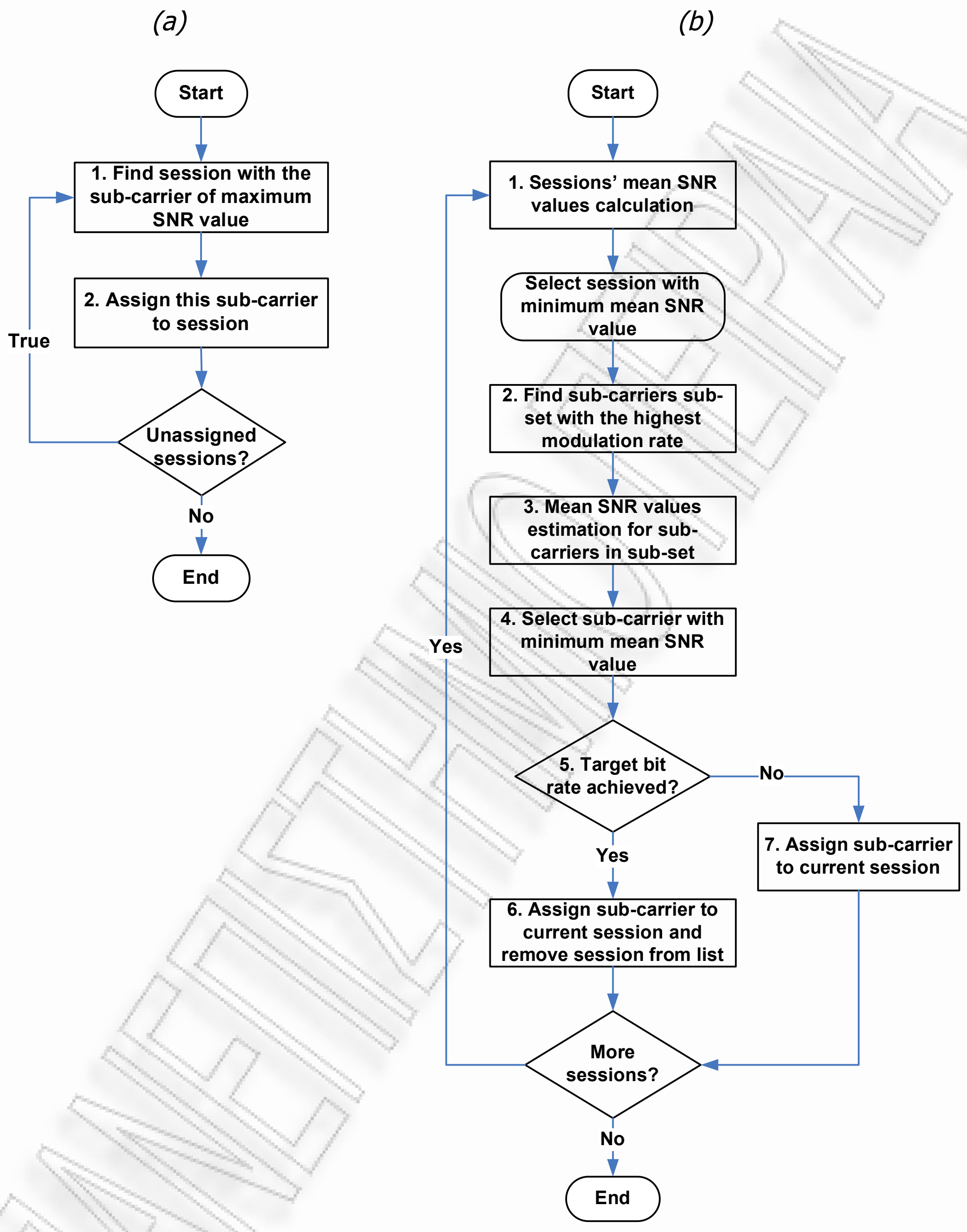

Figure 4-5: (a) Flowchart for the Max-SNR algorithm, (b) Flowchart for the CPP-DSA algorithm

## 4.5. Results

In this section a performance evaluation and comparative analysis of the above described algorithms is given. The algorithms are developed into Java code and run on a Pentium-4 3.0 GHz with 1.5 GB of RAM.

Two scenarios are considered. In the first scenario, the input will comprise only context information so as to evaluate the performance and also to compare results among Hungarian, aDA, B-CPP-DSA and Max-SNR algorithms. In the second scenario the efficiency of CPP-DSA algorithm will be studied considering not only context input but also profiles and policies in order to deal with real network conditions.

In both scenarios a service area is assumed which is covered by LTE RAT and the focus is placed on the OFDMA-based downlink [14]. The following context information is available: the number of active sessions in the system, the number of available sub-carriers, as well as their mean SNR values for each session. In addition, we consider the following modulation rates based on relation (4.1):

$$MR(snr) = \left\{ \begin{array}{ll} 3\ bits/symbol & (8-QAM) \\ 4\ bits/symbol & (16-QAM) \\ 6\ bits/symbol & (64-QAM) \end{array} \right\}$$

Taking into account the above MRs as well as the symbol rate (SR) of LTE RAT, which is 1 symbol per 66.7 $\mu s$ [15], the bit rates for each one of the above MRs are summarized in Table 4-I.

Table 4-I: Bit rates in LTE for each MR

| **Modulation Rate (bits/symbol)** | **Bit rate (Kbps)** |
|---|---|
| *3* | *45* |
| *4* | *60* |
| *6* | *90* |

Finally, three SNR classes are employed for the categorization of the sub-carriers according to the bit rate that can be achieved based on the perceived SNR values. The sub-carriers capable to achieve 45 Kbps are classified to the Basic class. Sub-carriers achieving 60 Kbps and 90 Kbps are classified to Medium and High classes, respectively.

### 4.5.1. Scenario 1 – Performance evaluation

In this scenario and in order to facilitate the comparisons to the optimal Hungarian-based algorithm, the number of available sub-carriers is assumed to be equal to the number of active sessions. Figure 4-6 depicts the percentage of sessions for each SNR class, provided by context information.

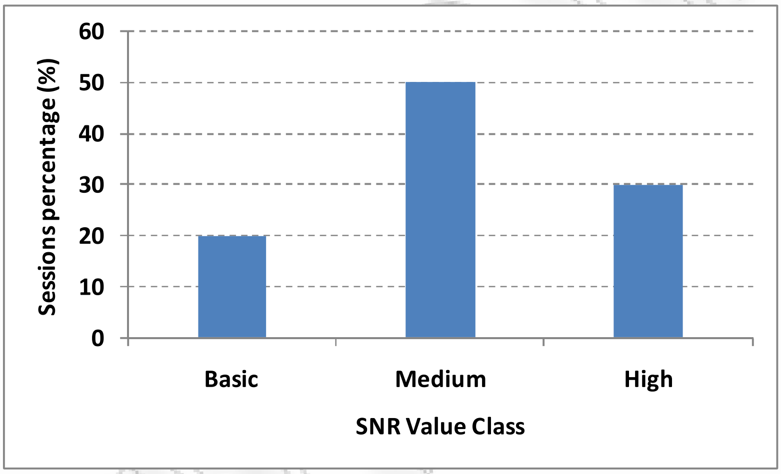

Figure 4-6: Scenario 1 – Percentages of sessions per SNR class

It is clear that 50% of the active sessions are covered by sub-carriers of Medium SNR class meaning that each sub-carrier of this class can offer up to 60 Kbps. Furthermore, the percentage of sessions that are covered by sub-carriers of High SNR class, meaning that each one of these sub-carriers can offer up to 90 Kbps, is 30%. Finally, 20% of active sessions are covered by sub-carriers of Basic SNR class which can offer low bit rates up to 45 Kbps due to bad channel quality.

In this scenario we consider seven traffic cases which differ on the number of active sessions. The number of active sessions for the first traffic case is 50 and each of the next cases derives from a 25 sessions increase in the number of sessions of its previous case. Thus, we have the traffic cases of 50, 75, 100, 125, 150, 175 and 200 active sessions. Given the assignment sets of each DSA algorithm, the data rate Bs (as given in relation (4.2)) for each session in the traffic cases can be estimated. The capacity is equal to the sum of Bs (as given in relation (4.3)) of all sessions s in the traffic case and it is depicted in Figure 4-7.

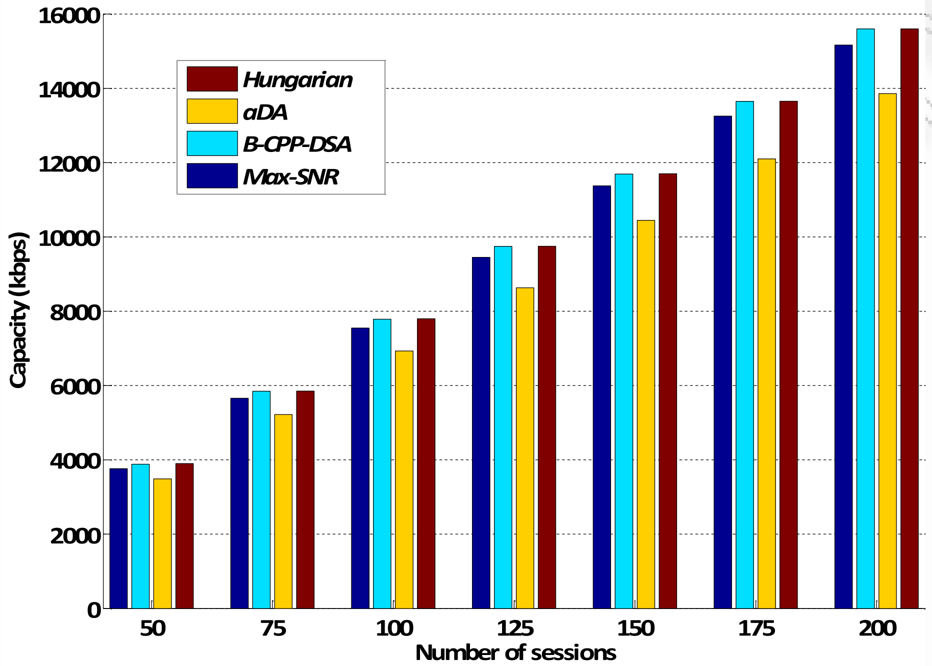

Figure 4-7: Scenario 1 – Average capacity of the service area for several traffic cases

As expected, the Hungarian algorithm provides the optimum decisions for each traffic case. Thus, the capacity of the service area estimated by the corresponding allocation sets is always the maximum possible. On the contrary, aDA algorithm provides allocation sets with the minimum capacity for each traffic case compared to the other algorithms. Thus, the capacity which B-CPP-DSA and Max-SNR algorithms provide is among the capacity provided by the Hungarian and aDA algorithms. As it is depicted in Figure 4-7, the capacity estimated by the allocation sets of B-CPP-DSA algorithm for each traffic case is the closest to the optimum capacity, compared to the other algorithms, and sometimes are even equal. Finally, the Max-SNR algorithm managed to provide allocation sets achieving capacity close to the optimum one because of the fact that it tries to exploit as much as possible the sub-carrier's channel quality regardless the fairness of the assignment sets.

Furthermore, Figure 4-8 depicts the capacity difference between the sub-optimum algorithms (aDA, B-CPP-DSA and Max-SNR) and optimum algorithm (Hungarian).

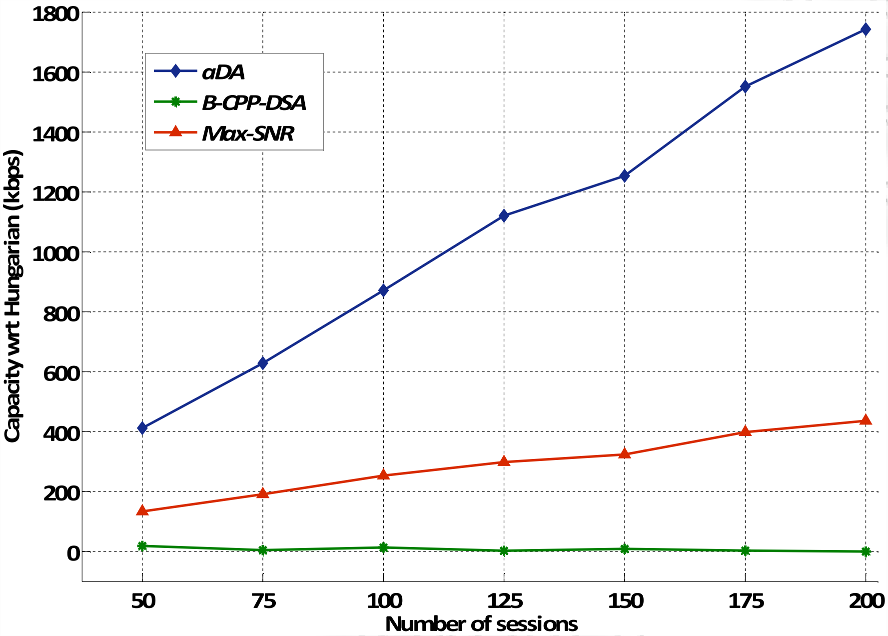

Figure 4-8: Scenario 1 – Capacity difference of aDA, B-CPP-DSA and Max-SNR algorithms from Hungarian algorithm

It is clear that the capacity difference between algorithms aDA and Hungarian is the maximum since aDA provided the minimum average capacity in the service area (Figure 4-7). For example, in case of 100 active sessions the capacity difference for aDA from Hungarian is almost 900 Kbps while for Max-SNR the difference is 250 Kbps. B-CPP-DSA algorithm has the minimum difference from Hungarian for all traffic cases. More specifically, for the case of 100 sessions the difference is 14 Kbps since the Hungarian algorithm provides 7800 Kbps capacity and CPP-DSA algorithm provides 7786 Kbps which corresponds to 99.82% of the maximum possible capacity that can be achieved, as provided by the Hungarian algorithm. The maximum difference for the considered cases of the scenario is 19 Kbps in the first case where 50 sessions are active and corresponds to 99.5% of the optimum decision. It is of great importance also to notice that in the last case of 200 active sessions both Hungarian and CPP-DSA algorithms provided the same achieved capacity of 15600Kbps. Thus, in this case the capacity provided by the sub-optimum CPP-DSA algorithm corresponds to 100% of the optimum capacity that could be achieved by the Hungarian algorithm.

Another significant indicator, beyond the achieved capacity, is the algorithms' mean execution delay which can be studied in accordance with algorithms' complexity. Figure 4-9 depicts the mean delay for each algorithm and traffic case.

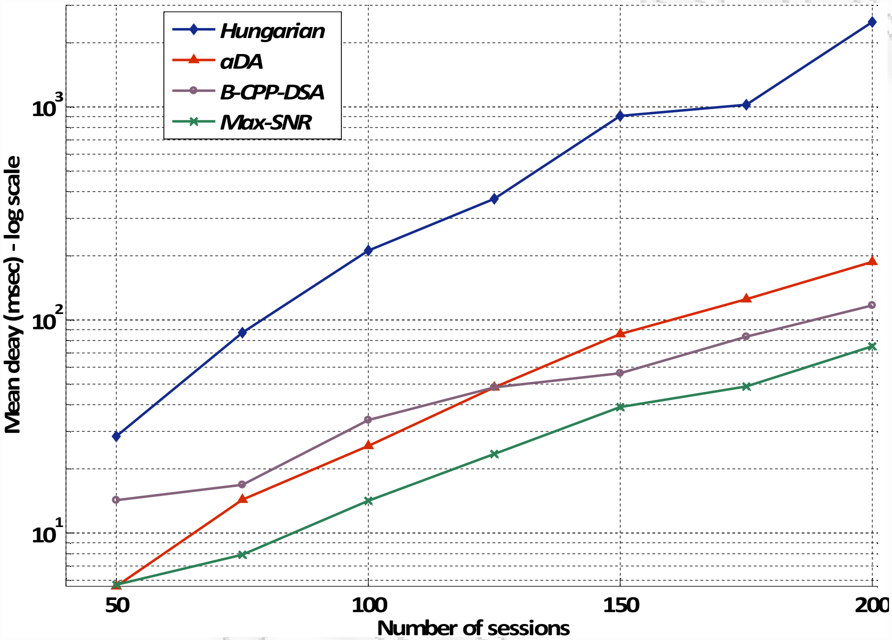

Figure 4-9: Scenario 1 – Mean delay for each algorithm and traffic case

Since the Hungarian algorithm provides optimum allocation sets and its complexity is the highest compared to the other algorithms, the execution delay is the highest and increases exponentially with the number of sessions. Algorithm aDA is much faster than the Hungarian but still it is the slowest compared to the others when the number of sessions are above 175. The variance of mean execution delay of algorithm CPP-DSA is 15-90 msec, however the fastest among all the algorithms is the Max-SNR due to its low complexity with 6-70 msec variance.

### 4.5.2. Scenario 2 – Awareness of Context, Profiles and Policies

In the first scenario it was assumed that the number of available sub-carriers is equal to the number of active sessions and thus, each session will be served only by one sub-carrier. In this scenario it is assumed that the number of available sub-carriers is greater than the number of active sessions, thus each session can be served by several sub-carriers. Furthermore, the target bit rate for each session that must be achieved will be also considered. Hence, the CPP-DSA algorithm will be used for this scenario.

The target bit rate for each session that should be achieved by the sub-carriers assignment set is estimated by the corresponding user profile for each session as well as the NO's policies as described in relations (4.5) and (4.6). In this scenario it is assumed that the maximum allowed bit rate (NO's policy) is equal to the user's profile target bit rate in order the maximum possible bit rate for each session to be achieved. The considered user profiles as well as their QoS level to be achieved, expressed in Kbps, are depicted in Table 4-II.

Table 4-II: Scenario 2 – User profiles and QoS levels

| **User profile** | **Bit rate (Kbps)** |
|---|---|
| *Basic* | *64* |
| *Bronze* | *128* |
| *Silver* | *384* |
| *Gold* | *512* |

Seven cases are considered for this scenario, which differ in the percentage of sessions that they assume to be allocated in each of the user profiles. The sessions' percentages per user profile for each case are depicted in Table 4-III. It is quite easy to notice that the percentage of sessions in high QoS level user profiles is increasing with the case index. Thus, in the first case the target bit rate for all the sessions is the QoS level of the Basic user profile which is 64 Kbps, while in the last case the target bit rate for all the sessions is the QoS level of the Gold user profile which is 512 Kbps. Case 4 is an indicative traffic case where the highest percentages are of Bronze and Silver user profiles while the percentages of Basic and Gold are lower, with the Basic profile to be a little bit higher than Gold.

Table 4-III: Scenario 2 – Percentages of sessions per user profile

| Case | Basic (%) | Bronze (%) | Silver (%) | Gold (%) |
|---|---|---|---|---|
| *1* | *100* | *0* | *0* | *0* |
| *2* | *10* | *90* | *0* | *0* |
| *3* | *40* | *30* | *20* | *10* |
| *4* | *24* | *32* | *27* | *17* |
| *5* | *0* | *50* | *50* | *0* |
| *6* | *10* | *20* | *30* | *40* |
| *7* | *0* | *0* | *0* | *100* |

Taking into account all the aforementioned, the CPP-DSA algorithm will be executed for each one of the above cases and for different LTE channel sizes. Actually, LTE system is expected to operate in scalable bandwidths of 5MHz, 10MHz, 15MHz and 20MHz, as well as in less than 5MHz bandwidths i.e. 1.25MHz, 1.6MHz, 2.5MHz, in both downlink and uplink [14]. Moreover, the entire channel is divided into sub-sets of several numbers of sub-carriers, called chunks. In [16], the number of available sub-carriers for several of the aforementioned different spectrum sizes for accommodating the traffic demand is provided. In this scenario, spectrum bandwidth of 5 MHz, 10 MHz and 15 MHz is assumed. An indicative example is given for a 10MHz channel in Table 4-IV.

Table 4-IV: 10MHz channel configuration

| Number of chunks | *1* | *5* | *10* | *15* | *30* |
|---|---|---|---|---|---|
| **Data sub-carriers per chunk (no pilot sub-carriers in OFDM symbol)** | *600* | *120* | *60* | *40* | *20* |
| **Data sub-carriers per chunk (pilot sub-carriers in OFDM symbol)** | *450* | *90* | *45* | *30* | *15* |
| **Chunk bandwidth (MHz)** | *9.0* | *2.8* | *0.9* | *0.6* | *0.3* |

Based on the corresponding tables for each one of the aforementioned LTE channels Table 4-V is extracted, which provides the total number of available sub-carriers for each channel bandwidth.

Table 4-V: Total available sub-carriers for each LTE channel

| LTE channel (MHz) | Total sub-carriers |
|---|---|
| 5 | 225 |
| 10 | 450 |
| 15 | 675 |

The CPP-DSA algorithm was executed for 100 sessions in a service area considering also the management information described above. Figure 4-10, Figure 4-11 and Figure 4-12, provide information on the percentage of sessions that were assigned 1 to 6 sub-carriers for the channels of 5MHz, 10MHz and 15MHz respectively, as retrieved from the sub-carriers' assignment set of CPP-DSA algorithm.

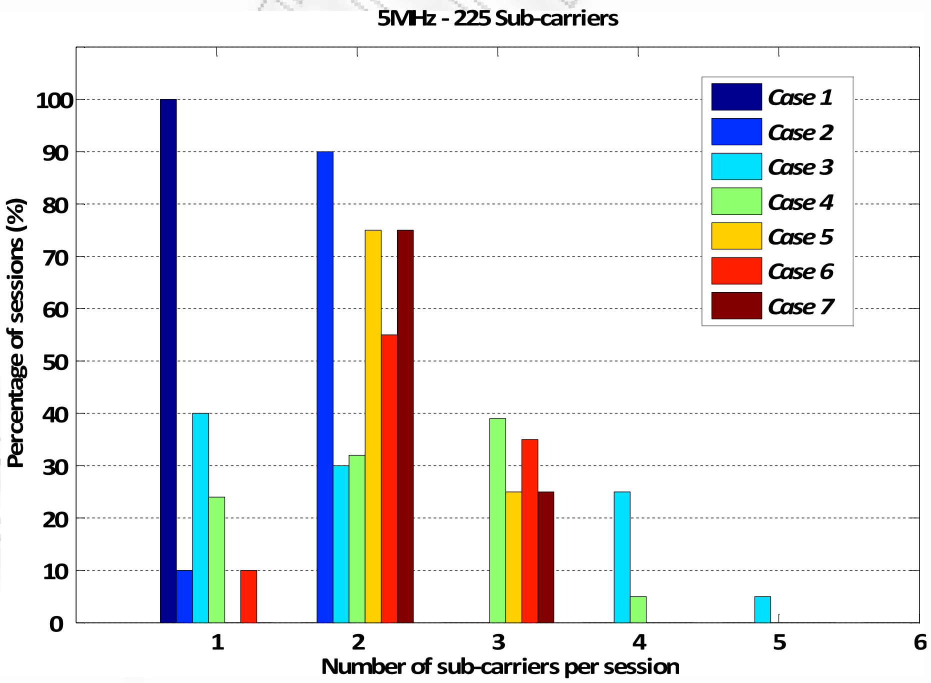

Figure 4-10: Scenario 2 - The percentage of sessions allocated with a specific number of sub-carriers in 5MHz channel

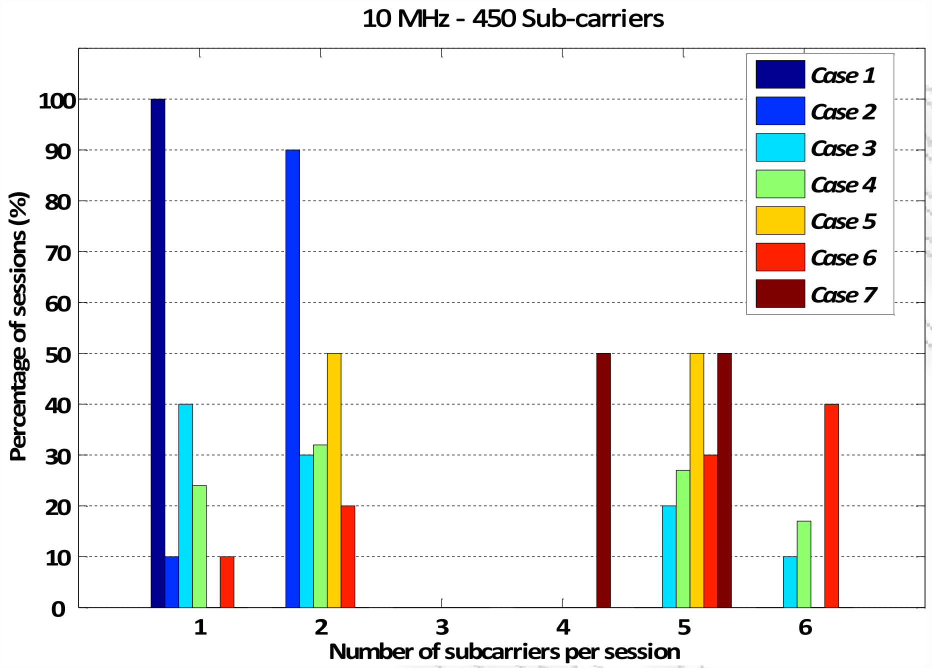

Figure 4-11: Scenario 2 - The percentage of sessions allocated with a specific number of sub-carriers in 10MHz channel

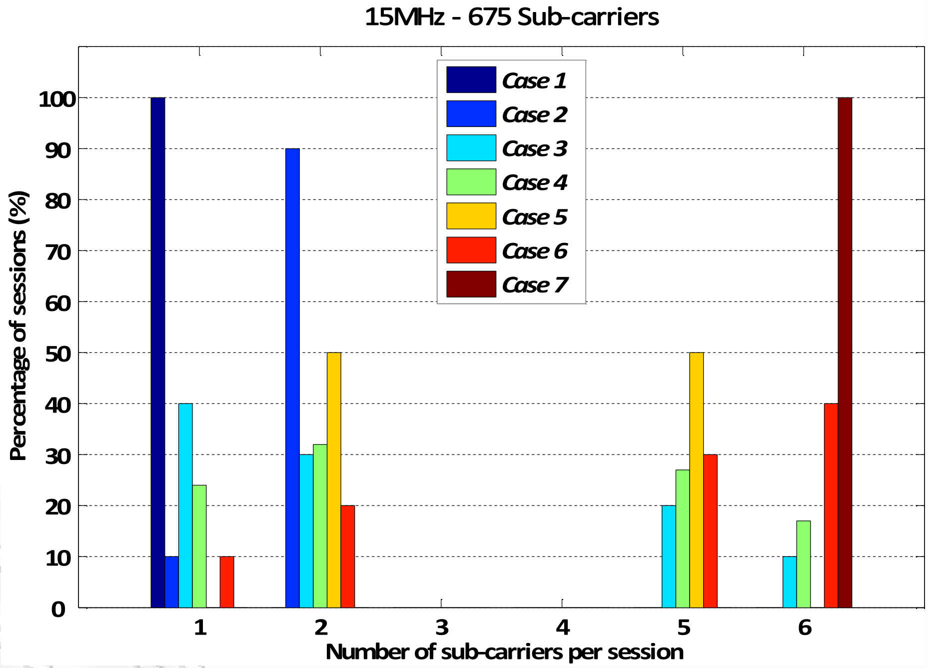

Figure 4-12: Scenario 2 - The percentage of sessions allocated with a specific number of sub-carriers in 15MHz channel

Based on the number of sub-carriers assigned to each session as well as on the modulation type per session, the achieved capacity in each case is estimated by using (4.3) and it is depicted in Figure 4-13.

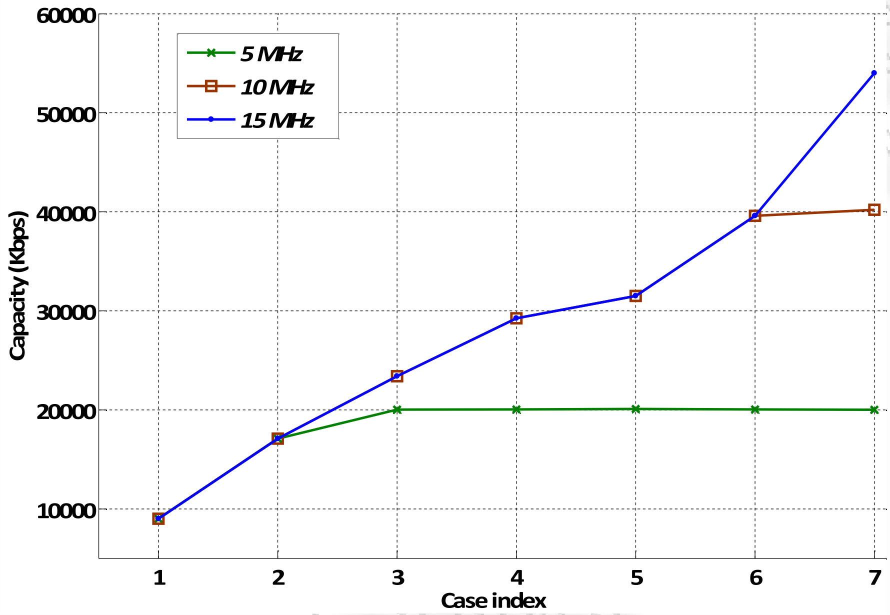

Figure 4-13: Scenario 2 – Achieved capacity for each LTE channel and case

The percentage of sub-carriers' utilization (Figure 4-14) is estimated based on the number of utilized sub-carriers in each case out of the total available for each channel. It is clear that as long as the traffic load increases in each case the achieved capacity for each channel is also increasing until all the available sub-carriers for each channel are assigned to the users' sessions. Furthermore, Figure 4-13 and Figure 4-14 provide information regarding the maximum capacity that each channel can offer. For the 5MHz channel the maximum capacity can be 20Mbps, for the 10MHz channel the maximum capacity can be 40Mbps while for the 15MHz channel the maximum capacity is 54Mbps when utilizing only the 90% of the available sub-carriers and all users' sessions are served with the Gold QoS level of 512Kbps.

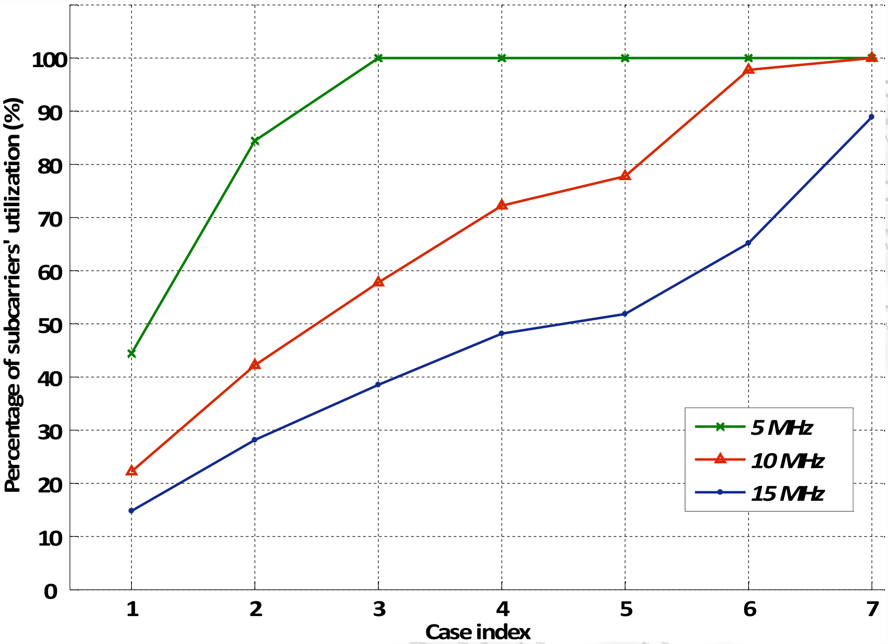

Figure 4-14: Scenario 2 – Percentage of sub-carriers' utilization for each LTE channel and case

Moreover, the combination of these comprehensive results provides us with useful insight on the appropriate channel selection for each case. More specifically the following results can be extracted.

The most appropriate channel for the first three cases is the 5MHz one since, a) its utilization percentages are higher compared to the others and thus resulting to the maximum possible exploitation of resources, b) the achieved capacity for each channel is almost the same for all the cases and c) the algorithm execution delay (Figure 4-15) is the minimum compared to the others, which means faster decisions for the given traffic cases.

For the rest of the cases, the utilization percentage for the channel of 5MHz is always 100%, which means that all the available sub-carriers are utilized and the maximum possible capacity is achieved. However, the percentage of sessions assigned to more than four sub-carriers is almost zero (Figure 4-10) which means that this channel, despite the fact that it offers the maximum possible capacity, it cannot serve the users at high QoS levels.

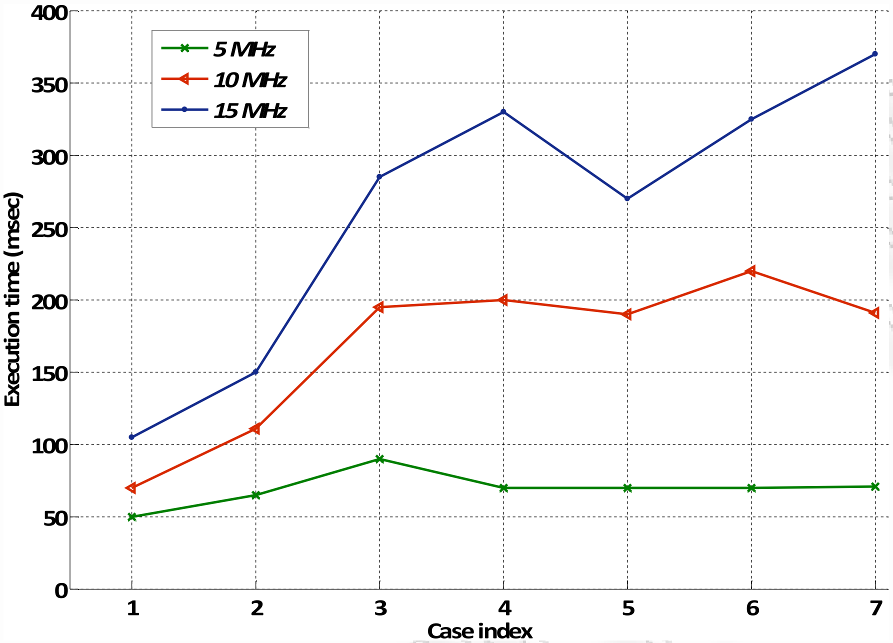

Figure 4-15: Scenario 2 - Execution delay for each LTE channel and case

In cases 4, 5 and 6, only the channels of 10MHz and 15MHz are capable to provide the appropriate QoS level to the users' sessions. The capacity they offer is the same, however the utilization of the 15MHz channel is lower compared to 10MHz channel which means that if the channel of 15MHz is selected for these cases the remaining sub-carriers of this channel will be wasted. On the other hand, the channel of 10MHz is not only capable to provide the appropriate capacity but also the percentage of sub-carriers' utilization is approaching the value of 100%, which means that the available resources are efficiently utilized to provide the maximum possible QoS levels for all sessions. Furthermore, the algorithm execution delay for the channel of 10MHz is lower compared to the channel of 15MHz.

For the last case, the channel of 10MHz has reached the utilization percentage of 100% and there is no more capacity that can be offered. Given this traffic situation and a channel of 10MHz, CPP-DSA algorithm decides that the offered QoS level per session should be dropped in order to be able to serve all the sessions. Thus, as it is depicted in Figure 4-11, the percentage of sessions assigned with 4 or 5 sub-carriers has been increased compared with the percentage of sessions which received 5 or 6 sub-carriers in case 6. On the other hand, the percentage of sessions in the channel of 15MHz

(Figure 4-12) which were assigned with 6 sub-carriers, experiencing services with the highest possible QoS level, is 100% while the sub-carriers utilization is still below 100%.

## 4.6. Realizing DSA by means of Channel Segregation

The execution speed as well as the complexity levels of DSA algorithms (which consider channel state information like SNR values for each session and sub-carriers) depends on the number of sessions and the corresponding SNR values of the sub-carriers that are sensed by the user equipment. DSA algorithms which are based on that input will decide on the appropriate sub-carriers that each session should be served from. However, considering that in heavy traffic situations this input can be extremely large (eg. 675 sub-carriers sensed by 300 active sessions) there could be such a delay, so as the best possible assignment sets to be provided, that could be forbidden for some DSA algorithms to run in real-time.

An efficient way to make DSA algorithms to perform faster is to minimize this input by efficiently filtering the full set of sub-carriers based on their past utilization priorities. The output of this filtering will be a subset of sub-carriers which is more likely to be assigned to users' sessions while sub-carriers never used in the past will be excluded from the subset.

This method which is known as Channel Segregation (CS) consists of building a list of preferred channels by increasing the priority of a given channel after each successful assignment. In the context of DSA technique, CS priority list will be created for the past assigned sub-carriers (instead of channels). Thus, DSA algorithm will exploit in the future the priority list for each sub-carrier in order to filter the full set of sub-carriers by selecting sub-carriers of high priority. The sub-carrier priority function is the following:

$$P_{n+1}(i) = \begin{cases} \dfrac{n \cdot P_n(i) + 1}{n+1} & i \to assigned \\ \dfrac{n \cdot P_n(i)}{n+1} & i \to unassigned \end{cases}$$

where *n* denotes the DSA execution attempt, *i* is the sub-carrier for which the priority is estimated and $P_n(i)$ is the priority for sub-carrier *i* at $n^{th}$ DSA execution.

Figure 4-16 depicts an overview of the CS scheme based on DSA assignment sets, framed in the context of DSNPM functionalities.

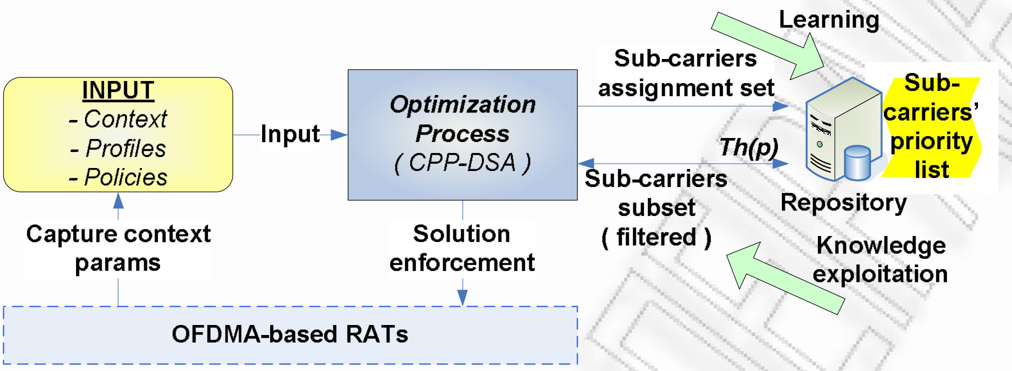

Figure 4-16: Channel segregation scheme based on DSA assignment sets

Each time that DSA algorithm (eg. CPP-DSA) provides the sub-carrier assignment set, the sub-carriers priority list is updated as part of the learning procedure. Thus, after several executions of DSA algorithm the sub-carriers priority list (as the indicative one depicted in Table 4-VI) will be available.

Table 4-VI: Indicative priority list

| **Sub-carrier *i*** | **Priority *P(i)*** |
|---|---|
| *0* | *0.95* |
| *1* | *0.87* |
| *2* | *0.5* |
| …… | …… |
| *N* | *0.17* |

Given the priority list for each sub-carrier it is possible to remove not only zero priority sub-carriers from the full set of the sub-carriers but also low priority sub-carriers depending on a *Th(p)* threshold. Thus, the algorithm will consider a filtered input regarding the number of sub-carriers that should be assigned, hence minimizing the algorithm execution delay.

## 4.7. Conclusions and Future Work

In this chapter the enhancement of DSNPM with DSA techniques for OFDMA networks was presented. Two sub-optimum DSA algorithms that consider Context, Profiles and Policies (CPP) information, namely Basic-CPP-DSA and CPP-DSA, were also presented. The B-CPP-DSA algorithm will provide the capability to DSNPM to exploit all the available sub-carriers, to deliver services at the maximum possible QoS level. On the other hand, by applying the CPP-DSA, the requested services will be delivered at the maximum allowed QoS level since the user profiles as well as the NOs policies information are taken into account. Simulation results show that CPP-DSA algorithm can provide solutions close to the optimum while there are important gains in terms of the algorithm's execution delay. Furthermore, the consideration of management information regarding user's preferences introduces fairness which is reflected by the algorithm's decisions in terms of the number of sub-carriers assigned per session as well as their quality. As a result, the NOs are capable to increase the sub-carriers utilization efficiency, so as to increase their profit, while the users will be served fair enough based on their preferences. The analysis of simulation results also reveal that based on the management information and the efficient network resources utilization, it is possible to address issues regarding the appropriate channel selection in the service area. Future work, will introduce cognitive functionalities in trying to exploit knowledge that is gained from past interactions of the system with the network and radio environment. Thus, the decisions regarding the appropriate assignment sets of sub-carriers and/or the appropriate channel selection in the service area will be provided faster by skipping time consuming optimization procedures.

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# 5. PLATFORM VALIDATION

Chapter Outline

This chapter presents the integrated CWN platform environment which encompasses several hardware entities like FBS boards and FTC equipment as well as software entities like the control applications of FBS and FTC and the network decision entity, DSNPM. This chapter describes thoroughly each one of the hardware and software entities as well as their interconnection aspects. The platform environment provides the means for the conduction of validation activities in terms of scenarios and use cases, enabling the incorporation and refinement of management functionality for RRSs.

Keywords: Integrated platform, hardware and software entities, interconnection, use cases

## 5.1. Introduction

The architecture of the platform environment follows the Service Oriented (SO) paradigm. Hence, each entity in the environment can offer several services related to its role and functionality, while, on the other hand and in order to accomplish its objective, it is taking benefit of the services offered by other entities. Thus the entities in the system can act as service providers and service consumers at the same time. They are able to advertise their services and to discover useful services through a service directory. The implementation of these service interoperability mechanisms is based on an intelligent agent platform, namely Java Agent DEvelopment Framework (JADE) [1], which is fully built on Java and is compliant with the Foundation for Intelligent Physical Agents (FIPA) [2]. JADE has all these features that are necessary for developing a virtual environment where all the network infrastructure and functionalities can be represented in, like the Directory Facilitator (DF) offering yellow pages services and the asynchronous exchange of messages etc. The capabilities of JADEX add-on [3] were also exploited, making possible to embed into the agents, rationality and goal-directedness, since JADEX features a Belief-Desire-Intention (BDI) engine [4], which is an excellent way to fill the gap between middleware and reasoning-centred systems.

Based on JADE/JADEX the platform environment can hide the complexity and the diversity of the underlying tiers, in terms of hardware, type of networks or operating systems. Each entity in the environment is bound to a specific intelligent agent that actually acts as a mediator between the entity's functionality and the rest of the system. The agent is actually a high level interface that can be used for the easy, guaranteed and unobtrusive interaction between an entity in the platform and any other. It is also the virtual representation of this entity in the platform. For instance, the FBS Agent is responsible for the interaction between the FBS and the DSNPM, performing the necessary abstraction of information from the FBS to DSNPM and the translation of commands from the DSNPM to the FBS. Similarly, the User Agent is actually managing the user's mobile terminal, by perceiving the context in which the user currently is, obtaining information about i.e. location, time epoch or running applications and ensuring the provision of highly personalized and sophisticated services that are tailored to the needs of users and applications. Also, the platform environment incorporates the traffic Generator which generates load conditions for a different number of situations (eg. RATs, traffic characteristics, propagation, mobility models, etc) and provides a set of measurements to the other platform entities. Figure 5-1 shows most of the agents that are typically present in the platform environment. Their role and functionality is presented in detail in the subsequent sections.

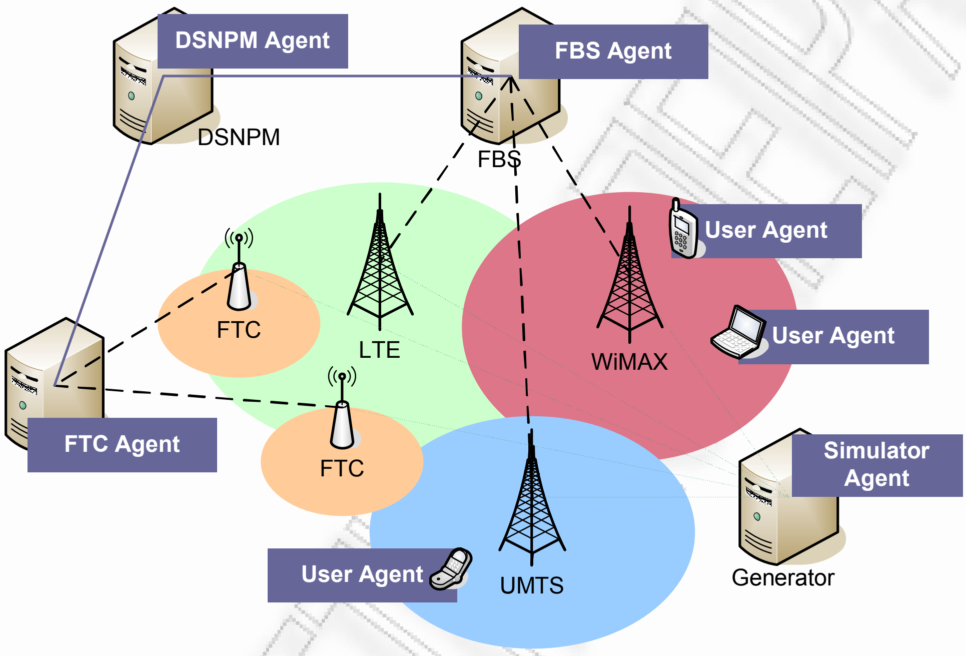

Figure 5-1: Overview of the prototyping CWN platform environment

It has to be noted that all entities in the platform are only loosely coupled through the agents and thus they are free to join and leave the platform according to their needs. This fact endorses their autonomic behaviour and facilitates their integration, increasing at the same time the reliability and dependability of the platform environment.

In the next sub-sections, the building blocks of the platform environment are presented in detail, as well as the hardware or software entities that comprise them. Furthermore an indicative demonstration scenario is also thoroughly described, in order to clarify system's behaviour and operation. Finally, several traffic test cases will be studied from the DSNPM point of view.

## 5.2. FBS Board Equipment

The control application is the first major element for the FBS and represents an interface between DSNPM and the FBS. This application translates different reconfiguration commands from DSNPM into well-known radio equipment statements. The communication and interaction with the DSNPM is done via JADE agent platform with JADEX extension. The communication messages are specified in configuration XML files for the agent platform. The control application itself registers the equipment on an agent as well as the DSNPM so as to be feasible a direct communication between these two agents. Thus, the control application sends a registration request including the capabilities of the equipment to DSNPM which acknowledges with a response message. After the registration of the control application DSNPM has the capability to manage the FBS equipment upon reconfiguration requests. Furthermore, the FBS radio hardware can provide additional capabilities to the DSNPM after the initial registration. Figure 5-2 shows an extended version of the control application, implemented using Java programming language, with the capability to control beside Field Programmable Gate Arrays (FPGAs) boards Digital Signal Processors (DSPs) boards too.

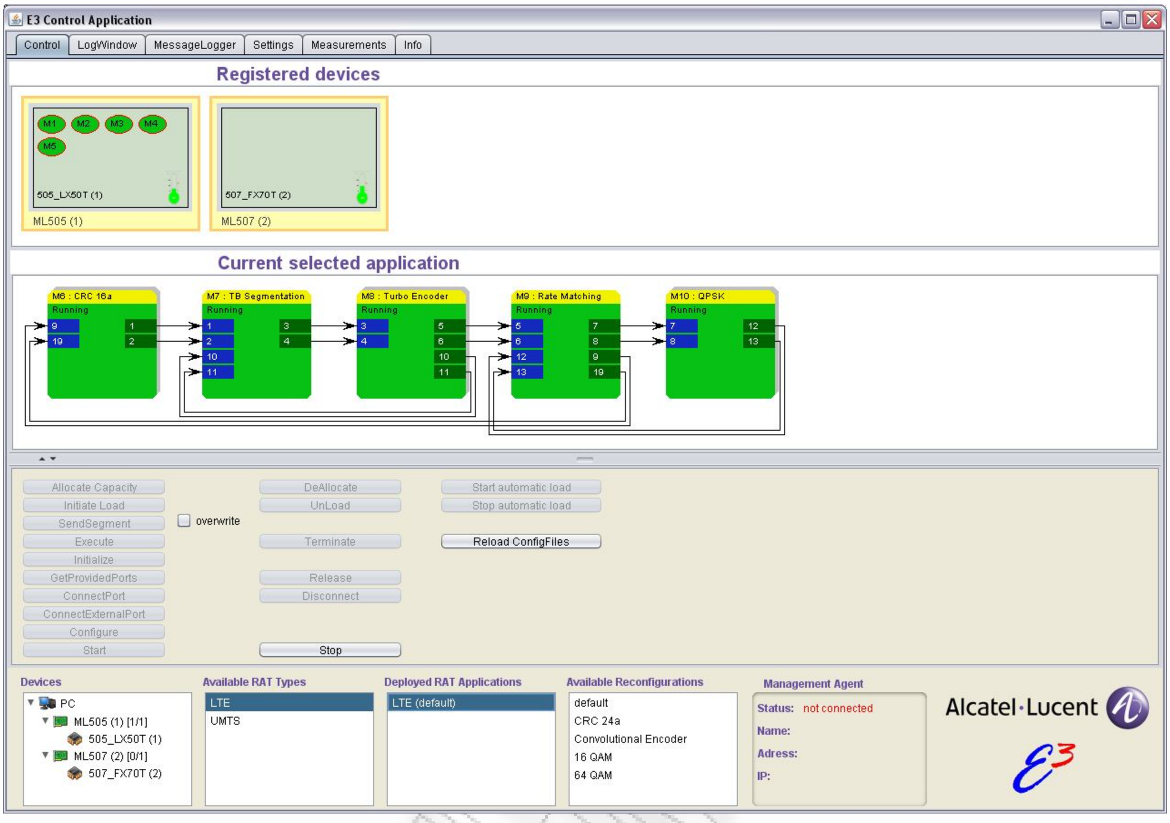

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Figure 5-2: Extended FBS control application

The control application has an interface to the embedded control system (Figure 5-3), on which an embedded Operating System (OS) is running. This OS can be a hardware OS in case of FPGA boards. Beside the interface to the control application the embedded control system have additional physical interfaces, e.g. to transmit and receive user data. Currently, the PCI-Express as well as the Gigabit Ethernet interface is supported. The master of the complete system is a microprocessor. This microprocessor (e.g. MicroBlaze or PowerPC (PPC)) receives the control and reconfiguration commands from the control application and perform measurements. Furthermore, the microprocessor executes the control and reconfiguration commands. The memory controller is needed to provide additional memory (e.g. Double Data Rate - Random Access Memory (DDR-RAM), static RAM) to the system. Especially the microprocessor requires a lot of additional RAM. One reconfiguration option is the partial reconfiguration. This technology from Xilinx [5], [6], needs an Internal Configuration Access Port (ICAP). A special wrapper in the embedded system enables the access to this hardware module.

The System Advanced Configuration Environment (System ACE) wrapper enables the access to the Compact Flash (CF) cards. These cards are related to local databases and store all needed files for the normal and partial reconfiguration. The Bus Bridge is a special Intellectual Property (IP) core for the communication with the flexible baseband processing chains. This communication includes for instance the controlled setup of radio-standard processing chains, the reconfiguration of these chains, the provision of parameters etc.

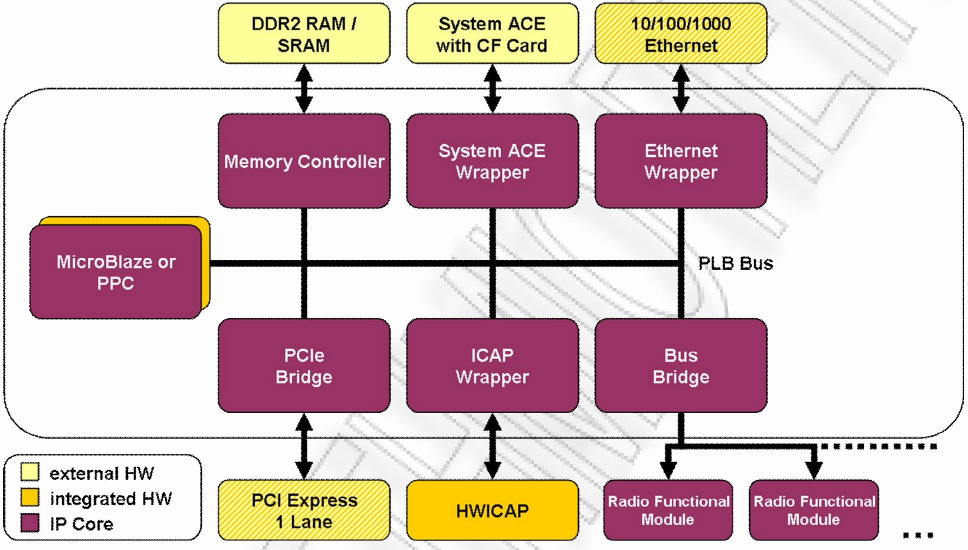


Figure 5-3: Architecture of the embedded control system

One major element or module of the embedded control architecture, depicted in Figure 5-3, is the Bus Bridge. This module connects the embedded system with the radio-standard processing chains and thus with the classical baseband processing. One key enabler for the FBS is the flexibility of this chain(s) and this flexibility will be controlled by the embedded system. Figure 5-4 depicts an overview about the complete architecture of the flexible baseband processing including the control application (part of CCM in sub-section 2.2) and the embedded control system (On-Chip μP).

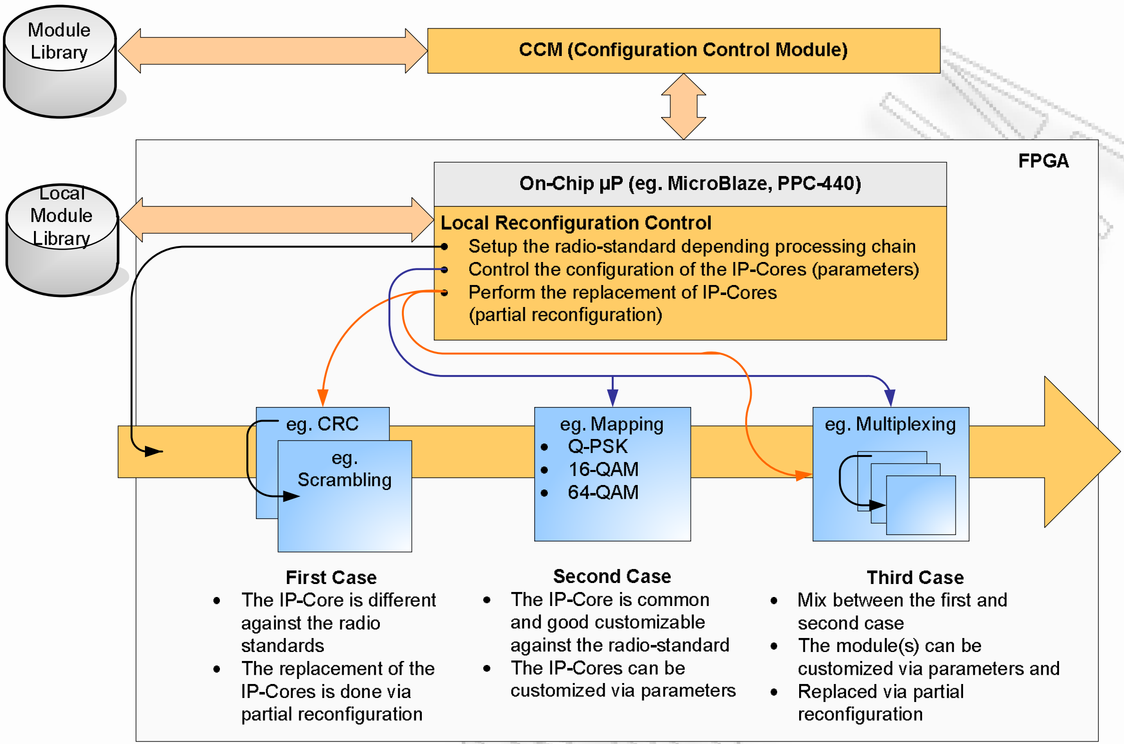


Figure 5-4: Architecture of the flexible baseband processing

This architecture enables the reconfiguration of a FBS in the following scopes:

- Setup a radio-standard processing chain
- Replacing a radio-standard processing chain by another
- Changing functionalities of a processing by replacing several modules
- Changing parameters of a radio technology module

For the replacement, the setup or the changing of the functionalities of a radio-standard processing chain, a lot of radio modules must be arranged and configured. This process can be divided into three major independent cases.

The first case is related to completely different radio modules between the different radio technologies. In this case the whole radio module must be changed. This process can be done via partial reconfiguration. Thus, all other processing chains keep alive and only the addressed processing chain has an outage period. All needed radio modules are stored in the local module database. This database is realised with help of the System ACE and a CF card, but all other storage elements like hard disk are also imaginable.

The second case is related to very common and good customizable radio modules between different technologies. In this case the reconfiguration can be done via parameters only. The parameters will be provided by the CCM via the control application and the embedded control system. The outage time in this case is very small compared to first case. In analogy to the first case all other processing chains won’t be affected.

The third case is a mix between the first and the second case. One example for this case is the multiplexing in current and future radio technologies. In UMTS the multiplexing will be realized via Code Division Multiple Access (CDMA). Since the multiplexing in WiMAX is completely different, it will be realized via the Inverse Fast Fourier Transform (IFFT). Thus, the complete multiplexing module must be exchanged (via partial reconfiguration, first case) during the reconfiguration from UMTS to WiMAX. In the same context (regarding the multiplexing module) only the IFFT size must be configured during the reconfiguration from WiMAX to LTE. This can be done via parameters (second case).

Figure 5-5 shows the testbed setup, which consist of three FPGA evaluation boards from Xilinx to execute the embedded control system and the flexible baseband processing and also classical personal computers to execute the control application. This setup enables amongst others the demonstration of the scalability, the reconfiguration and the remote controllability. Furthermore the interaction with higher layer management modules can be demonstrated.

Figure 5-5: Testbed setup

## 5.3. FemToCell Equipment

Another important part of the platform environment is the FemToCell (FTC) equipment which consists of:

- A HSDPA HomeNB (FTC): the FTC provide the HSDPA connectivity to the mobile terminals and is connected to a high speed backbone network
- A HomeNB Management system (HMS): the HMS allow the remote management (configuration) of the FTC from an NO's Operation and Management (O&M) system
- A file server: the file server collects XML measurement reports sent by the FTC. Additionally, this server collects measurements coming from mobile terminals connected to the FTC.

This FTC equipment (Figure 5-6) allows DSNPM to collect measurements regarding the performance of the HSDPA air interface and reconfigure the FTC.

Figure 5-6: Femtocell equipment

In order to provide the HSDPA connectivity to the mobile terminals, the HSDPA FTC is provided along with a management server allowing to collect performance measurements from the FTC and to manage its configuration. Such a deployment of the FTC with the corresponding management server is aligned with 3GPP specifications on FTCs (Home NBs – HNBs) as shown on Figure 5-7, taken from 3GPP TS 32.583-800 [7].

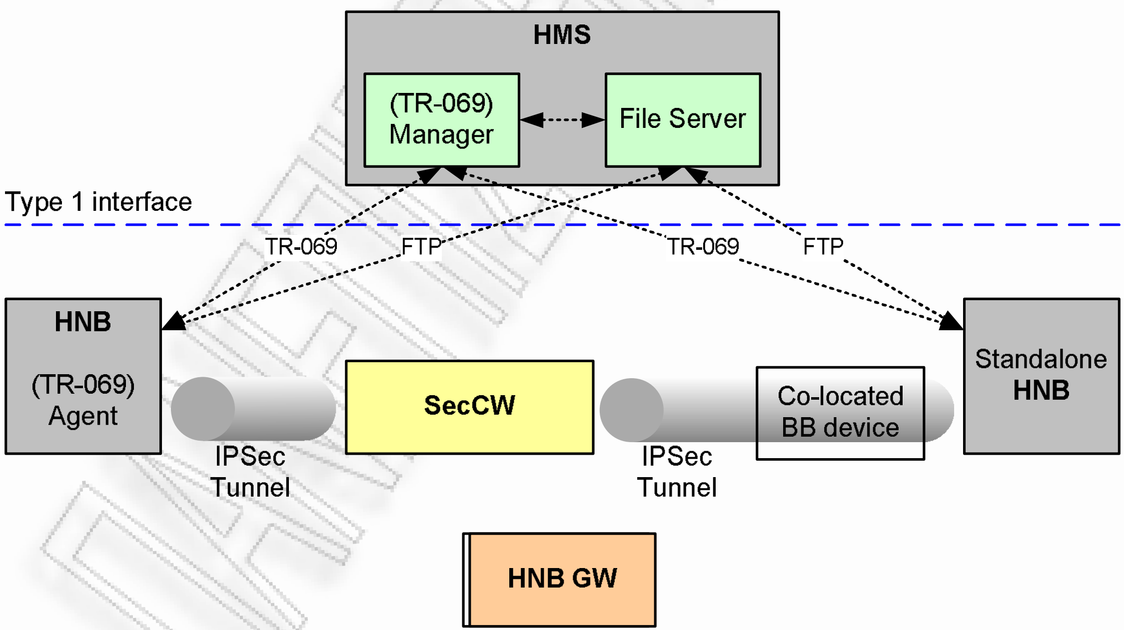


Figure 5-7: HNB management architecture

On this architecture, HNBs (either standalone or co-localized with a broadband router) are introduced. The HNBs communicates with the HMS deployed in the operator O&M system. This communication between HNBs and the HMS is done over the HNB GW / Security GW. The HMS is made of two entities: the Manager and the File Server.

### 5.3.1. TR-069 Manager

The TR-069 Manager which is also called Auto-Configuration Server (ACS), is the end-point of the TR-069 protocol in the network. The TR-069 protocol has been defined by the Broadband Forum [8] and is used for the management of Customer Premise Equipments (CPE), including FTCs. The TR-069 protocol relies on Remote Procedure Calls (RPC) to allow the ACS to issue commands/queries onto a CPE. As an example, some of the mandatory RPC methods that the CPEs must support are listed below:

- GetRPCMethod: to get the list of the methods (mandatory and optional) supported by the CPE
- SetParameterValues: to set the value of a particular parameter
- GetParameterValues: to get the value of a particular parameter
- GetParameterNames: to get the list of the parameters of the CPE

Using these commands, the Manager is capable of getting the FTC configuration and modifying the FTC operation parameters. The list below is a subset of the parameters that can be retrieved / set from / on the FTC using the TR-069 protocol:

- Device Information (Manufacturer, Model Name, Hardware verion, uptime, IMSI, Video Codec…)
- Management Server (URL, username,…)
- Performance Management (FTP Server location, username, …)
- LAN Interface (IP Address, upstream rate,…)
- Cell configuration (MCC, MNC, cell ID, downlink UARFCN, scrambling code, CCPCH power, …)

### 5.3.2. File Server

The File Serve is a FTP server that can receive measurement reports coming from HNBs. These reports are sent by the HNBs either periodically or on events or on request from the TR-069 Manager. The list below is a subset of the information contained in the FTP reports:

- Call setup quality (CS Video drop rate, number of successful CS video calls, …)
- Call quality (CS Video BLER, CS Audio BLER, …)

The entities deployed in the platform for the management of the FTC (collection of measurements and reconfiguration) by the DSNPM are shown on Figure 5-8.

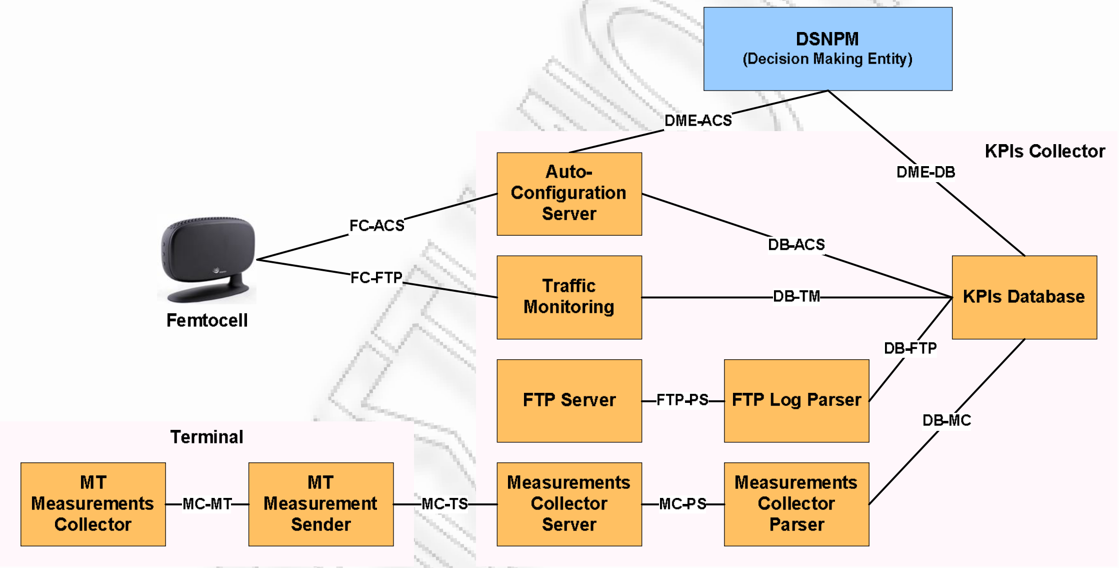


Figure 5-8: Architecture for measurements collection and FTC reconfiguration

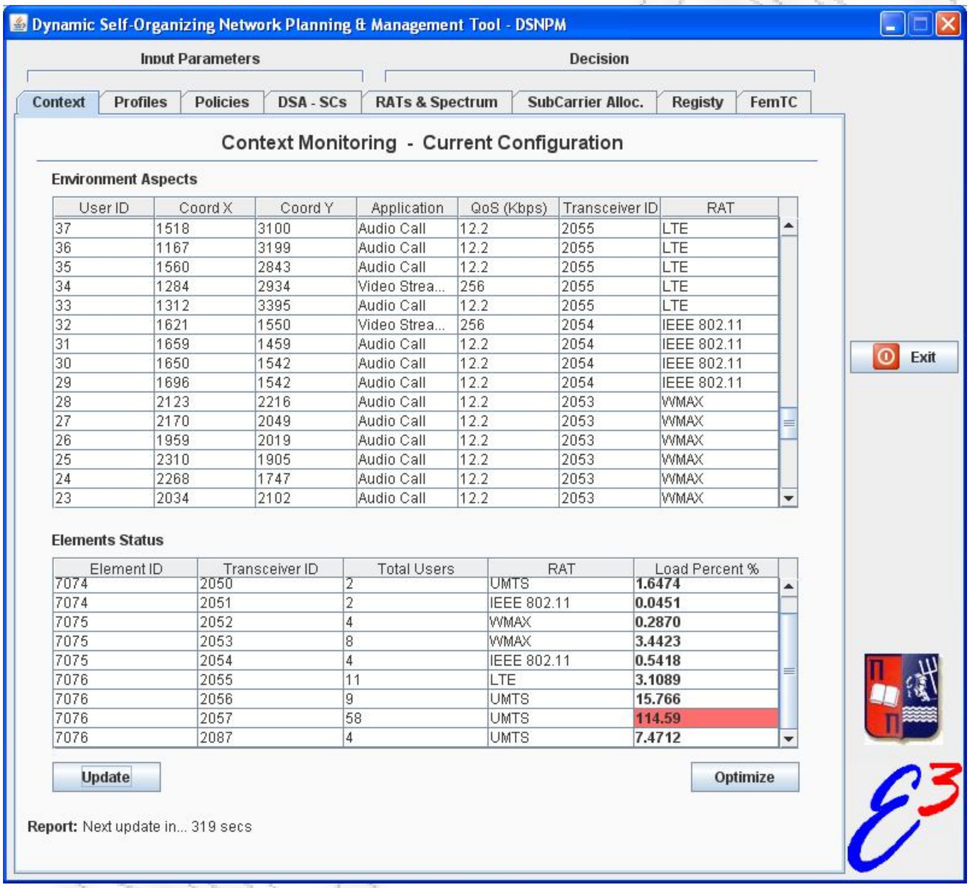
The interfaces between the functional blocks are described in Table 2 1.

Table 5-I: Interfaces for KPIs collection and reconfiguration of the FTC

| Name | Entities | Description |
|---|---|---|
| FC-ACS | FTC and ACS | Based on TR-069 protocol it is used a) by the ACS for the collection of parameters and KPIs from the FTC and b) by the ACS to set FTC parameters. |
| FC-FTP | FTC and FTP Server | It is used by the FTC to upload Performance Monitoring reports onto the FTP Server. |
| DB-ACS | Database and ACS | Used by the ACS server to store the parameters and KPIs obtained from the FTC. |
| DB-TM | Database and Traffic Monitoring | Used by the Traffic Monitoring to store traffic measurements into the database. |
| DB-FTP | Database and FTP Log Parser | Used by the FTP Log Parser to store the KPIs extracted from the reports received via FTP. |
| MC-MT | MT Measurement Sender and MT Measurement Collector | This interface uses the file system for the exchange of data between the MT Measurement Collector and the MT Measurements Sender. |
| MC-TS | MT Measurements Sender and Measurements Collector Server | Used by the MT Measurement Sender to send the data obtained from the MT Measurement Collector to the Measurement Collector Server. The underlying protocol is TCP. |
| MC-PS | Measurement Collector Server and Measurement Collector Parser | Used by the Measurement Collector Server to call the Measurement Collector Parser upon reception of a new report coming from the MT Measurement Sender. |
| DB-MC | Database and Measurement Collector Parser | Used by the Measurement Collector Parser to store the KPIs extracted from the reports received from the MT Measurement Sender. |
| DME-DB | Decision Making Entity (DSNPM and database | Used by DSNPM platform to get the measurements from the FTC and HSDPA terminals. |
| DME-ACS | Decision Making Entity (DSNPM) and ACS | Used by DSNPM platform to trigger the reconfiguration of the FTC (specifying the parameters to modify). |

## 5.4. DSNPM Implementation

DSNPM was implemented using Java programming language not only for the Graphical User Interface (GUI) but also for the communication between the DSNPM-FBS and DSNPM-FTC (JADE/JADEX) as well as for all the algorithms depicted in Figure 2-2 (RDQ-A, CMA and CPP-DSA). The GUI for the context information of DSNPM is depicted in Figure 5-9.



Context Monitoring - Current Configuration

Environment Aspects

| User ID | Coord X | Coord Y | Application | QoS (Kbps) | Transceiver ID | RAT |
|---|---|---|---|---|---|---|
| 37 | 1518 | 3100 | Audio Call | 12.2 | 2055 | LTE |
| 36 | 1167 | 3199 | Audio Call | 12.2 | 2055 | LTE |
| 35 | 1560 | 2843 | Audio Call | 12.2 | 2055 | LTE |
| 34 | 1284 | 2934 | Video Strea... | 256 | 2055 | LTE |
| 33 | 1312 | 3395 | Audio Call | 12.2 | 2055 | LTE |
| 32 | 1621 | 1550 | Video Strea... | 256 | 2054 | IEEE 802.11 |
| 31 | 1659 | 1459 | Audio Call | 12.2 | 2054 | IEEE 802.11 |
| 30 | 1650 | 1542 | Audio Call | 12.2 | 2054 | IEEE 802.11 |
| 29 | 1696 | 1542 | Audio Call | 12.2 | 2054 | IEEE 802.11 |
| 28 | 2123 | 2216 | Audio Call | 12.2 | 2053 | WMAX |
| 27 | 2170 | 2049 | Audio Call | 12.2 | 2053 | WMAX |
| 26 | 1959 | 2019 | Audio Call | 12.2 | 2053 | WMAX |
| 25 | 2310 | 1905 | Audio Call | 12.2 | 2053 | WMAX |
| 24 | 2268 | 1747 | Audio Call | 12.2 | 2053 | WMAX |
| 23 | 2034 | 2102 | Audio Call | 12.2 | 2053 | WMAX |

Elements Status

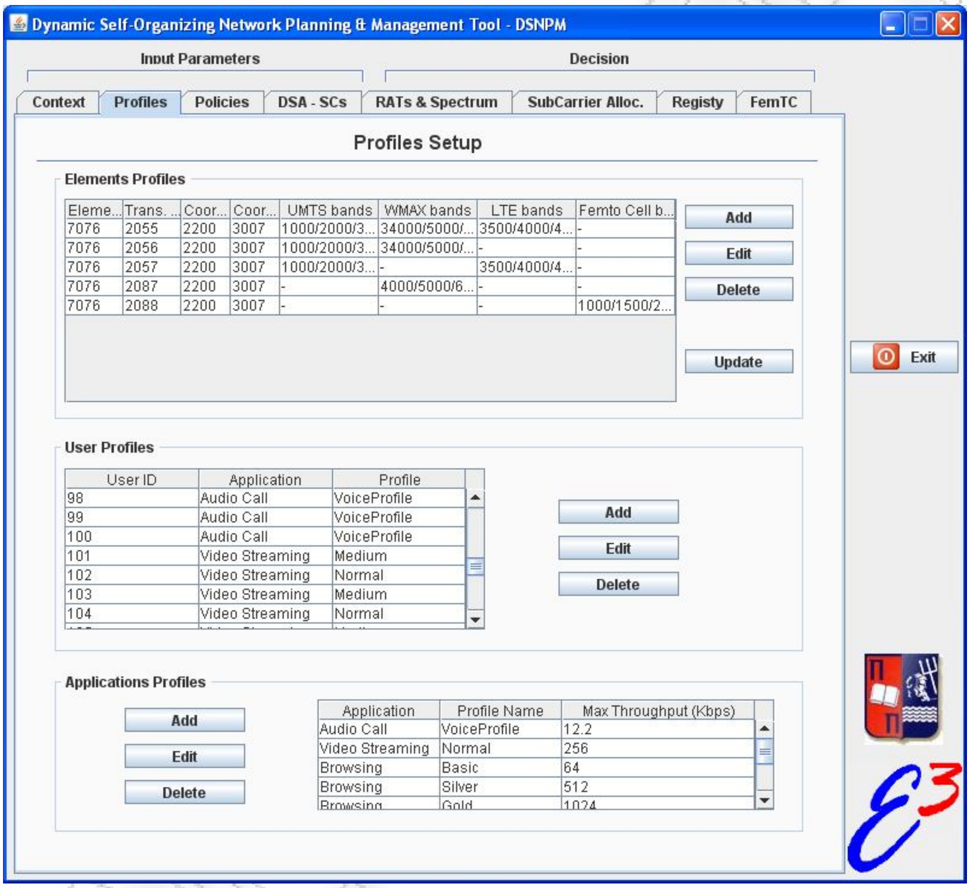
| Element ID | Transceiver ID | Total Users | RAT | Load Percent % |
|---|---|---|---|---|
| 7074 | 2050 | 2 | UMTS | **1.6474** |
| 7074 | 2051 | 2 | IEEE 802.11 | **0.0451** |
| 7075 | 2052 | 4 | WMAX | **0.2870** |
| 7075 | 2053 | 8 | WMAX | **3.4423** |
| 7075 | 2054 | 4 | IEEE 802.11 | **0.5418** |
| 7076 | 2055 | 11 | LTE | **3.1089** |
| 7076 | 2056 | 9 | UMTS | **15.766** |
| 7076 | 2057 | 58 | UMTS | **114.59** |
| 7076 | 2087 | 4 | UMTS | **7.4712** |

**Report:** Next update in... 319 secs

Figure 5-9: DSNPM – Context information

The first table depicts specific information for each active user in the service area like the actual location coordinates, the running applications and the corresponding QoS level in terms of Kbps as well as the assigned transceiver from which the application is served and the corresponding RAT activated for this transceiver. Furthermore, the second table depicts the status of the network elements in the service area (eg. FBSs) in terms of the activated transceivers, the total number of users served per transceiver as well as the RAT currently activated. Moreover, the last column of this table depicts the load percentage for each one of the transceivers considering the capacity that can be offered by the activated RAT. In case where any of the transceivers is overloaded, the corresponding table cell is highlighted in order to indicate the need for reconfiguration.

The second tab of the DSNPM application GUI provides information about the Profiles as it is depicted in Figure 5-10.



| Eleme... | Trans. ... | Coor... | Coor... | UMTS bands | WMAX bands | LTE bands | Femto Cell b... |
|---|---|---|---|---|---|---|---|
| 7076 | 2055 | 2200 | 3007 | 1000/2000/3... | 34000/5000/... | 3500/4000/4... | - |
| 7076 | 2056 | 2200 | 3007 | 1000/2000/3... | 34000/5000/... | - | - |
| 7076 | 2057 | 2200 | 3007 | 1000/2000/3... | - | 3500/4000/4... | - |
| 7076 | 2087 | 2200 | 3007 | - | 4000/5000/6... | - | - |
| 7076 | 2088 | 2200 | 3007 | - | - | - | 1000/1500/2... |

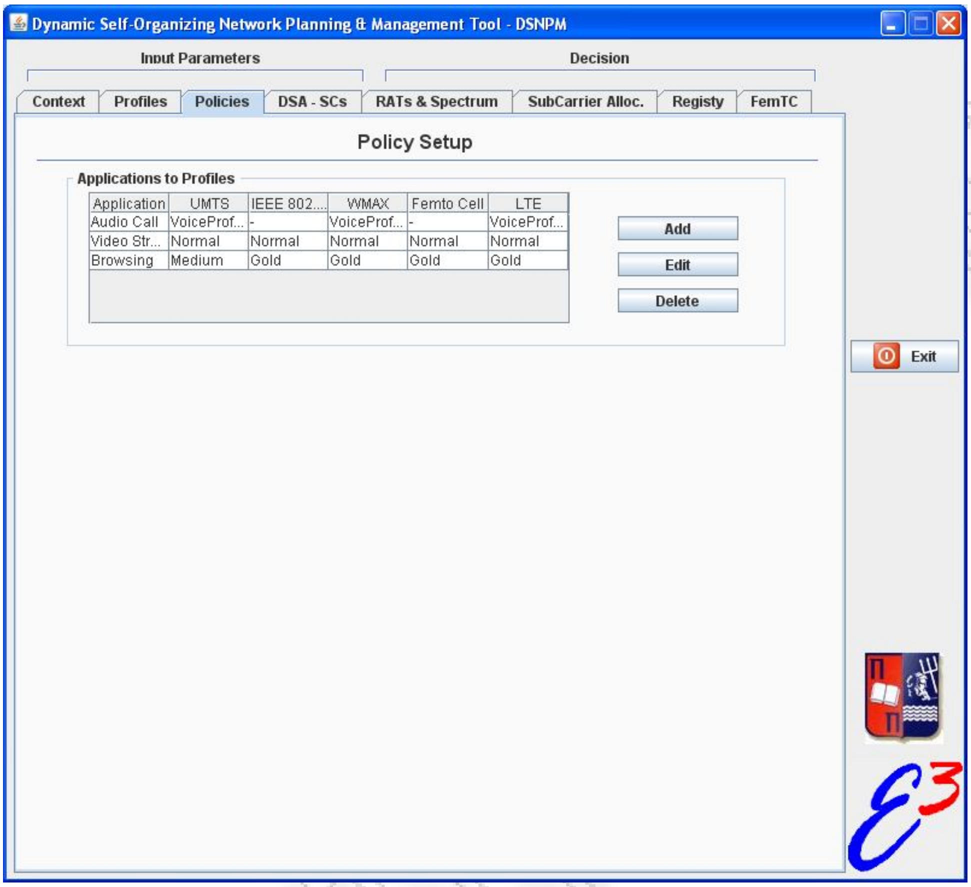
| User ID | Application | Profile |
|---|---|---|
| 98 | Audio Call | VoiceProfile |
| 99 | Audio Call | VoiceProfile |
| 100 | Audio Call | VoiceProfile |
| 101 | Video Streaming | Medium |
| 102 | Video Streaming | Normal |
| 103 | Video Streaming | Medium |
| 104 | Video Streaming | Normal |

| Application | Profile Name | Max Throughput (Kbps) |
|---|---|---|
| Audio Call | VoiceProfile | 12.2 |
| Video Streaming | Normal | 256 |
| Browsing | Basic | 64 |
| Browsing | Silver | 512 |
| Browsing | Gold | 1024 |

Figure 5-10: DSNPM – Profiles information

The first table provides information on the transceivers profiles regarding their location in the service area as well as the supported RATs for each one of them. For instance, the transceiver ID 2055 supports three RATs (UMTS, WiMAX and LTE) to operate at the corresponding frequency bands. That means that the transceiver is capable to operate in any of these RATs and supports the reconfiguration capability to change from one RAT to another (eg. from UMTS to LTE, from WiMAX to UMTS, etc). However, the last to transceiver IDs 2087 and 2088 support single RAT operation, WiMAX and FTC (providing HSDPA connectivity) respectively. The second kind of profiles is the user profiles which provide information on the QoS level (in terms of Kbps) that each user would like to be served per application while the last table provides information on the target bit rate that must be achieved for each application and user profile. The considered applications are Audio Call as a circuit switching service, Browsing and Video Streaming as packet switching services. Thus, the Audio Call can be offered at the QoS level of VoiceProfile (12.2 Kbps) while Browsing can be offered in Basic (64 Kbps), Medium (128 Kbps), Normal (256 Kbps), Bronze (384 Kbps), Silver (512 Kbps) and Gold (1024 Kbps) and Video Streaming can be offered in Medium and Normal.

The Policies tab provides information regarding the NO policies. Figure 5-11 depicts an indicative example of the NO policies. In particular, the NO has configured the user profiles (maximum QoS level in terms of target bit rate) for each application when served by a specific RAT. For example, the Audio Call will be served only by UMTS, WiMAX and LTE RATs while the other applications can be served by all the RATs at the corresponding user profiles. Furthermore, it should be mentioned that the maximum user profile that Browsing application is configured to be offered by UMTS is Medium (128 Kbps) in order to avoid bandwidth misuse due to capacity limitations of UMTS.



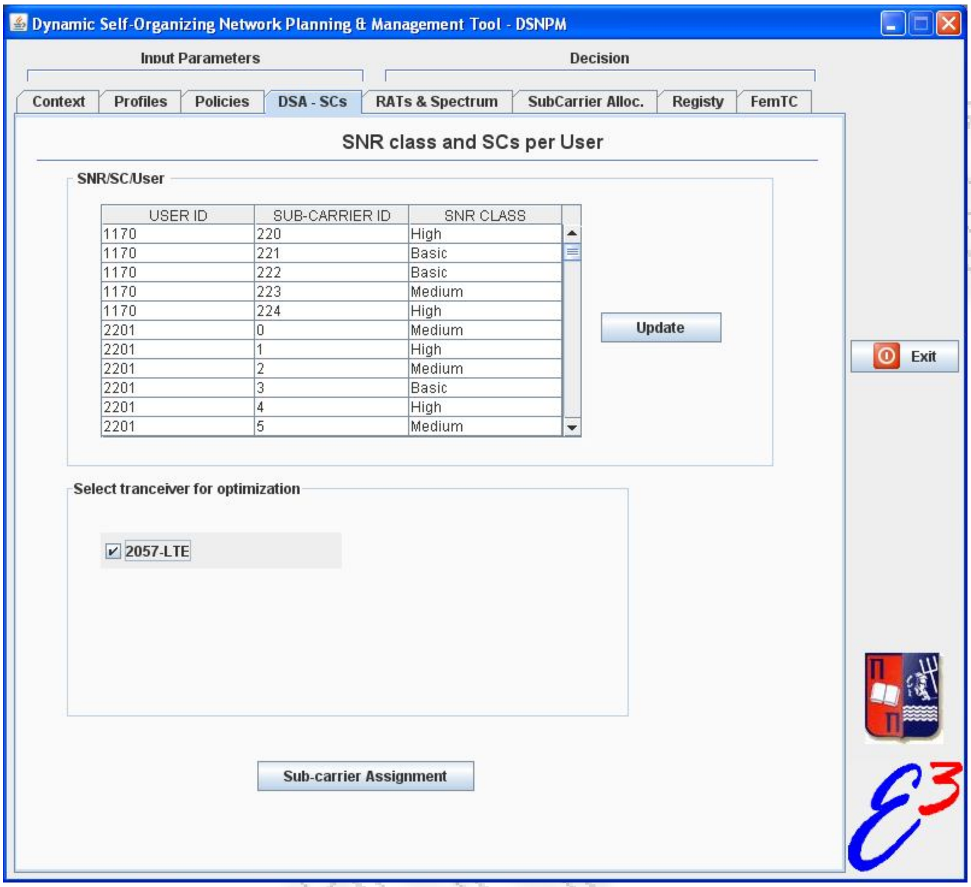
Policy Setup

Applications to Profiles

| Application | UMTS | IEEE 802.... | WMAX | Femto Cell | LTE |
|---|---|---|---|---|---|
| Audio Call | VoiceProf... | - | VoiceProf... | - | VoiceProf... |
| Video Str... | Normal | Normal | Normal | Normal | Normal |
| Browsing | Medium | Gold | Gold | Gold | Gold |

Figure 5-11: DSNPM – Policies information

As already described, since DSNPM is also enhanced with CPP-DSA algorithm it is necessary to be aware of the channel state information of the available sub-carriers per user, as reflected by the corresponding SNR class (see also sub-section 4.5). Each table row in Figure 5-12 provides the SNR class that a sub-carrier is sensed by the user equipment. Since the user equipment may sense multiple sub-carriers, there will be a specific row for each combination of user and sub-carrier providing the corresponding SNR class.



SNR class and SCs per User

SNR/SC/User

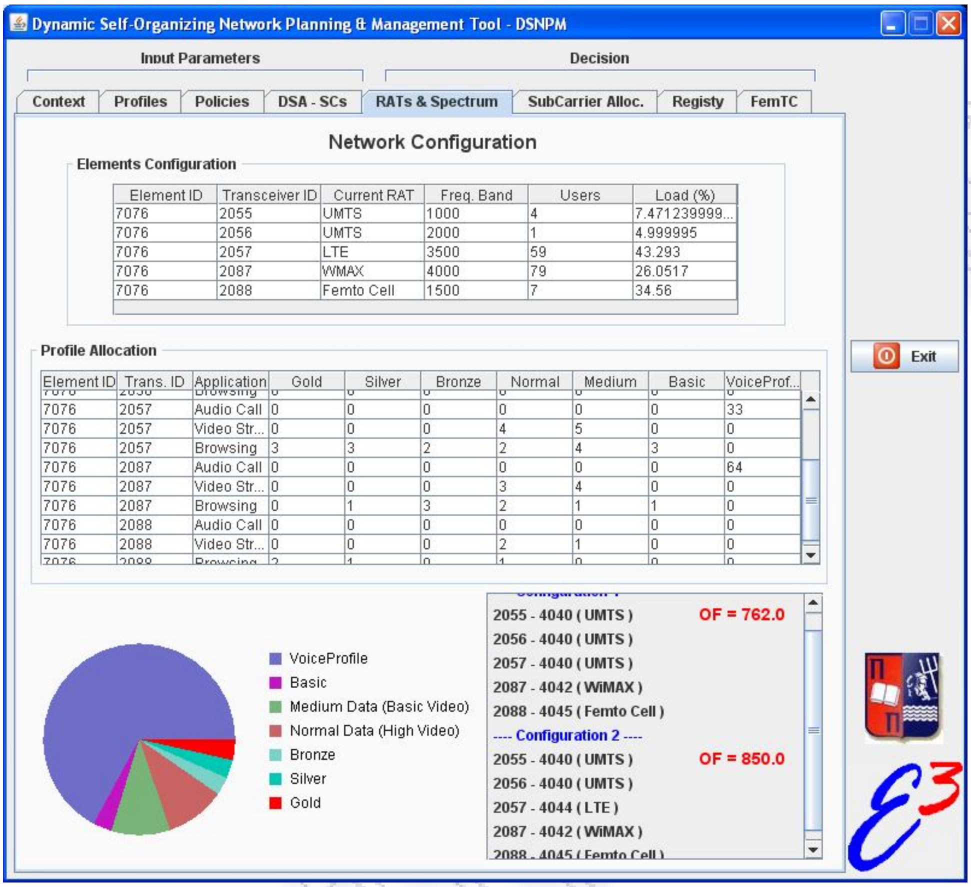
| USER ID | SUB-CARRIER ID | SNR CLASS |
|---|---|---|
| 1170 | 220 | High |
| 1170 | 221 | Basic |
| 1170 | 222 | Basic |
| 1170 | 223 | Medium |
| 1170 | 224 | High |
| 2201 | 0 | Medium |
| 2201 | 1 | High |
| 2201 | 2 | Medium |
| 2201 | 3 | Basic |
| 2201 | 4 | High |
| 2201 | 5 | Medium |

Select tranceiver for optimization

☑ 2057-LTE

Figure 5-12: DSNPM – SNR class per sub-carrier for each user

As already described in sub-section 2.3.1, the optimization process of DSNPM is targeted to provide inter-RAT configuration decisions as well as intra-RAT configuration decisions. Figure 5-13 depicts an indicative inter-RAT configuration decision. The first table provides information on the transceivers configuration in terms of the new activated RAT, the frequency band that will operate from now on as well as the number of users assigned for each transceiver and the corresponding load percentage based on the users' applications and the QoS level (profile) that they have been allocated to. The second table provide information on the number of users which have been assigned to specific QoS levels for each transceiver and application. Furthermore, the possible combinations that were checked by the optimization algorithm are shown at the bottom right of this figure as well as the corresponding objective function value. Finally, the pie is used in order to graphically depict the percentage of users that were allocated to the corresponding QoS levels (in terms of user profiles).



Network Configuration

Elements Configuration

| Element ID | Transceiver ID | Current RAT | Freq. Band | Users | Load (%) |
|---|---|---|---|---|---|
| 7076 | 2055 | UMTS | 1000 | 4 | 7.471239999... |
| 7076 | 2056 | UMTS | 2000 | 1 | 4.999995 |
| 7076 | 2057 | LTE | 3500 | 59 | 43.293 |
| 7076 | 2087 | WMAX | 4000 | 79 | 26.0517 |
| 7076 | 2088 | Femto Cell | 1500 | 7 | 34.56 |

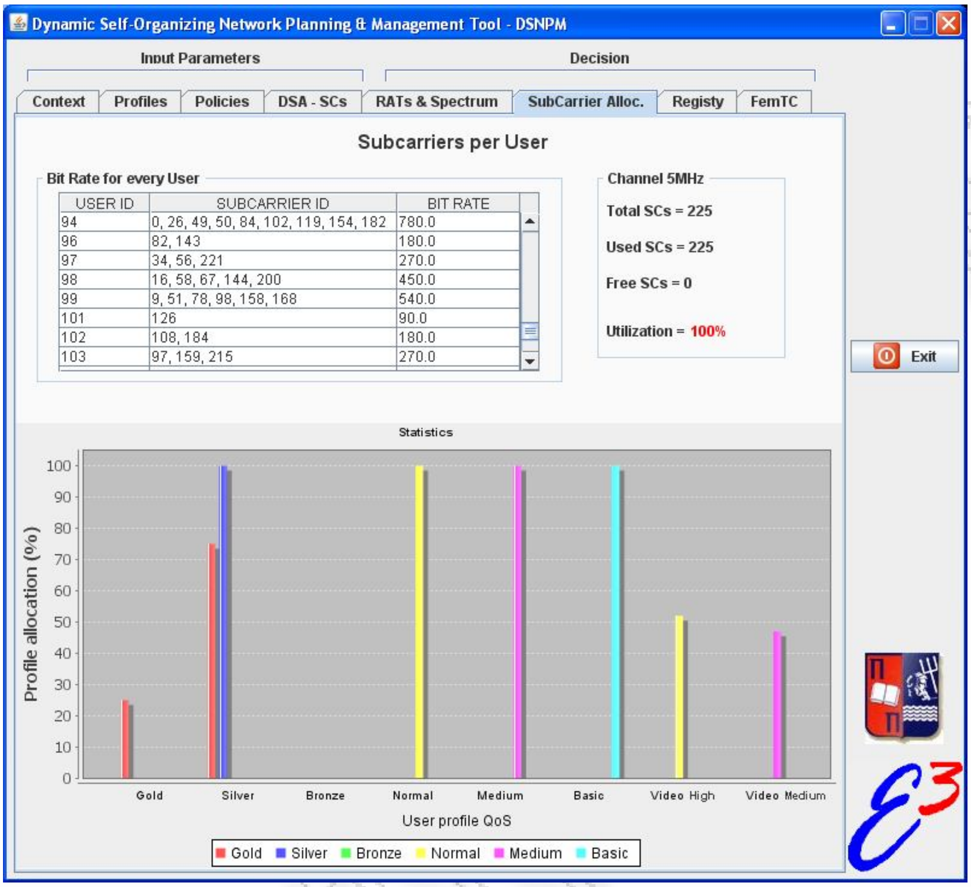
Profile Allocation

| Element ID | Trans. ID | Application | Gold | Silver | Bronze | Normal | Medium | Basic | VoiceProf... |
|---|---|---|---|---|---|---|---|---|---|
| 7076 | 2057 | Audio Call | 0 | 0 | 0 | 0 | 0 | 0 | 33 |
| 7076 | 2057 | Video Str... | 0 | 0 | 0 | 4 | 5 | 0 | 0 |
| 7076 | 2057 | Browsing | 3 | 3 | 2 | 2 | 4 | 3 | 0 |
| 7076 | 2087 | Audio Call | 0 | 0 | 0 | 0 | 0 | 0 | 64 |
| 7076 | 2087 | Video Str... | 0 | 0 | 0 | 3 | 4 | 0 | 0 |
| 7076 | 2087 | Browsing | 0 | 1 | 3 | 2 | 1 | 1 | 0 |
| 7076 | 2088 | Audio Call | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7076 | 2088 | Video Str... | 0 | 0 | 0 | 2 | 1 | 0 | 0 |
| 7076 | 2088 | Browsing | 2 | 1 | 0 | 1 | 0 | 0 | 0 |

2055 - 4040 ( UMTS ) OF = 762.0
2056 - 4040 ( UMTS )
2057 - 4040 ( UMTS )
2087 - 4042 ( WiMAX )
2088 - 4045 ( Femto Cell )
---- Configuration 2 ----
2055 - 4040 ( UMTS ) OF = 850.0
2056 - 4040 ( UMTS )
2057 - 4044 ( LTE )
2087 - 4042 ( WiMAX )
2088 - 4045 ( Femto Cell )

Figure 5-13: DSNPM – RATs and spectrum selection (inter-RAT decision)

Figure 5-14 depicts an indicative sub-carrier assignment configuration for each user assigned to LTE, in the context of intra-RAT decision of DSNPM. The table provides information on the sub-carriers that have been assigned to each user as well as the achieved bit rate for each one based on the quality (SNR class) of the assigned sub-carriers. Moreover, there is information provided regarding the channel bandwidth and the corresponding available number of sub-carriers as well as their utilization percentage for this context case.



Subcarriers per User

Bit Rate for every User

| USER ID | SUBCARRIER ID | BIT RATE |
|---|---|---|
| 94 | 0, 26, 49, 50, 84, 102, 119, 154, 182 | 780.0 |
| 96 | 82, 143 | 180.0 |
| 97 | 34, 56, 221 | 270.0 |
| 98 | 16, 58, 67, 144, 200 | 450.0 |
| 99 | 9, 51, 78, 98, 158, 168 | 540.0 |
| 101 | 126 | 90.0 |
| 102 | 108, 184 | 180.0 |
| 103 | 97, 159, 215 | 270.0 |

Channel 5MHz

Total SCs = 225

Used SCs = 225

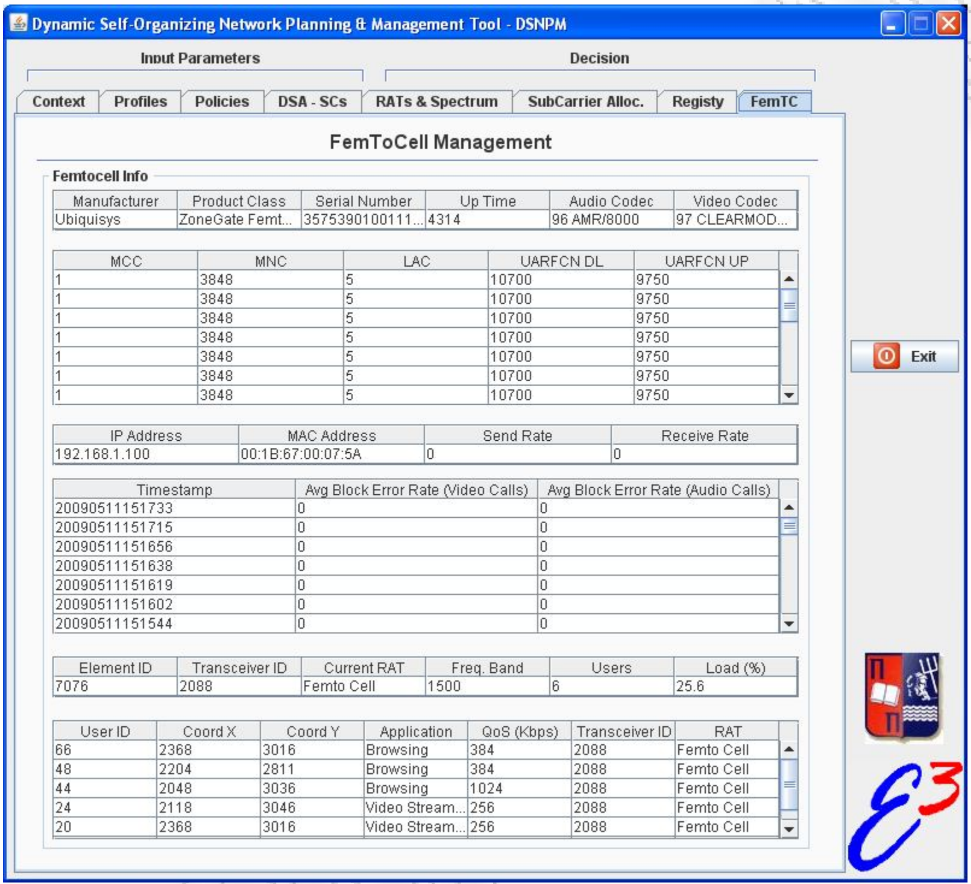
Free SCs = 0

Utilization = 100%

Figure 5-14: DSNPM – Sub-carrier assignment (intra-RAT decision)

Finally, the statistics graph provides useful insight regarding the percentage of users that where assigned to their preferred QoS level (profile). As it is shown in this indicative case, 100% of the Normal, Medium and Basic profiles users received the necessary number of sub-carriers so as to be served with the appropriate QoS level. However, during the assignment the number of available sub-carriers was constantly shrinking. As a result only 25% of the Gold profile users received the necessary number of sub-carriers so as to be served with 1024 Kbps while the 75% of the Gold profile users were allocated to Silver profile (512 Kbps) instead. Furthermore, the last two bars indicate the percentage of users received the Video Streaming application in high QoS level (256 Kbps) and medium (128 Kbps) based on their profile preferences.

DSNPM decisions are implemented by the network elements upon their reception. Moreover, DSNPM is capable to periodically capture the status of the FTC as well as its operating parameters as depicted in Figure 5-15.



| Manufacturer | Product Class | Serial Number | Up Time | Audio Codec | Video Codec |
|---|---|---|---|---|---|
| Ubiquisys | ZoneGate Femt... | 3575390100111... | 4314 | 96 AMR/8000 | 97 CLEARMOD... |

| MCC | MNC | LAC | UARFCN DL | UARFCN UP |
|---|---|---|---|---|
| 1 | 3848 | 5 | 10700 | 9750 |
| 1 | 3848 | 5 | 10700 | 9750 |
| 1 | 3848 | 5 | 10700 | 9750 |
| 1 | 3848 | 5 | 10700 | 9750 |
| 1 | 3848 | 5 | 10700 | 9750 |
| 1 | 3848 | 5 | 10700 | 9750 |
| 1 | 3848 | 5 | 10700 | 9750 |

| IP Address | MAC Address | Send Rate | Receive Rate |
|---|---|---|---|
| 192.168.1.100 | 00:1B:67:00:07:5A | 0 | 0 |

| Timestamp | Avg Block Error Rate (Video Calls) | Avg Block Error Rate (Audio Calls) |
|---|---|---|
| 20090511151733 | 0 | 0 |
| 20090511151715 | 0 | 0 |
| 20090511151656 | 0 | 0 |
| 20090511151638 | 0 | 0 |
| 20090511151619 | 0 | 0 |
| 20090511151602 | 0 | 0 |
| 20090511151544 | 0 | 0 |

| Element ID | Transceiver ID | Current RAT | Freq. Band | Users | Load (%) |
|---|---|---|---|---|---|
| 7076 | 2088 | Femto Cell | 1500 | 6 | 25.6 |

| User ID | Coord X | Coord Y | Application | QoS (Kbps) | Transceiver ID | RAT |
|---|---|---|---|---|---|---|
| 66 | 2368 | 3016 | Browsing | 384 | 2088 | Femto Cell |
| 48 | 2204 | 2811 | Browsing | 384 | 2088 | Femto Cell |
| 44 | 2048 | 3036 | Browsing | 1024 | 2088 | Femto Cell |
| 24 | 2118 | 3046 | Video Stream... | 256 | 2088 | Femto Cell |
| 20 | 2368 | 3016 | Video Stream... | 256 | 2088 | Femto Cell |

Figure 5-15: DSNPM – Femtocell management

Part of the output of DSNPM, after the reconfiguration decisions are sent to the network elements and terminals, is also the statistics depicted in Figure 5-16 and thoroughly described in sub-section 3.7.

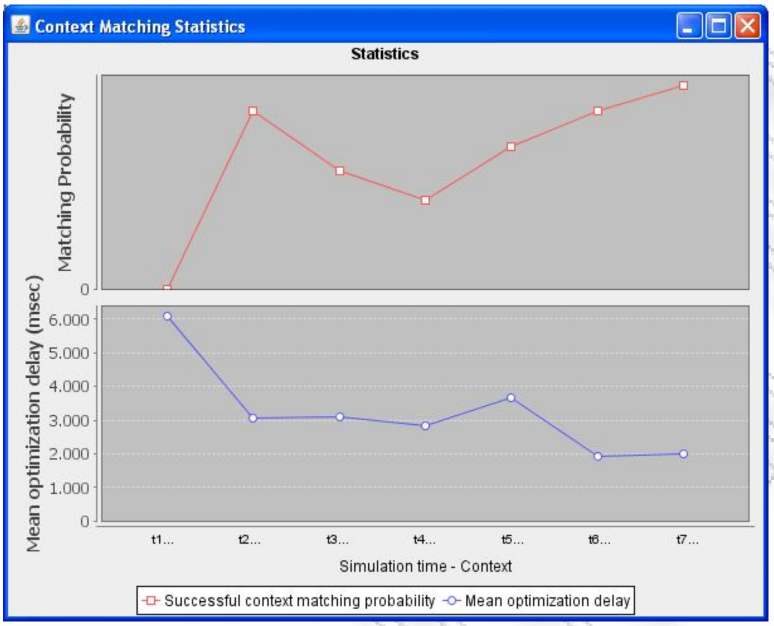


Figure 5-16: DSNPM – Context matching statistics

## 5.5. Indicative Scenario Cases

The following sub-sections present two indicative scenarios as part of the platform validation activities, showcasing the collaboration of the aforementioned entities that where thoroughly described.

### 5.5.1. Scenario 1: Management functionality for FBS and FTC

The purpose of this scenario is to show how DSNPM, FTC and FBS can co-operate for maximum exploitation of network resources targeted to offer the best possible QoS levels and user satisfaction. The DSNPM can reconfigure a network segment made of HSDPA FTCs and FBS in order to serve users with the appropriate QoS levels while trying to achieve load balancing goals as well as to gain knowledge and experience.

In order to take the right reconfiguration decisions, the DSNPM needs to get the FTC context parameters and the KPIs collected from it. When the DSNPM decides that a reconfiguration of a FTC is needed, it sends the reconfiguration decision to the ACS which enforces it, as shown on Figure 5-17.

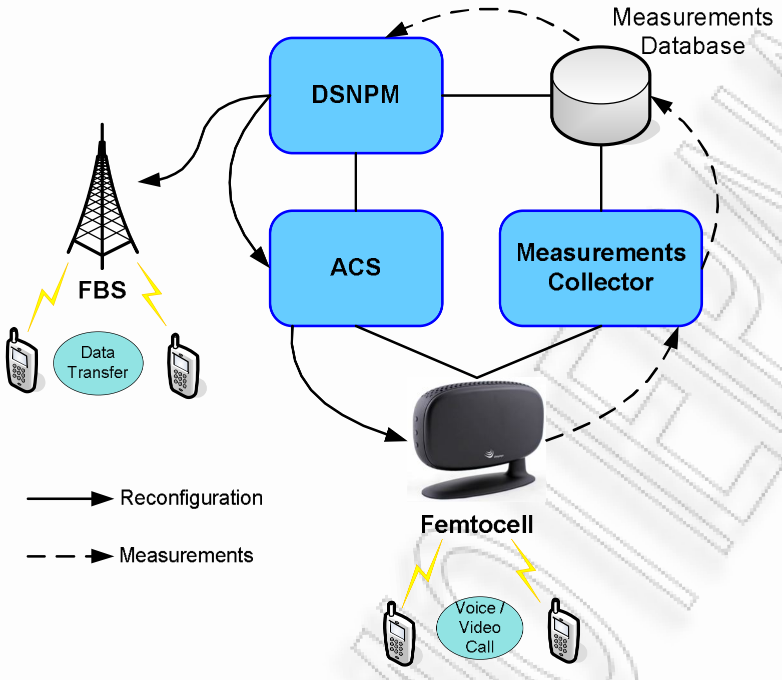


Figure 5-17: Scenario 1 – Measurements and reconfiguration messages exchanged

Initially the FBS operates in UMTS and LTE modes supporting two cells of both. A lot of HSDPA FTCs power-up in the FBS area. When the threshold on the number of FTCs required to takeover the macro-cell service is reached, and based on the measurements collected from them, the DSNPM decides to a) reconfigure the FBS for it to release the resources corresponding to one UMTS macro cell and allocate resources to a new LTE cell and b) reconfigure the FTCs to decrease the maximum allowed bit rate for packet switched data call so that the mobile terminals using data services will connect to the macro network rather than to FTCs, making the FTCs available for voice or video calls. The message sequence chart showing the interaction between the DSNPM, the FBS and the FTCs is depicted in Figure 5-18.

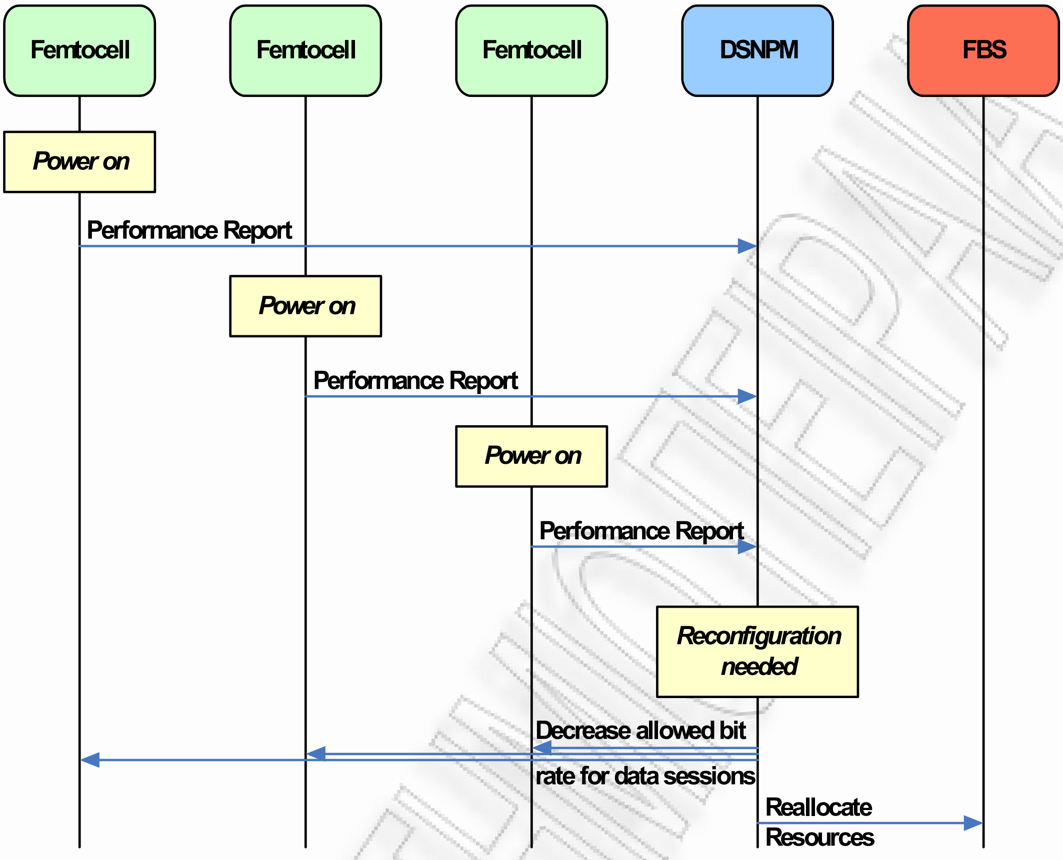


Figure 5-18: Scenario 1 – Message sequence diagram

### 5.5.2. Scenario 2: Network cooperation and self-healing based on cognitive management functionality

Scenario 1 presented the necessary actions for proper network reconfiguration in an indicative case in which UMTS, LTE and HSDPA (FTC) RATs where managed by DSNPM. The focus in scenario 2 is to demonstrate how the efficient cognitive management functionality of DSNPM is capable to realize a) the cooperation among different RATs and b) knowledge-based network self-healing. Figure 5-19 depicts the scenario states as well as the internal steps. After initializing the platform, by powering up the necessary hardware and starting the corresponding control applications and DSNPM, a new context is generating which is captured by DSNPM. DSNPM provides the corresponding decisions which will be stored in order to be exploited in the future upon successful context identification. The second context is captured by activating a WiMAX transceiver and the traffic load is balanced by DSNPM among the new available network resources. Upon WiMAX transceiver deactivation the context is identified while the already known decision is provided realizing knowledge-based network self-healing functionality.

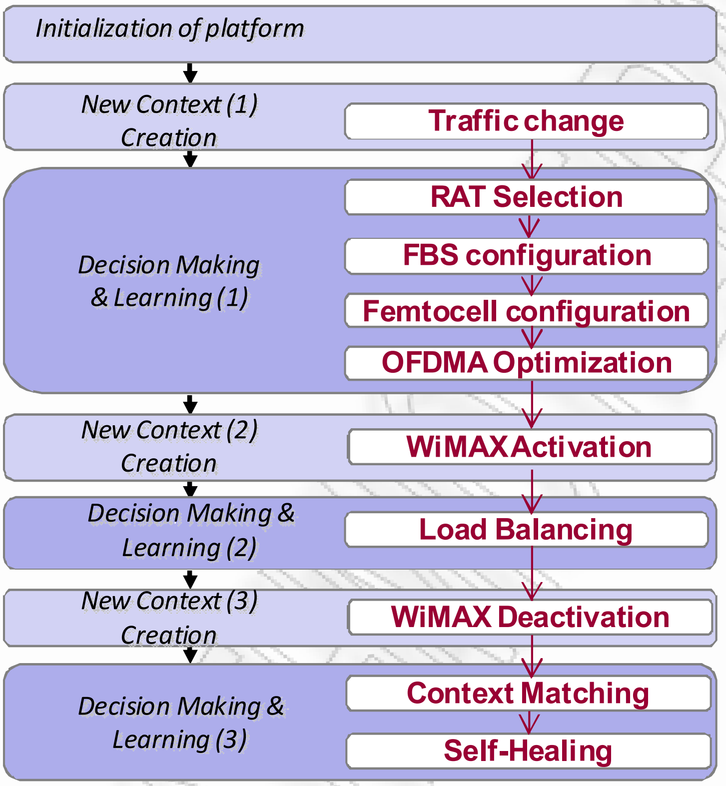
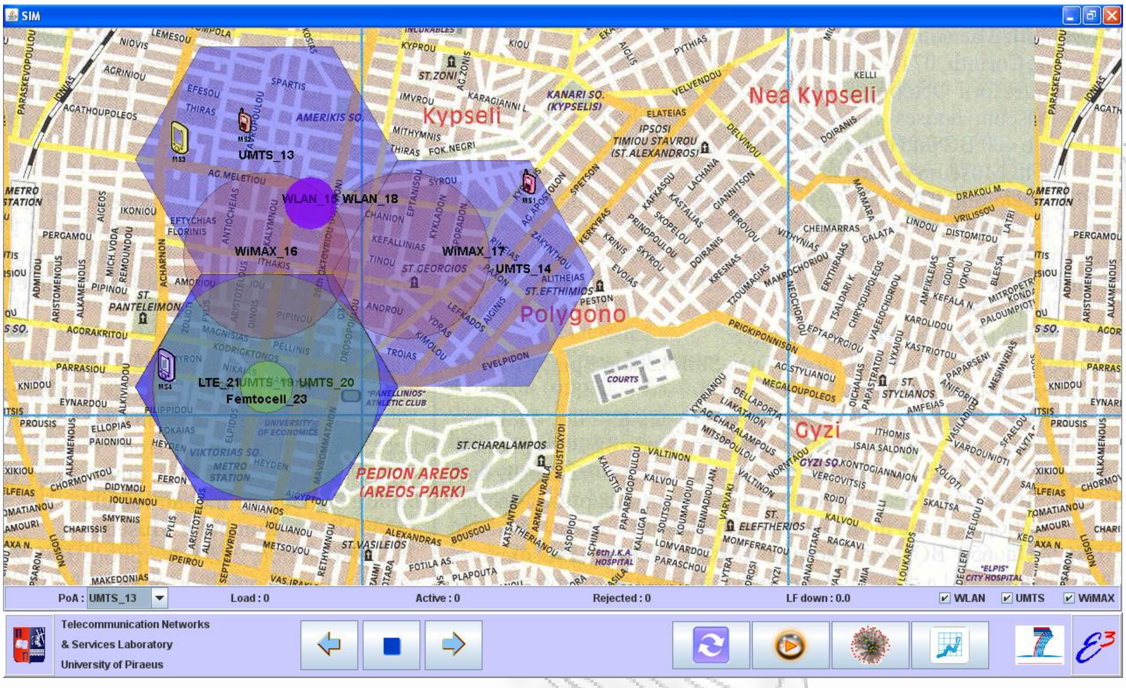


Figure 5-19: Scenario 2 – States and steps illustration

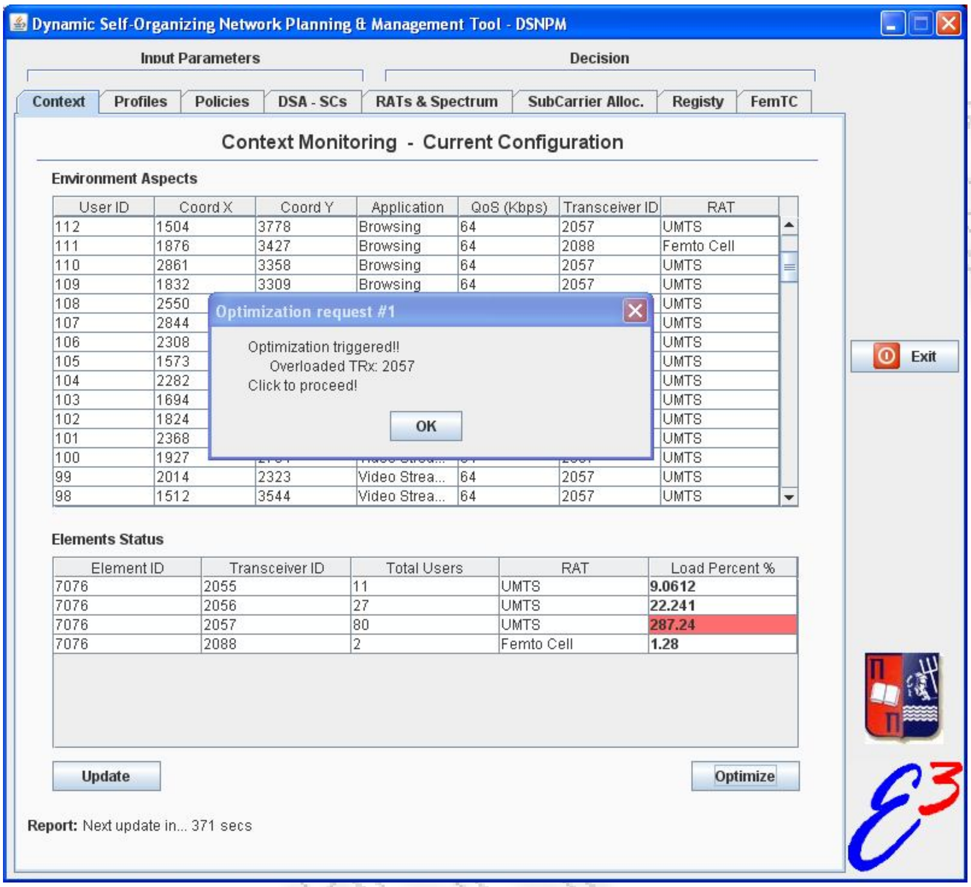
Beginning with the scenario, after the platform has been initialized (meaning that all the involved entities are up and running) a new context is created in the service area by utilizing the traffic generator as it is depicted in Figure 5-1. Figure 5-20 depicts the GUI of the traffic generator/simulator used in order to change the traffic conditions in the service area as well as to display the whole network topology and current configuration.



PoA : UMTS_13 Load : 0 Active : 0 Rejected : 0 LF down : 0.0 ☑ WLAN ☑ UMTS ☑ WiMAX

Figure 5-20: Scenario 2 – Traffic generator and simulator used

The new context that was generated includes 65 sessions of audio call application, 35 sessions of video streaming application and 20 sessions of browsing application. Initially, all FBS transceivers operate in UMTS RAT while there is also one activated FTC transceiver. Furthermore, all data applications are served with the basic QoS level which is 64 Kbps for the browsing application and 128 Kbps for the video streaming applications. This Context information is captured by the DSNPM and a new optimization request is triggered as it is depicted in Figure 5-21.



Context Monitoring - Current Configuration

**Environment Aspects**

| User ID | Coord X | Coord Y | Application | QoS (Kbps) | Transceiver ID | RAT |
|---|---|---|---|---|---|---|
| 112 | 1504 | 3778 | Browsing | 64 | 2057 | UMTS |
| 111 | 1876 | 3427 | Browsing | 64 | 2088 | Femto Cell |
| 110 | 2861 | 3358 | Browsing | 64 | 2057 | UMTS |
| 109 | 1832 | 3309 | Browsing | 64 | 2057 | UMTS |
| 108 | 2550 | | | | | UMTS |
| 107 | 2844 | | | | | UMTS |
| 106 | 2308 | | | | | UMTS |
| 105 | 1573 | | | | | UMTS |
| 104 | 2282 | | | | | UMTS |
| 103 | 1694 | | | | | UMTS |
| 102 | 1824 | | | | | UMTS |
| 101 | 2368 | | | | | UMTS |
| 100 | 1927 | | | | | UMTS |
| 99 | 2014 | 2323 | Video Strea... | 64 | 2057 | UMTS |
| 98 | 1512 | 3544 | Video Strea... | 64 | 2057 | UMTS |

Optimization request #1

Optimization triggered!!
Overloaded TRx: 2057
Click to proceed!

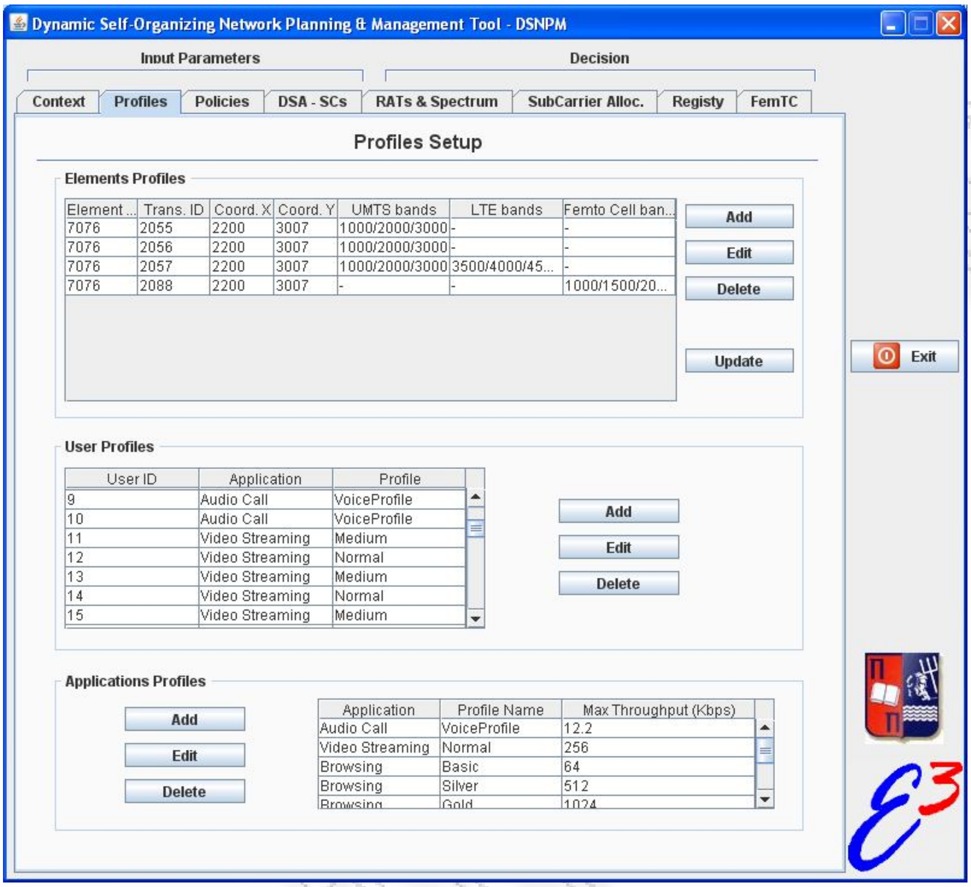
**Elements Status**

| Element ID | Transceiver ID | Total Users | RAT | Load Percent % |
|---|---|---|---|---|
| 7076 | 2055 | 11 | UMTS | **9.0612** |
| 7076 | 2056 | 27 | UMTS | **22.241** |
| 7076 | 2057 | 80 | UMTS | **287.24** |
| 7076 | 2088 | 2 | Femto Cell | **1.28** |

**Report:** Next update in... 371 secs

Figure 5-21: Scenario 2 – DSNPM Context information

Figure 5-22 depicts the Profile information regarding the supported RATs for each transceiver of the FBS as well as the FTC. It is clear that there are two available UMTS transceivers as well as a reconfigurable transceiver which is supports the operation of UMTS and LTE RATs. Finally, there is a FTC transceiver available. The location for all the aforementioned transceivers is the same since they are all located at the centre of the service area considered for this scenario.



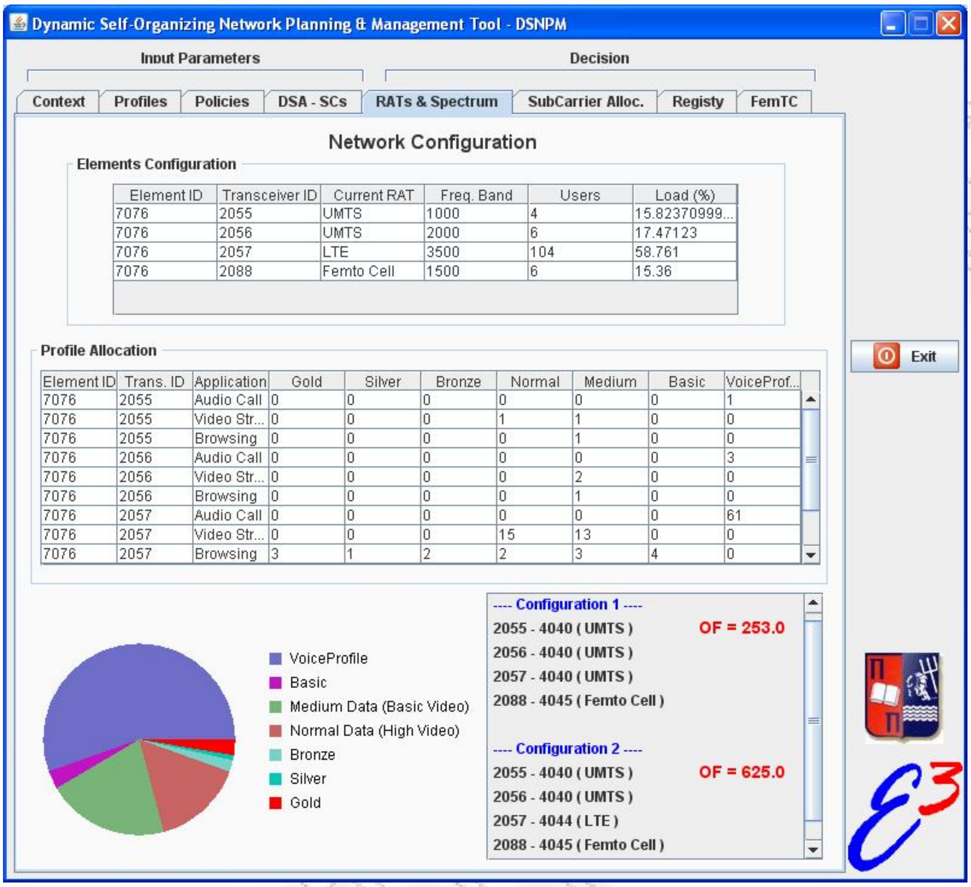
| Element ... | Trans. ID | Coord. X | Coord. Y | UMTS bands | LTE bands | Femto Cell ban... |
|---|---|---|---|---|---|---|
| 7076 | 2055 | 2200 | 3007 | 1000/2000/3000 | - | - |
| 7076 | 2056 | 2200 | 3007 | 1000/2000/3000 | - | - |
| 7076 | 2057 | 2200 | 3007 | 1000/2000/3000 | 3500/4000/45... | - |
| 7076 | 2088 | 2200 | 3007 | - | - | 1000/1500/20... |

| User ID | Application | Profile |
|---|---|---|
| 9 | Audio Call | VoiceProfile |
| 10 | Audio Call | VoiceProfile |
| 11 | Video Streaming | Medium |
| 12 | Video Streaming | Normal |
| 13 | Video Streaming | Medium |
| 14 | Video Streaming | Normal |
| 15 | Video Streaming | Medium |

| Application | Profile Name | Max Throughput (Kbps) |
|---|---|---|
| Audio Call | VoiceProfile | 12.2 |
| Video Streaming | Normal | 256 |
| Browsing | Basic | 64 |
| Browsing | Silver | 512 |
| Browsing | Gold | 1024 |

Figure 5-22: Scenario 2 – DSNPM Profiles information

Given the current profile information, DSNPM decided that the best possible inter-RAT reconfiguration decision is the one depicted in Figure 5-23. More specifically, the demand is uniformly distributed among the transceivers based on their characteristics like range, capacity etc. Regarding the FBS, the first two transceivers are configured to activate UMTS RAT while the third one is configured for LTE RAT operation by utilizing the sub-carriers of a 5MHz channel achieving 20Mbps capacity. Based on the achieved capacity, the majority of the users are allocated to the LTE transceiver since it is able to deliver data services at high QoS levels. Finally, 6 users have been assigned to the FTC served with their preferred QoS levels.



Network Configuration

**Elements Configuration**

| Element ID | Transceiver ID | Current RAT | Freq. Band | Users | Load (%) |
|---|---|---|---|---|---|
| 7076 | 2055 | UMTS | 1000 | 4 | 15.82370999... |
| 7076 | 2056 | UMTS | 2000 | 6 | 17.47123 |
| 7076 | 2057 | LTE | 3500 | 104 | 58.761 |
| 7076 | 2088 | Femto Cell | 1500 | 6 | 15.36 |

**Profile Allocation**

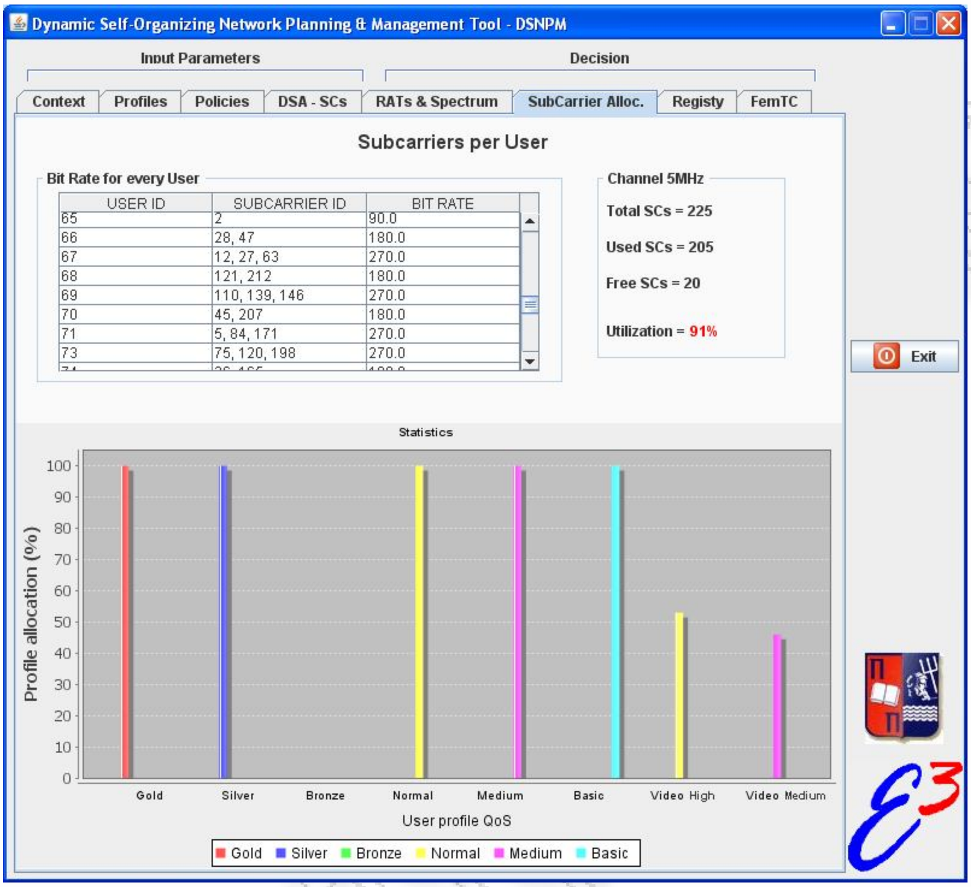
| Element ID | Trans. ID | Application | Gold | Silver | Bronze | Normal | Medium | Basic | VoiceProf... |
|---|---|---|---|---|---|---|---|---|---|
| 7076 | 2055 | Audio Call | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 7076 | 2055 | Video Str... | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 7076 | 2055 | Browsing | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 7076 | 2056 | Audio Call | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| 7076 | 2056 | Video Str... | 0 | 0 | 0 | 0 | 2 | 0 | 0 |
| 7076 | 2056 | Browsing | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 7076 | 2057 | Audio Call | 0 | 0 | 0 | 0 | 0 | 0 | 61 |
| 7076 | 2057 | Video Str... | 0 | 0 | 0 | 15 | 13 | 0 | 0 |
| 7076 | 2057 | Browsing | 3 | 1 | 2 | 2 | 3 | 4 | 0 |

---- Configuration 1 ----
2055 - 4040 ( UMTS ) OF = 253.0
2056 - 4040 ( UMTS )
2057 - 4040 ( UMTS )
2088 - 4045 ( Femto Cell )

---- Configuration 2 ----
2055 - 4040 ( UMTS ) OF = 625.0
2056 - 4040 ( UMTS )
2057 - 4044 ( LTE )
2088 - 4045 ( Femto Cell )

Figure 5-23: Scenario 2 - DSNPM inter-RAT decision

It is obvious that the decision including the activated LTE transceiver achieves higher objective function value since the capacity offered by LTE can easily serve the users' sessions at the highest possible QoS levels. Figure 5-24 depicts the intra-RAT decision DSNPM provided for the LTE transceiver.



Subcarriers per User

Bit Rate for every User

| USER ID | SUBCARRIER ID | BIT RATE |
|---|---|---|
| 65 | 2 | 90.0 |
| 66 | 28, 47 | 180.0 |
| 67 | 12, 27, 63 | 270.0 |
| 68 | 121, 212 | 180.0 |
| 69 | 110, 139, 146 | 270.0 |
| 70 | 45, 207 | 180.0 |
| 71 | 5, 84, 171 | 270.0 |
| 73 | 75, 120, 198 | 270.0 |

Channel 5MHz

Total SCs = 225

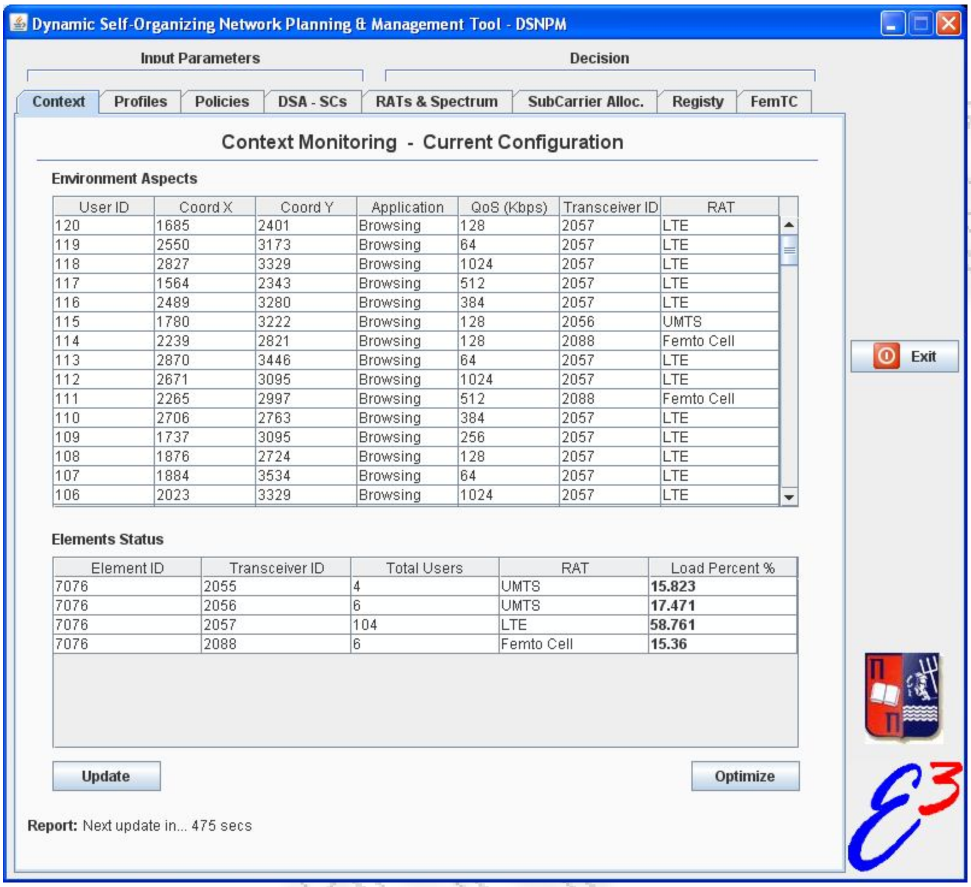
Used SCs = 205

Free SCs = 20

Utilization = 91%

Figure 5-24: Scenario 2 – DSNPM intra-RAT (LTE) decision

It is clear that all users are experiencing the requested services at the preferred QoS levels while the channel of 5MHz for the LTE is utilized by 91% since there are 20 free sub-carriers out of 225. The new Context information after the decision implementation is depicted in Figure 5-25.



**Environment Aspects**

| User ID | Coord X | Coord Y | Application | QoS (Kbps) | Transceiver ID | RAT |
|---|---|---|---|---|---|---|
| 120 | 1685 | 2401 | Browsing | 128 | 2057 | LTE |
| 119 | 2550 | 3173 | Browsing | 64 | 2057 | LTE |
| 118 | 2827 | 3329 | Browsing | 1024 | 2057 | LTE |
| 117 | 1564 | 2343 | Browsing | 512 | 2057 | LTE |
| 116 | 2489 | 3280 | Browsing | 384 | 2057 | LTE |
| 115 | 1780 | 3222 | Browsing | 128 | 2056 | UMTS |
| 114 | 2239 | 2821 | Browsing | 128 | 2088 | Femto Cell |
| 113 | 2870 | 3446 | Browsing | 64 | 2057 | LTE |
| 112 | 2671 | 3095 | Browsing | 1024 | 2057 | LTE |
| 111 | 2265 | 2997 | Browsing | 512 | 2088 | Femto Cell |
| 110 | 2706 | 2763 | Browsing | 384 | 2057 | LTE |
| 109 | 1737 | 3095 | Browsing | 256 | 2057 | LTE |
| 108 | 1876 | 2724 | Browsing | 128 | 2057 | LTE |
| 107 | 1884 | 3534 | Browsing | 64 | 2057 | LTE |
| 106 | 2023 | 3329 | Browsing | 1024 | 2057 | LTE |

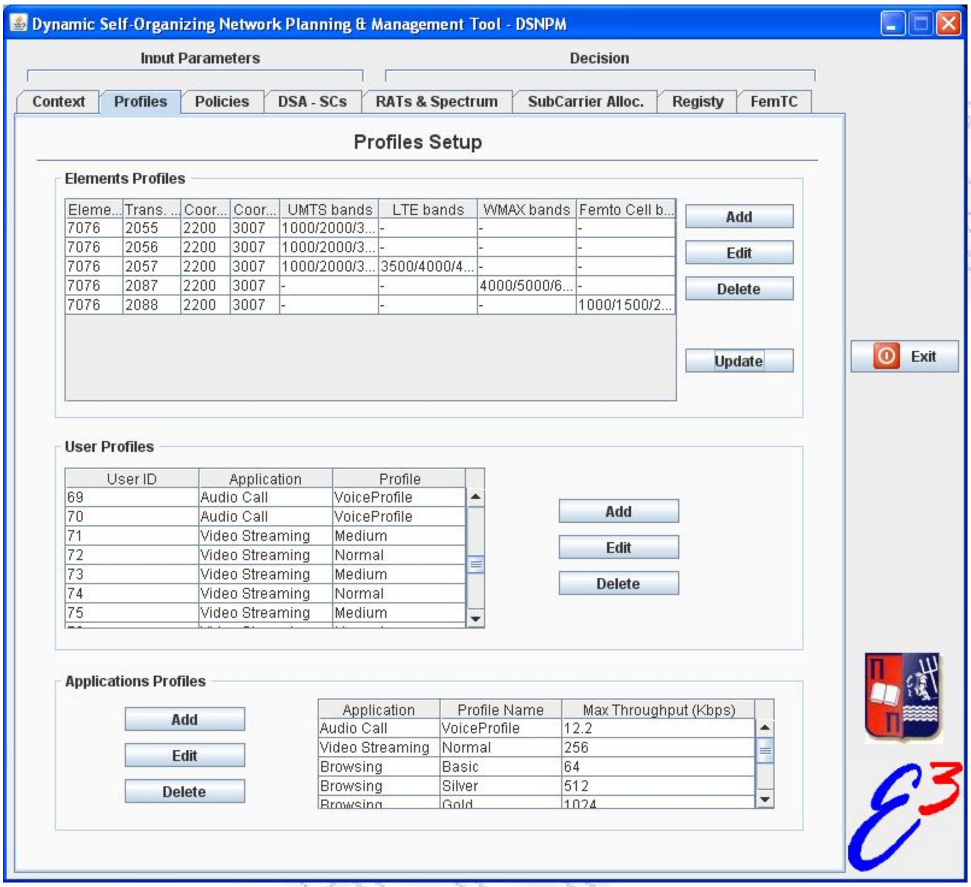
**Elements Status**

| Element ID | Transceiver ID | Total Users | RAT | Load Percent % |
|---|---|---|---|---|
| 7076 | 2055 | 4 | UMTS | **15.823** |
| 7076 | 2056 | 6 | UMTS | **17.471** |
| 7076 | 2057 | 104 | LTE | **58.761** |
| 7076 | 2088 | 6 | Femto Cell | **15.36** |

**Report:** Next update in... 475 secs

Figure 5-25: Scenario 2 – DSNPM Context information after decision enforcement

In order to demonstrate the cooperation of different RATs as it is realized by DSNPM, it is assumed that a new FBS board is activated supporting WiMAX RAT. The corresponding profile is depicted in Figure 5-26 for the transceiver ID 2087.



Profiles Setup

Elements Profiles

| Eleme... | Trans. ... | Coor... | Coor... | UMTS bands | LTE bands | WMAX bands | Femto Cell b... |
|---|---|---|---|---|---|---|---|
| 7076 | 2055 | 2200 | 3007 | 1000/2000/3... | - | - | - |
| 7076 | 2056 | 2200 | 3007 | 1000/2000/3... | - | - | - |
| 7076 | 2057 | 2200 | 3007 | 1000/2000/3... | 3500/4000/4... | - | - |
| 7076 | 2087 | 2200 | 3007 | - | - | 4000/5000/6... | - |
| 7076 | 2088 | 2200 | 3007 | - | - | - | 1000/1500/2... |

User Profiles

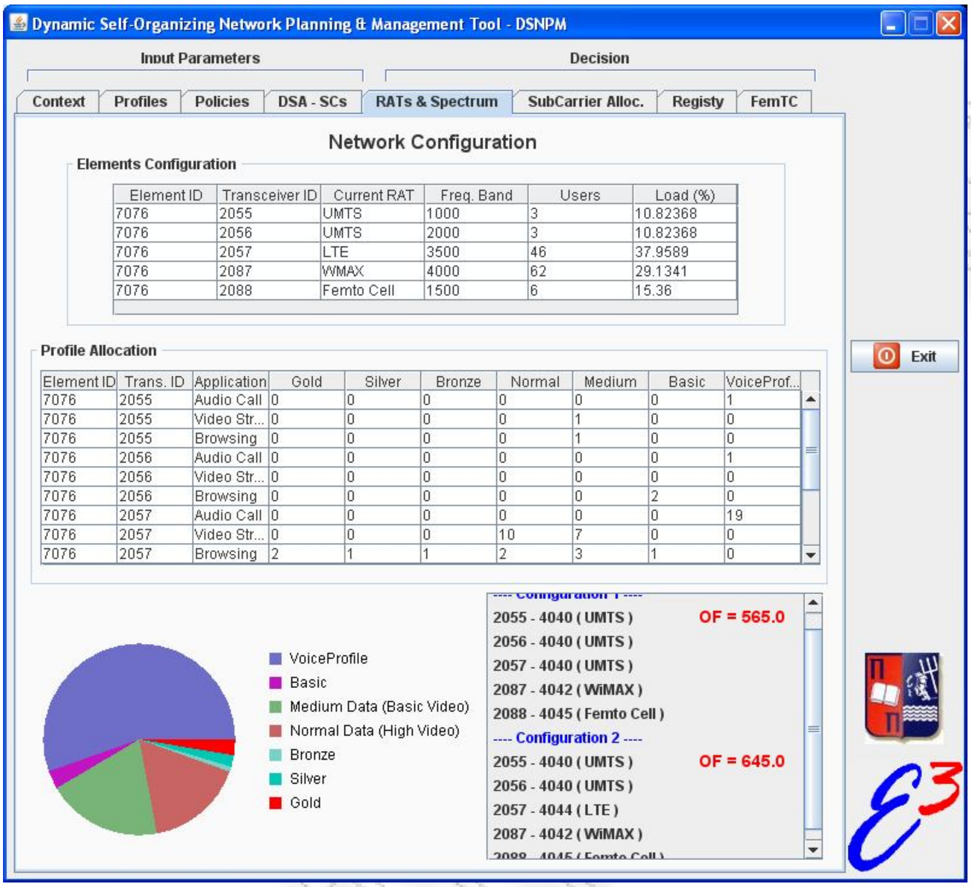
| User ID | Application | Profile |
|---|---|---|
| 69 | Audio Call | VoiceProfile |
| 70 | Audio Call | VoiceProfile |
| 71 | Video Streaming | Medium |
| 72 | Video Streaming | Normal |
| 73 | Video Streaming | Medium |
| 74 | Video Streaming | Normal |
| 75 | Video Streaming | Medium |

Applications Profiles

| Application | Profile Name | Max Throughput (Kbps) |
|---|---|---|
| Audio Call | VoiceProfile | 12.2 |
| Video Streaming | Normal | 256 |
| Browsing | Basic | 64 |
| Browsing | Silver | 512 |
| Browsing | Gold | 1024 |

Figure 5-26: Scenario 2 – DSNPM Profiles information after WiMAX transceiver activation

The activation of a new WiMAX transceiver for the FBS has impact on the available network resources monitored by DSNPM. Thus, DSNPM decides to trigger a new optimization request since there is new available network resource that can be efficiently utilized for proper load balancing. Figure 5-27 depicts the new inter-RAT decision utilizing also the new WiMAX transceiver.



Network Configuration

Elements Configuration

| Element ID | Transceiver ID | Current RAT | Freq. Band | Users | Load (%) |
|---|---|---|---|---|---|
| 7076 | 2055 | UMTS | 1000 | 3 | 10.82368 |
| 7076 | 2056 | UMTS | 2000 | 3 | 10.82368 |
| 7076 | 2057 | LTE | 3500 | 46 | 37.9589 |
| 7076 | 2087 | WMAX | 4000 | 62 | 29.1341 |
| 7076 | 2088 | Femto Cell | 1500 | 6 | 15.36 |

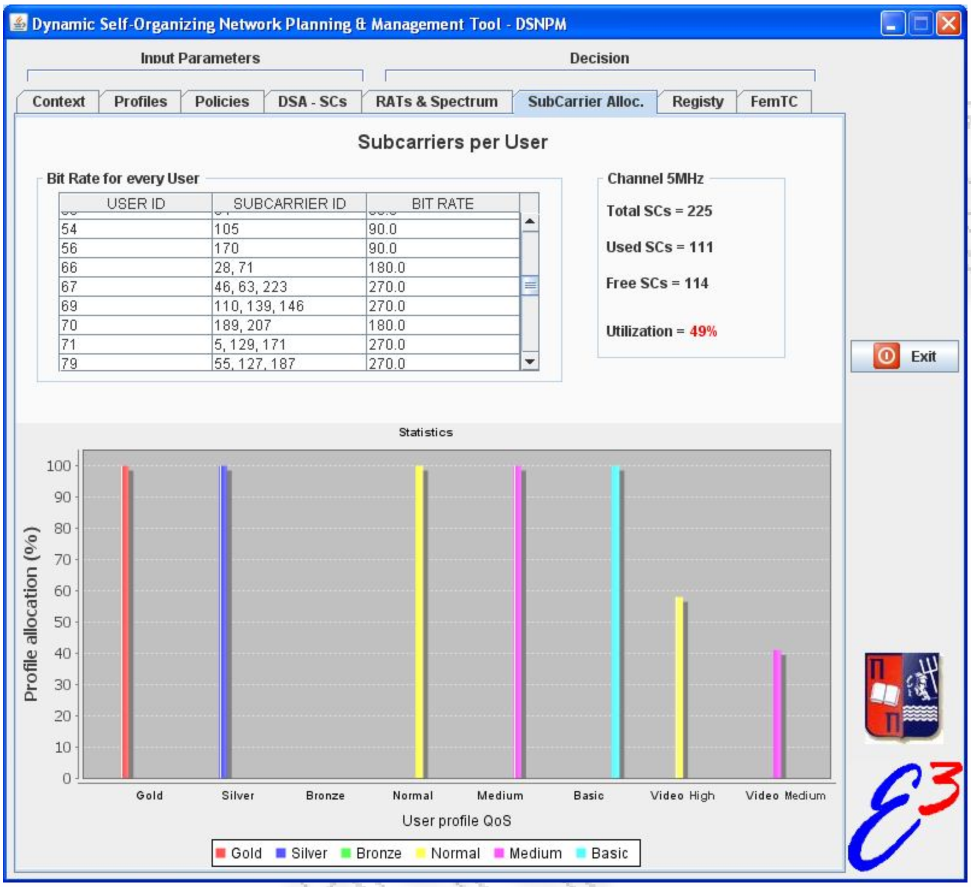
Profile Allocation

| Element ID | Trans. ID | Application | Gold | Silver | Bronze | Normal | Medium | Basic | VoiceProf... |
|---|---|---|---|---|---|---|---|---|---|
| 7076 | 2055 | Audio Call | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 7076 | 2055 | Video Str... | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 7076 | 2055 | Browsing | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 7076 | 2056 | Audio Call | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 7076 | 2056 | Video Str... | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7076 | 2056 | Browsing | 0 | 0 | 0 | 0 | 0 | 2 | 0 |
| 7076 | 2057 | Audio Call | 0 | 0 | 0 | 0 | 0 | 0 | 19 |
| 7076 | 2057 | Video Str... | 0 | 0 | 0 | 10 | 7 | 0 | 0 |
| 7076 | 2057 | Browsing | 2 | 1 | 1 | 2 | 3 | 1 | 0 |

```
---- Configuration 1 ----
2055 - 4040 ( UMTS )          OF = 565.0
2056 - 4040 ( UMTS )
2057 - 4040 ( UMTS )
2087 - 4042 ( WiMAX )
2088 - 4045 ( Femto Cell )
---- Configuration 2 ----
2055 - 4040 ( UMTS )          OF = 645.0
2056 - 4040 ( UMTS )
2057 - 4044 ( LTE )
2087 - 4042 ( WiMAX )
2088 - 4045 ( Femto Cell )
```

Figure 5-27: Scenario 2 – DSNPM inter-RAT decision utilizing WiMAX transceiver

The number of users assigned to LTE transceiver has been minimized since a part of the initial number of users has now been assigned to WiMAX, considering of course that they are inside the WiMAX range. Figure 5-28 depicts the new intra-RAT decision after the WiMAX transceiver activation.



Subcarriers per User

Bit Rate for every User

| USER ID | SUBCARRIER ID | BIT RATE |
|---|---|---|
| 54 | 105 | 90.0 |
| 56 | 170 | 90.0 |
| 66 | 28, 71 | 180.0 |
| 67 | 46, 63, 223 | 270.0 |
| 69 | 110, 139, 146 | 270.0 |
| 70 | 189, 207 | 180.0 |
| 71 | 5, 129, 171 | 270.0 |
| 79 | 55, 127, 187 | 270.0 |

Channel 5MHz

Total SCs = 225

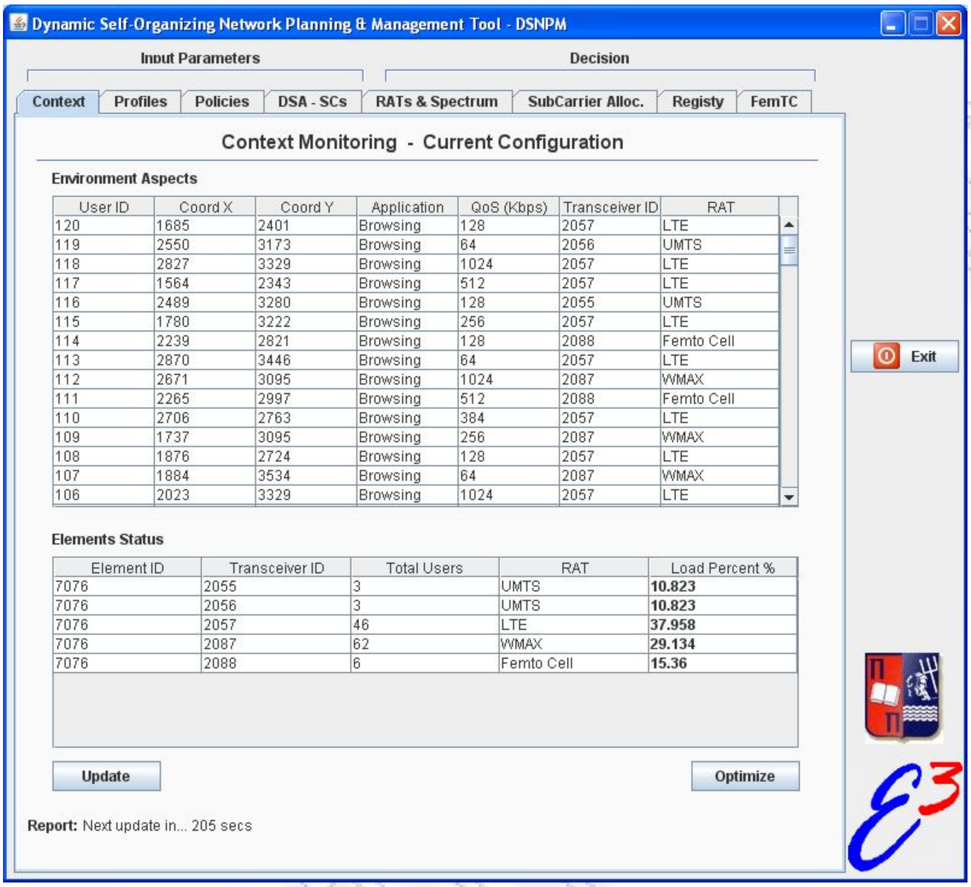
Used SCs = 111

Free SCs = 114

Utilization = 49%

Figure 5-28: Scenario 2 – DSNPM intra-RAT (LTE) decision after WiMAX transceiver activation

Although the impact of this change to the intra-RAT decision of DSNPM for LTE doesn't seem to be of great level, since the users are still served with the QoS level they prefer, however the sub-carriers utilization percentage has been dropped to 49% from 91%. This is of great importance since it is possible for the remaining sub-carriers to be used, for instance, in a different area or nearby cell in order to address potential problems caused by a hot-spot.



Context Monitoring - Current Configuration

**Environment Aspects**

| User ID | Coord X | Coord Y | Application | QoS (Kbps) | Transceiver ID | RAT |
|---|---|---|---|---|---|---|
| 120 | 1685 | 2401 | Browsing | 128 | 2057 | LTE |
| 119 | 2550 | 3173 | Browsing | 64 | 2056 | UMTS |
| 118 | 2827 | 3329 | Browsing | 1024 | 2057 | LTE |
| 117 | 1564 | 2343 | Browsing | 512 | 2057 | LTE |
| 116 | 2489 | 3280 | Browsing | 128 | 2055 | UMTS |
| 115 | 1780 | 3222 | Browsing | 256 | 2057 | LTE |
| 114 | 2239 | 2821 | Browsing | 128 | 2088 | Femto Cell |
| 113 | 2870 | 3446 | Browsing | 64 | 2057 | LTE |
| 112 | 2671 | 3095 | Browsing | 1024 | 2087 | WMAX |
| 111 | 2265 | 2997 | Browsing | 512 | 2088 | Femto Cell |
| 110 | 2706 | 2763 | Browsing | 384 | 2057 | LTE |
| 109 | 1737 | 3095 | Browsing | 256 | 2087 | WMAX |
| 108 | 1876 | 2724 | Browsing | 128 | 2057 | LTE |
| 107 | 1884 | 3534 | Browsing | 64 | 2087 | WMAX |
| 106 | 2023 | 3329 | Browsing | 1024 | 2057 | LTE |

**Elements Status**

| Element ID | Transceiver ID | Total Users | RAT | Load Percent % |
|---|---|---|---|---|
| 7076 | 2055 | 3 | UMTS | **10.823** |
| 7076 | 2056 | 3 | UMTS | **10.823** |
| 7076 | 2057 | 46 | LTE | **37.958** |
| 7076 | 2087 | 62 | WMAX | **29.134** |
| 7076 | 2088 | 6 | Femto Cell | **15.36** |

**Report:** Next update in... 205 secs

Figure 5-29: Scenario 2 – DSNPM Context information after decision enforcement including activated WiMAX transceiver

The last aspect that should be addressed in this scenario is the realization of knowledge-based network self-healing. In order to demonstrate this aspect it is assumed that WiMAX transceiver is no longer available (eg. due to malfunction). To this respect, the Profile information regarding the transceiver ID 2087 is no longer available as it was initially captured in Figure 5-22 and DSNPM triggers automatically an optimization request so as to efficiently balance the load at the service area exploiting the capabilities of the remaining network resources. Assuming that the Context characteristics haven't changed in great level and the network traffic remains the same in average level as depicted in Figure 5-21, DSNPM based on the identification process successfully identified that this Context has already been addressed in the past and the necessary decisions are already available, Figure 5-23 and Figure 5-24. Figure 5-30 depicts the statistics regarding the matching probability and mean optimization delay for DSNPM in this scenario.

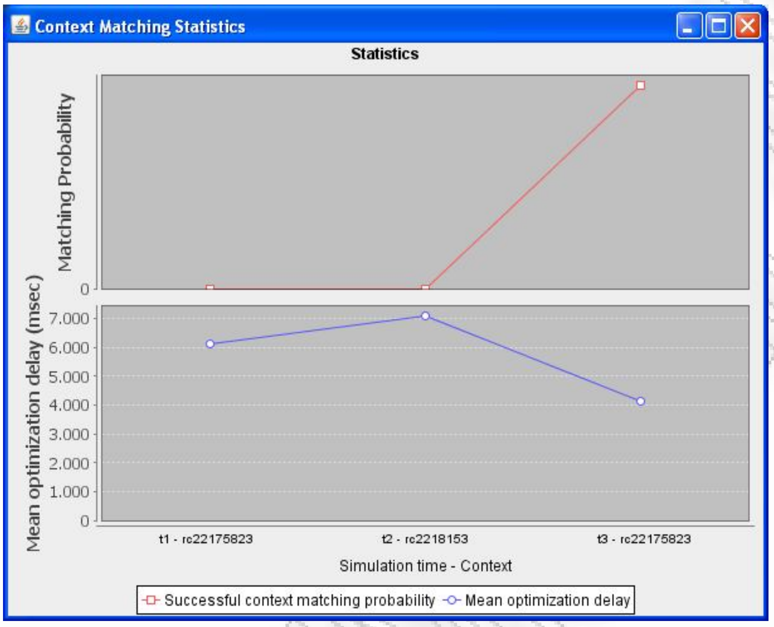


Figure 5-30: Scenario 2 – DSNPM context matching statistics

The first time that DSNPM captured the context information it wasn't possible to be successfully identified since this is the first context ever captured. The mean optimization delay for the first context is quite high since it rises up to 6 seconds. After the activation of WiMAX transceiver the optimization procedure had to be triggered for second time in order the new available network resources to be efficiently exploited. The delay for the second time has been increased by 1 second compared to the first one since there are more possible feasible configurations to be checked by the optimization procedure. However, when the WiMAX transceiver was deactivated, for the sake of the scenario, the matching probability increased since DSNPM identified that the context and profiles information is the same as in the first captured context. Hence, the delay for the self-healing actions provided by DSNPM, based on knowledge gained in the past, was significantly dropped to 4 seconds.

## 5.6. Conclusions

This chapter presented the implementation of a platform environment in which the prototypes of FBS, FTC and DSNPM were integrated as part of the architecture designed and developed inside Work Package 6 of the E3 project [9] which was funded by the European Commission during the 7th Framework Programme (FP7). Further details about the platform can be found in [10] and [11].

The equipment and control applications for the FBS and FTC were presented while the application for the DSNPM was thoroughly described. In particular, the architectures for the embedded control system and the flexible baseband processing for the FBS were analyzed as well as the internal management architecture for the FTC and the necessary interfaces for the KPIs collection. DSNPM application was described in detail in terms of input information (Context, Profiles and Polices) and the decisions provided in terms of intra-RAT and inter-RAT specific decisions.

Having all the involved entities interconnected, two indicative scenarios were studied where the target was to serve users with the appropriate QoS levels while trying to achieve load balancing goals as well as to gain knowledge and experience. Scenario 1 focused on the necessary reconfiguration actions as realized by the decisions of DSNPM for a network segment served by the FBS and a FTC. Finally scenario 2 focused to demonstrate how DSNPM realizes the cooperation among different RATs of FBS and FTC while the knowledge that DSNPM gained from past decisions can be also utilized in the future for network self-healing purposes.

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[11] E3 project deliverable D6.4 "Simulation based recommendations for DSA and self-management", July 2009

# 6. SUMMARY – ONGOING CHALLENGES

CWNs are comprised by heterogeneous RATs, most of them developed in the recent years, and are also enhanced with reconfiguration capabilities. The flexibility they introduce necessitates advanced and efficient management functionality in order to achieve the maximum possible exploitation of RATs capabilities.

In the context of this dissertation, a FA for the management and control of CWNs was proposed in order to increase radio and spectrum resources efficiency. DSNPM, as the decision entity of the FA and the first topic of this dissertation contribution, was analyzed and described in detail. The most important features that were thoroughly described were a) the mechanisms for perception and learning of user and environment information in order to determine and configure dynamically its operation based on knowledge gained in the past and b) the inter-RAT and intra-RAT decisions targeted to address load balancing aspects among the different kinds of co-existed RATs.

The learning procedure of DSNPM enhanced with context identification procedure was presented, enabling DSNPM to retrieve knowledge from past interactions with the network segments and overcome problems by applying already known solutions. CMA was also presented in detail as part of the identification procedure while it is the second topic of this dissertation contribution. Furthermore, CMA realized DSNPM as a cognitive management system able to provide decisions faster as it becomes more and more experienced, regardless of the complexity introduced by the optimization procedures.

The third topic of this dissertation contribution was the enhancement of the optimization procedure of DSNPM so as to be able to provide intra-RAT configuration decisions for OFDMA-based systems. More specifically, the DSA technique for OFDMA-based systems was analyzed while the CPP-DSA algorithm was presented. The most important aspect regarding this algorithm is the capability to consider not only channel state information but also management information so as to decide on the best possible sub-carriers assignment to users' sessions based on their preferences. Indicative results ,targeted for LTE RAT, were also presented showcasing the algorithms efficiency since the assignments are close to the optimum ones while the execution delay is low compared to other algorithms.

Last, but not least, topic of this dissertation is the platform validation which was consisted by the FBS and FTC equipment, the corresponding control applications as well as the management application of DSNPM. Each one of the aforementioned was thoroughly described with the focus on DSNPM. The platform provided the means to realize scenarios in order to demonstrate the necessary reconfiguration actions, the cooperation aspects among the RATs as well as knowledge exploitation for network self-healing.

However, there are still plenty of challenges ahead regarding the topics described.

**FA standardization**

The most important challenge is the need for the FA standardization so as to support the implementation of various business models in order to make reconfiguration implementation mechanisms efficient.

**Context prediction**

Beyond context matching as realized by CMA, DSNPM should be also capable for context prediction in order to act proactively so as to apply the corresponding solutions before the problem occurs. Thus, there is a need for efficient prediction algorithms towards that scope either to exploit the time dimension of past decisions or to consider the short term traffic behaviour in order to predict future KPIs.

**Channel Segregation**

Since DSA algorithms, in general, are targeted for short term decisions the execution delay play a significant role for their implementation to the NO’s infrastructure. The first promising approach is to efficiently minimize the considered input without loosing vital information regarding users and the sub-carriers sensed by their equipment. Channel segregation technique provides a prominent way in order to realize this approach by filtering the full set of sub-carriers by utilizing the most popular among them. Furthermore, the classic approach of channel segregation technique can also be used for the appropriate channel selection to a network segment based on past decisions of DSA technique upon channel requests from FBSs and/or FTCs.

**Ad-hoc networking scheme selection**

CMN depicted in Figure 1-1 and described in sub-section 1.1.2 provide the capability to MUE to establish also ad-hoc connections among themselves. Such flexibility also requires advanced management functionality in order to decide on the best connection for the MUEs either for ad-hoc or infrastructure-based. Framed within this concept, a method can be proposed in order to decide on the appropriate infrastructure-less Ad-Hoc Networking Scheme (A-HNS). This method can be based on offline past network conditions analysis while the A-HNS includes a) the MUEs ad-hoc connections, b) the appropriate routing protocols and c) the transmission power for each MUE which is the most important since it can be used for interference limitation. Combined with the learning capabilities of the management infrastructures as well as the context identifications capabilities for knowledge exploitation, it is possible in the future to apply the same or similar A-HNS when similar conditions are addressed.

# 7. APPENDIX A – ACRONYMS

| Acronym | Explanation |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| **A** | |
| ACS | Auto-Configuration Server |
| AM | Adaptive Modulation |
| APA | Adaptive Power Allocation |
| **B** | |
| B3G | Beyond 3rd Generation |
| BDI | Belief-Desire-Intention |
| BER | Bit Error Rate |
| **C** | |
| CAPEX | CAPital EXpenditures |
| CCM | Configuration Control Module |
| CDMA | Code Division Multiple Access |
| CF | Compact Flash |
| CNR | Channel to Noise Ratio |
| CPE | Customer Premise Equipments |
| CS | Channel Segregation |
| CWN | Composite Wireless Network |
| **D** | |
| DDR-RAM | Double Data Rate - Random Access Memory |
| DF | Directory Facilitator |

| | |
|---|---|
| DSA | Dynamic Sub-carrier Assignment |
| DSM | Dynamic Spectrum Management |
| DSNPM | Dynamic Self-organizing Network Planning and Management |
| DSP | Digital Signal Processor |
| **E** | |
| E-UTRAN | Evolved Universal Terrestrial Radio Access Network |
| EDGE | Enhanced Data rates for GSM Evolution |
| eNB | evolved Node-B |
| EPC | Evolved Packet Core |
| ETSI | European Standards Telecommunication Institute |
| **F** | |
| FA | Functional Architecture |
| FBS | Flexible Base Station |
| FIPA | Foundation for Intelligent Physical Agents |
| FPGA | Field Programmable Gate Array |
| FSA | Fixed Spectrum Allocation |
| FTC | Femto Cell |
| **G** | |
| GUI | Graphical User Interface |
| GSM | Global System for Mobile Communications |
| **H** | |
| HNB | Home Node B |
| HSDPA | High-Speed Downlink Packet Access |
| HSS | Home Subscribing Server |
| **I** | |

| | |
|---|---|
| ICAP | Internal Configuration Access Port |
| IEEE | Institute of Electrical and Electronics Engineers |
| IFFT | Inverse Fast Fourier Transform |
| IP core | Intellectual Property core |
| **J** | |
| JADE | Java Agent DEveloment Framework |
| JRRM | Joint Radio Resources Management |
| **K** | |
| k-NN | k-Nearest Neighbour |
| KPI | Key Performance Indicator |
| **L** | |
| LTE | Long Term Evolution |
| **M** | |
| MAC | Medium Access Control |
| MME | Mobility Management Entity |
| MR | Modulation Rate |
| **N** | |
| NO | Network Operator |
| **O** | |
| O&M | Operation and Management |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| OPEX | Operation Expenditures |
| OS | Operating System |
| **P** | |

| | |
|---|---|
| PCRF | Policy and Charging Rules Function |
| PDN GW | Packet Data Network Gateway |
| PPC | PowerPC |
| **Q** | |
| QoS | Quality of Service |
| **R** | |
| R-RBS | Reconfigurable Radio Base Stations |
| RAT | Radio Access Technology |
| RDQ-A | RAT Demand and QoS Assignment |
| RPC | Remote Procedure Calls |
| RRS | Reconfigurable Radio System |
| RRS TC | RRS Technical Committee |
| **S** | |
| S-GW | Serving Gateway |
| SDR | Software Defined Radio |
| SNR | Signal to Noise Ratio |
| SO | Service Oriented |
| SR | Symbol Rate |
| System ACE | System Advanced Configuration Environment |
| **T** | |
| **U** | |
| UE | User Equipment |
| UMTS | Universal Mobile Telecommunications System |
| **V** | |
| **W** | |

| | |
|---|---|
| WLAN | Wireless Local Area Network |
| **X** | |
| XML | eXtensible Markup Language |
| **Y** | |
| **Z** | |

# 8. APPENDIX B – LIST OF PUBLICATIONS (MARCH 2010)

**Short CV**

Aggelos Saatsakis was born in Athens, Greece, in 1982. He has received the Diploma and Master Degree in Digital Systems, from the University of Piraeus. He has been involved in "Phase II of End-to-End Reconfigurability" (E2RII) and "End-to-End Efficiency" (E3) projects which were partially funded by the European Commission under 6th and 7th Framework Programmes (FP6 and FP7), respectively. Furthermore, he participated in "Integrated Multimodal Platform for Ubiquitous Multimedia Service Execution" (IMPULSE) project which was partially funded by the Cooperation for a sustained European Leadership in Telecommunications (CELTIC).

He worked in several companies in IT and Telecom industry until 2006 as well as a research engineer at the University of Piraeus Research Center (UPRC) until 2010, in the area of networked information systems, broadband networks, network and radio resources management and Beyond 3rd Generation (B3G) reconfigurable-radio systems optimization.

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