ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ **UNIVERSITY OF PIRAEUS**

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ΠΕΙΡΑΙΑΣ, 2011

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ UNIVERSITY OF PIRAEUS

PHD THESSIS

MANAGEMENT ARCHITECTURE FOR HETEROGENEOUS HIGH-SPEED FOURTH GENERATION WIRELESS COMMUNICATIONS ENVIRONMENTS

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DIPL. IN ELECTRICAL AND COMPUTER ENGINEERING

PIRAEUS, 2011

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Αρίστη Γαλάνη, 2011
Με επιφύλαξη παντός δικαιώματος

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΑ

Στους γονείς μου, Παναγιώτη και Ξανθούλα,
με αγάπη

Dedicated to my parents, Panagiotis and Xanthoula,
with love

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΑ

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΑ

Abstract

The heterogeneous high-speed 4th generation wireless communications environments will comprise reconfigurable wireless infrastructures, for accommodation of the augmented demands of users with multimode and/or multihoming terminals, in terms of economically service accessibility and quality. In this context, advanced network management techniques, especially in spectrum and radio resource management, will be key factor for accomplishment of the purposes of both users and network operators, namely the satisfaction of user's needs and the increment of profit, respectively. Framed within the above, this thesis presents a Management Architecture for optimized spectrum and radio resource management.

First, the Functional Architecture is introduced analytically. Then, the information flow between the functions that comprise the central management entity of the architecture, as well as the information flow between the central management entity and the external entities, are presented. In the sequel, based on the presented information flow, the messages, in terms of elementary procedures, which are exchanged between the central management entity and the managed entities, are determined (their included basic parameters and their structure), and their anticipated size is estimated. Thereafter, the assessment of the management architecture is presented, regarding the evaluation of the performance of the architecture and the estimation of the management burden that is induced by the incorporation of the

described management functionality into the network. The assessment was effectuated based on experimentation and simulation, and the assessment criteria, regarding the performance of the management architecture and the management burden, are specific metrics of network operation. Finally, the basic requirements for realization of the interfaces between the central management entity of the architecture and the external entities are presented, as well as, candidate solutions. The thesis is concluded by presenting the ongoing challenges and the future research activities.

Keywords: 4th generation networks, cognitive mobile terminals, reconfiguration, radio resource management, management architecture, policies, interfaces' implementation

Περίληψη

Το τοπίο των ασύρματων επικοινωνιών 4ης γενιάς θα συνίσταται από νοήμονα (cognitive) ετερογενή ασύρματα δίκτυα υψηλών ταχυτήτων και νοήμονα τερματικά, τα οποία θα επιτρέπουν την εναλλακτική σύνδεση μέσω διαφορετικών ασύρματων τεχνολογιών πρόσβασης (multimode terminals) ή/και την ταυτόχρονη σύνδεση σε διαφορετικά ασύρματα δίκτυα (multihoming terminals), όπως προκύπτει από τα αποτελέσματα της ανεξάρτητης και οργανωμένης έρευνας της διεθνούς επιστημονικής κοινότητας. Τα ασύρματα δίκτυα θα λειτουργούν σε διάφορες τεχνολογίες που θα συνιστούν το πλέγμα των τεχνολογιών των ασύρματων επικοινωνιών 4ης γενιάς (όπως GSM/GPRS, WLANs, UMTS, BWA, τεχνολογίες που βρίσκονται αυτή την στιγμή σε στάδιο ανάπτυξης από διεθνείς ερευνητικές ομάδες και οργανισμούς, όπως LTE από 3GPP, καθώς και αυτές που θα αναπτυχθούν στο μέλλον), και θα έχουν δυνατότητα δυναμικής αναδιάρθρωσης (reconfigurability). Σε αυτό το περιβάλλον, τα τερματικά θα αναζητούν σύνδεση με τα κατάλληλα δίκτυα, ώστε να ικανοποιήσουν τις απαιτήσεις των επιθυμητών υπηρεσιών και εφαρμογών με τον καλύτερο δυνατό τεχνοοικονομικό τρόπο. Ταυτόχρονα, οι πάροχοι δικτύων (network operators) θα αναζητούν την κατάλληλη διάρθρωση των δικτύων τους (σε επίπεδο ασύρματης τεχνολογίας πρόσβασης, συχνότητας λειτουργίας και άλλων λειτουργικών παραμέτρων), ώστε να αντιμετωπίσουν το περιορισμένο διαθέσιμο φάσμα συχνοτήτων και το ασταθές φορτίο κίνησης. Η επίτευξη των παραπάνω σκοπών των δικτύων και των τερματικών, απαιτεί την ανάπτυξη κατάλληλης λειτουργικότητας των περιβαλλόντων ασύρματων επικοινωνιών υψηλών ταχυτήτων 4ης γενιάς, η οποία επιτυγχάνεται με την υιοθέτηση καινοτόμων, ευέλικτων και αξιόπιστων αρχιτεκτονικών για την διαχείριση των δικτύων. Οι αρχιτεκτονικές αυτές για να επιτελέσουν τον στόχο τους, πρέπει να περιλαμβάνουν λειτουργίες που να εξασφαλίζουν την συνεχή παροχή υπηρεσιών (ubiquitous service provision) και την ανεμπόδιστη κινητικότητα (seamless mobility), την επίγνωση της κατάστασης του περιβάλλοντος (context awareness), την προσωποποιημένη λειτουργία (personalized computing), την απόκτηση γνώσης (knowledge acquisition), την ικανότητα λήψης αποφάσεων (decision making) και την εξαγωγή κανόνων/πολιτικών (policies derivation) για βελτιστοποιημένη λειτουργία των στοιχείων του δικτύου και την βέλτιστη σύνδεση των τερματικών (always-best connected terminals).

Σε αυτό το πλαίσιο, η συγκεκριμένη αρχιτεκτονική ικανοποιεί τις βασικές ανάγκες και απαιτήσεις διαχείρισης των ετερογενών περιβαλλόντων ασύρματων επικοινωνιών υψηλών ταχυτήτων 4^{ης} γενιάς, αντιμετωπίζοντας τις συνεχείς μεταβολές στο ετερογενές ασύρματο περιβάλλον και τα προβλήματα που προκύπτουν από την διακύμανση του φορτίου και την περιορισμένη διαθεσιμότητα των ραδιοπόρων (radio resources), και ταυτόχρονα διευκολύνοντας την αναδιάρθρωση (reconfiguration) των διαχειριζόμενων δικτύων σε επίπεδο δυναμικής μεταβολής ασύρματης τεχνολογίας πρόσβασης και συχνότητας λειτουργίας. Τελικός στόχος της αρχιτεκτονικής είναι η βελτιστοποίηση της χρήσης των διαθέσιμων ραδιοπόρων και του φάσματος συχνοτήτων, με τρόπο που να εξασφαλίζει την υλοποίηση των σκοπών των δικτύων και των τερματικών στα περιβάλλοντα ασύρματων επικοινωνιών 4ης γενιάς. Για την επίτευξη του στόχου αυτού, αξιοποιούνται οι δυνατότητες που προσφέρει η εξέλιξη της τεχνολογίας στα πεδία των νοημόνων ασύρματων συστημάτων (cognitive radio systems) και της ευέλικτης διαχείρισης του φάσματος (flexible spectrum management).

Η αρχιτεκτονική επηρέασε τις αντίστοιχες αρχιτεκτονικές δύο οργανισμών προτυποποίησης. Συγκεκριμένα, η αρχιτεκτονική έχει ληφθεί υπόψη στον καθορισμό της λειτουργικής αρχιτεκτονικής του IEEE 1900.4 συστήματος, το οποίο καθορίζει αρχιτεκτονικές δομικές ομάδες που καθιστούν δυνατή την κατανεμημένη λήψη απόφασης μεταξύ δικτύου και τερματικού για την βελτιστοποιημένη χρήση των ραδιοπόρων στα ετερογενή ασύρματα δίκτυα πρόσβασης (architectural building blocks enabling network-device distributed decision making for optimized radio resource usage in heterogeneous wireless access networks). Η αρχιτεκτονική έχει επίσης επηρεάσει την αντίστοιχη αρχιτεκτονική που έχει αναπτυχθεί στο πλαίσιο του ερευνητικού έργου «End-to-End Efficiency (E3)» της Ευρωπαϊκής Ένωσης (στόχος του οποίου ήταν ο σχεδιασμός, η ανάπτυξη, η τυποποίηση και επίδειξη λύσεων για την βελτιστοποιημένη χρήση των υπαρχόντων και μελλοντικών ασύρματων μέσων πρόσβασης, μέσω της ευέλικτης χρήσης του φάσματος συχνοτήτων και των τερματικών και δικτυακών στοιχείων και της διαλειτουργικότητας υπαρχόντων και μελλοντικών ασύρματων συστημάτων) και στο Working Group 3 (WG3) της Reconfigurable Radio Systems Technical Committee (RRS TC), που δημιουργήθηκε από το European Standards Telecommunication Institute (ETSI) Board, και στα οποία συμμετείχα με τις ερευνητικές ομάδες του Τμήματος Ψηφιακών Συστημάτων του Πανεπιστημίου Πειραιώς.

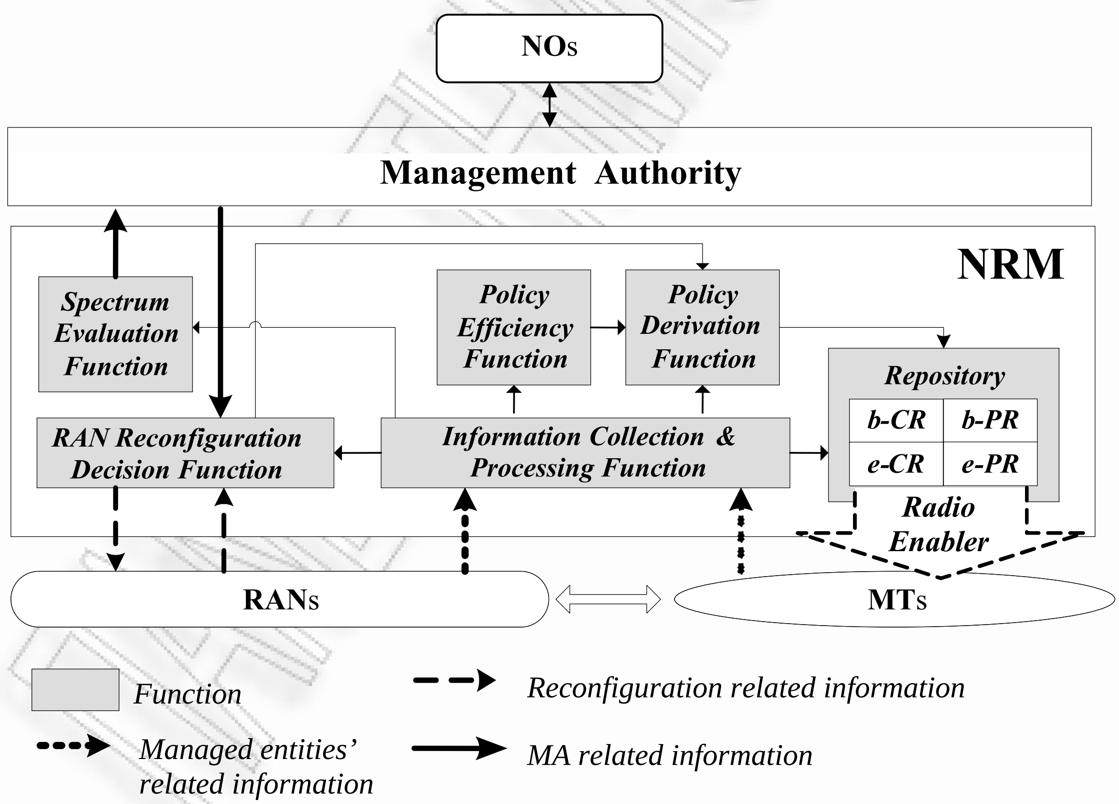
Ο σχεδιασμός της αρχιτεκτονικής διαχείρισης πραγματοποιήθηκε λαμβάνοντας υπόψη διαφορετικά υπάρχοντα και μελλοντικά επιχειρηματικά σενάρια και τα κοινά χαρακτηριστικά που θα διέπουν τα διαβλεπόμενα επιχειρηματικά μοντέλα στο χώρο των τηλεπικοινωνιακών δικτύων 4ης γενιάς, στο επίπεδο που σχετίζεται με τη διαλειτουργικότητα των δικτύων και την απελευθέρωση τμήματος του φάσματος συχνοτήτων. Η αρχιτεκτονική διευκολύνει την συνεργασία μεταξύ παρόχων δικτύων, ιδεατών παρόχων δικτύου (virtual network operators) και παρόχων υπηρεσιών (service providers), στο πλαίσιο κοινοπραξιών ή υπό την επίβλεψη ενός ανεξάρτητου ρυθμιστικού/οργανωτικού φορέα σε τοπικό ή εθνικό επίπεδο.

Για την σχεδίαση της IEEE προσέγγισης αρχιτεκτονικής που απεικονίζεται στο σχήμα 1, χρησιμοποιήθηκε η προσέγγιση της κατανεμημένης, μεταξύ δικτύου και τερματικού, διαδικασίας απόφασης για την τελική επιλογή της ραδιοσύνδεσης κάθε τερματικού, με κριτήριο τις απαιτήσεις των αιτούμενων υπηρεσιών και την υπάρχουσα κατάσταση των περιβαλλόντων δικτύων, όπως αυτή υλοποιείται με την χρήση κατάλληλων κανόνων/πολιτικών (policy-based distributed decision-making between network and terminals). Η προσέγγιση αυτή προσφέρει σημαντικά πλεονεκτήματα σε σχέση με τις άλλες προσεγγίσεις, την κεντροποιημένη/συγκεντρωτική δικτυακή επιλογή (centralised network decision-making) και την αποκεντρωμένη επιλογή που πραγματοποιείται στο τερματικό (decentralised terminal decision-making). Στην δεύτερη, το αυτοδύναμο τερματικό αποφασίζει για την επιλογή του δικτύου, βάση του «προφίλ» (profile) του χρήστη, όπως αυτό καθορίζεται από συγκεκριμένες προτιμήσεις και απαιτήσεις του χρήστη, τα χαρακτηριστικά των επιθυμητών υπηρεσιών και την πληροφορία που αποκτά από το ασύρματο περιβάλλον. Αυτό όμως ισοδυναμεί με σχεδόν συνεχή αναζήτηση της σχετικής πληροφορίας από τα δίκτυα και πιθανόν από τερματικά που βρίσκονται στον περιβάλλοντα χώρο. Αυτή η απαίτηση επιβαρύνει τους υπολογιστικούς και ενεργειακούς πόρους του τερματικού και είναι συχνά αναποτελεσματική, όχι μόνο εξαιτίας της εξαντλητικής διερεύνησης των γειτονικών δικτύων αλλά και λόγω ζητημάτων ασφαλείας. Στην κεντροποιημένη/συγκεντρωτική δικτυακή επιλογή (centralised network decision-making), ένα σύστημα διαχείρισης που έχει όλη την κατάλληλη πληροφορία από τα περιβάλλοντα δίκτυα και τα τερματικά, καθορίζει την «συμπεριφορά» των τελευταίων. Αυτό απαιτεί την λειτουργία ενός κεντρικού συστήματος με τεράστια υπολογιστική δύναμη, το οποίο προκαλεί σημαντικό φορτίο σηματαδοσίας (signalling load) και δεν είναι ευέλικτο σε πλήρη μεταβολή των προτιμήσεων των χρηστών. Στην προσέγγιση που επιλέχθηκε, ένα κεντροποιημένο σύστημα διαχείρισης καθοδηγεί τα τερματικά μέσω κανόνων/πολιτικών, τα οποία παίρνουν την τελική απόφαση βάση της δικής τους στρατηγικής. Η υβριδική αυτή προσέγγιση συνιστά μία αποτελεσματική λύση, αφού συγκεντρώνει τα σημαντικότερα πλεονεκτήματα και ταυτόχρονα αντιμετωπίζει την πλειονότητα των προαναφερόμενων προβλημάτων των δύο άλλων προσεγγίσεων.

Το σύστημα διαχείρισης αναδιάρθρωσης NRM (Network Reconfiguration Manager) διαχειρίζεται το σύνθετο ασύρματο περιβάλλον, που αποτελείται από ετερογενή ασύρματα δίκτυα πρόσβασης RAN (Radio Access Network), και τα κινητά τερματικά MT (Mobile Terminal). Η λειτουργία της οντότητας της αρχιτεκτονικής που ονομάζεται Διαχειριστική Αρχή (Management Authority – MA), καθορίζεται από το επιχειρηματικό σενάριο στο πλαίσιο του οποίου θα λειτουργεί η αρχιτεκτονική. Ο βασικός της ρόλος είναι η υλοποίηση των συμφωνιών/συμβάσεων των συνεργαζόμενων δικτυακών παρόχων NOs (Network Operators) στο τηλεπικοινωνιακό περιβάλλον. Δηλαδή, η μετατροπή των νομικών όρων των συμφωνιών σε κανόνες και περιορισμούς όσον αφορά τις ζώνες συχνοτήτων και τις ασύρματες τεχνολογίες πρόσβασης που μπορεί να χρησιμοποιεί κάθε διαχειριζόμενο δίκτυο.

Η αρχιτεκτονική του NRM περιλαμβάνει έξι λειτουργίες που υλοποιούν συγκεκριμένους στόχους της αρχιτεκτονικής και έχουν διακριτό αντικείμενο. Το αντικείμενο των λειτουργιών είναι:

- Η συλλογή της απαραίτητης πληροφορίας από τα διαχειριζόμενα δίκτυα και τερματικά, η επεξεργασία αυτής και η μετατροπή της σε κατάλληλη μορφή για την τροφοδότηση των υπολοίπων λειτουργιών του συστήματος [Λειτουργία Συλλογής & Επεξεργασίας Πληροφορίας (Information Collection & Processing Function)].



Σχήμα 1: Αρχιτεκτονική διαχείρισης νοημόνων ασύρματων δικτύων 4ης γενιάς IEEE προσέγγισης

- Η εξαγωγή των κατάλληλων κανόνων/πολιτικών (policies) για την υποβοήθηση των τερματικών στην επιλογή της βέλτιστης ραδιοσύνδεσης [Λειτουργία Εξαγωγής Πολιτικών (Policy Derivation Function)].

- Η αξιολόγηση της αποτελεσματικότητας των κανόνων/πολιτικών [Λειτουργία Αξιολόγησης Αποτελεσματικότητας Πολιτικών (Policy Efficiency Function)].

- Η αξιολόγηση της κατανομής των διαθέσιμων συχνοτήτων σε ασύρματες τεχνολογίες πρόσβασης [Λειτουργία Αξιολόγησης Διάθεσης Συχνοτήτων (Spectrum Evaluation Function)].

- Η επιλογή της βέλτιστης λύσης για την διάρθρωση των διαχειριζόμενων δικτύων [Μηχανισμός Επιλογής Αναδιάρθρωσης Δικτύου (RAN Reconfiguration Decision Function)].

- Η συγκέντρωση, αποθήκευση και αποστολή στα τερματικά, πληροφοριών για τις δυνατότητες των περιβαλλόντων ασύρματων δικτύων καθώς και των κανόνων/πολιτικών [Αποθήκη (Repository)].

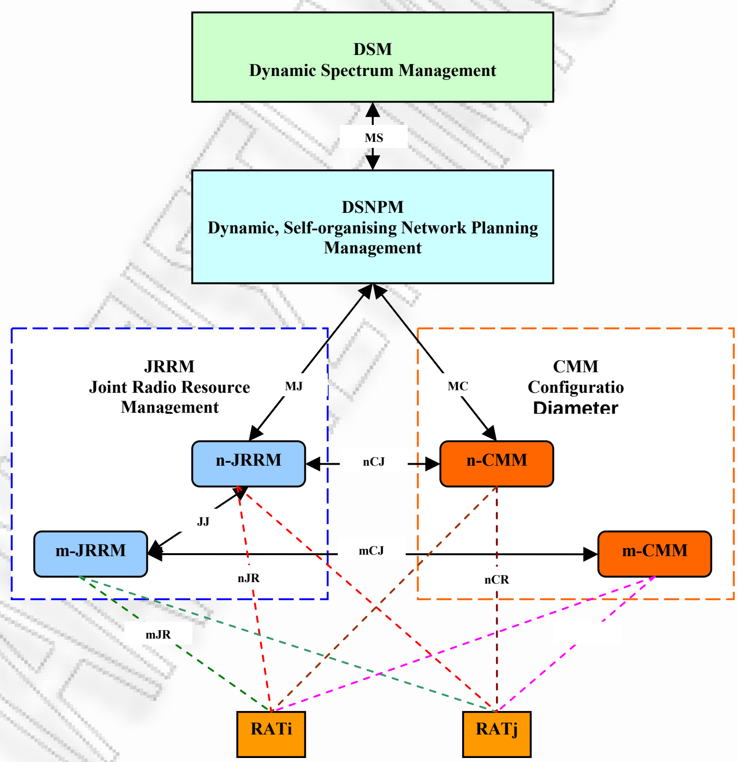
Η αρχιτεκτονική χρησιμοποιεί την βέλτιστη πρόταση, από τις υπάρχουσες τεχνολογικές λύσεις, για την αποστολή της σχετικής πληροφορίας για τις δυνατότητες των περιβαλλόντων δικτύων και των κανόνων/πολιτικών στα τερματικά [Radio Enabler (CPC- Cognitive Pilot Channel)].

Η αρχιτεκτονική E3/ETSI προσέγγισης, η οποία συνιστά μία ελαφρά διαφοροποιημένη προσέγγιση της προηγούμενης αρχιτεκτονικής, απεικονίζεται στο σχήμα 2. Η αρχιτεκτονική αυτή περιλαμβάνει τέσσερις λειτουργικές ομάδες (functional blocks) που ικανοποιούν συγκεκριμένες ανάγκες των διαχειριζόμενων δικτύων και τερματικών και στόχους της αρχιτεκτονικής, και ανάλογα με το αντικείμενό τους υλοποιούνται σε δικτυακά στοιχεία (σε όλα τα επίπεδα της δομής του δικτύου ανεξάρτητα από την ενδογενή αρχιτεκτονική του δικτύου, όπως αυτή καθορίζεται από την ασύρματη τεχνολογία πρόσβασης) ή/και στους τερματικούς σταθμούς. Το αντικείμενό τους είναι συνοπτικά:

- Η διαχείριση του διαθέσιμου φάσματος συχνοτήτων σε μεγάλη και μεσαία κλίμακα χρόνου [Δυναμική Διαχείριση Φάσματος (Dynamic Spectrum Management - DSM)].

- Η διαχείριση των δικτυακών στοιχείων (όσον αφορά τον καθορισμό της ασύρματης τεχνολογίας, των λειτουργικών τους συχνοτήτων και άλλων σχετικών λειτουργικών τους παραμέτρων) και η καθοδήγηση των τερματικών σταθμών στην επιλογή των κατάλληλων ραδιοπόρων για την ικανοποίηση των απαιτήσεων τους [Δυναμικός, Αυτο-Οργανωτικός Σχεδιασμός και Διαχείριση (Dynamic, Self-organising Planning and Management - DSNPM)].

- Η διαχείριση των ραδιοπόρων σε μικρή κλίμακα χρόνου [Συντονισμένη Διαχείριση Ραδιοπόρων (Joint Radio Resources Management – JRRM)].



Σχήμα 2: Αρχιτεκτονική διαχείρισης νοημόνων ασύρματων δικτύων 4^{ης} γενιάς E3-ETSI προσέγγισης

- Η υλοποίηση των αποφάσεων των λειτουργικών ομάδων DSNPM και JRRM σε δικτυακά στοιχεία και τερματικά [Μονάδα Ελέγχου Διάρθρωσης (Configuration Control Module - CCM)].

Η λειτουργία των DSM και DSNPM απαιτεί κεντρική επεξεργασία της πληροφορίας που αποστέλλεται από τις κατώτερες λειτουργικές ομάδες της αρχιτεκτονικής (DSNPM για την DSM και JRRM για την DSNPM, αντίστοιχα). Το γεγονός αυτό απαιτεί κεντροποιημένη/συγκεντρωτική λειτουργία αυτών σε ανώτερα δικτυακά στοιχεία. Αντίθετα, η λειτουργία των JRRM και CCM έχει ως αποτέλεσμα την υλοποίησή τους σε δικτυακά στοιχεία και σε τερματικά. Συγκεκριμένα για την CCM, η κατανεμημένη λειτουργία απαιτείται ώστε να εξασφαλιστεί η υλοποίηση των αποφάσεων των λειτουργικών ομάδων JRRM και DSNPM σε δικτυακά στοιχεία και τερματικά. Ταυτόχρονα, η συνολική λειτουργία της αρχιτεκτονικής απαιτεί την συλλογή ποικίλης πληροφορίας, εργασία η οποία υλοποιείται από την συμπληρωματική λειτουργία της JRRM στην πλευρά του δικτύου και του τερματικού. Σε αυτό το πλαίσιο, οι λειτουργίες των JRRM και CCM σε δικτυακά στοιχεία καλούνται n-JRRM και n-CCM αντίστοιχα, και οι ανάλογες λειτουργίες στα τερματικά καλούνται m-JRRM και m-CCM.

Η E3/ETSI προσέγγισης αρχιτεκτονική περιλαμβάνει βαθύτερο επίπεδο ανάλυσης στον καθορισμό της διάρθρωσης του δικτύου συγκριτικά με την IEEE προσέγγισης αρχιτεκτονική, καθώς επιτρέπει τον καθορισμό των λειτουργικών παραμέτρων των δικτυακών στοιχείων σε επίπεδο δικτύου πρόσβασης. Πραγματοποιεί ουσιαστικά, σε ένα δεύτερο επίπεδο ανάλυσης την λειτουργία της RAN Reconfiguration Decision Function της IEEE προσέγγισης αρχιτεκτονικής. Επιπρόσθετα, η IEEE προσέγγισης αρχιτεκτονική έχει ως καθοριστικό στοιχείο ανάπτυξης την τελική επιλογή της ραδιοσύνδεσης από το τερματικό βάση της στρατηγικής του, στο πλαίσιο πάντα που καθορίζεται από το σύστημα διαχείρισης, παρέχοντας σημαντικό βαθμό αυτονομίας στα τερματικά. Η E3/ETSI προσέγγισης αρχιτεκτονική επιτρέπει και αυτή την τελική επιλογή της ραδιοσύνδεσης από τους τερματικούς σταθμούς στο πλαίσιο που καθορίζεται από την λειτουργία της αρχιτεκτονικής, αλλά η δυνατότητα αυτή έχει δευτερεύοντα ρόλο στην στρατηγική του σχεδιασμού της αρχιτεκτονικής. Επιπλέον, η E3/ETSI προσέγγισης αρχιτεκτονική πρωταρχικά εστιάζει στη λειτουργία της αρχιτεκτονικής στο δίκτυο ενός παρόχου που λειτουργεί διαφορετικά δίκτυα πρόσβασης, και δευτερευόντως, στη συνεργασία δικτύων που ανήκουν σε διαφορετικούς παρόχους. Αυτό αναδεικνύεται και από το γεγονός ότι η αρχιτεκτονική προχωρά στον καθορισμό λειτουργικών παραμέτρων, πλέον της λειτουργικής ασύρματης τεχνολογίας πρόσβασης και της αντίστοιχης συχνότητας, των δικτυακών στοιχείων στο επίπεδο του ασύρματου δικτύου πρόσβασης, γεγονός το οποίο απαιτεί σημαντικό βαθμό διαφάνειας στο λειτουργικό επίπεδο του δικτύου. Αυτός ο βαθμός διαφάνειας δεν μπορεί να υπάρχει στην περίπτωση διαχειριζόμενων δικτύων διαφορετικών παρόχων για λόγους ασφάλειας καθώς και λόγους ανταγωνισμού. Στην περίπτωση της λειτουργίας της αρχιτεκτονικής στο πλαίσιο της συνεργασίας μεταξύ παρόχων με δίκτυα αντίστοιχης αρχιτεκτονικής, η πληροφορία που ανταλάσσεται μεταξύ των αντίστοιχων λειτουργικών ομάδων, καθορίζεται μεταξύ των παρόχων και δεν χρειάζεται τον προαναφερόμενο βαθμό διαφάνειας.

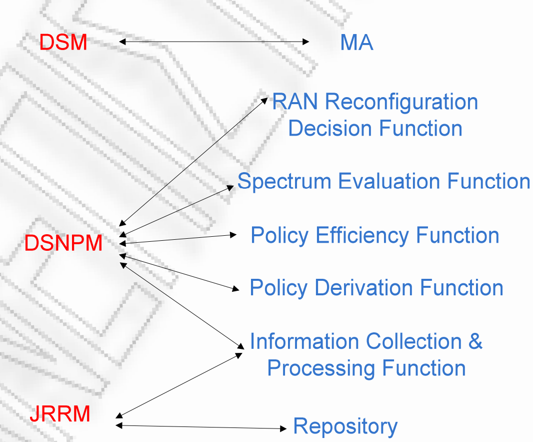
Η αντιστοιχία των λειτουργικών δομικών στοιχείων των αρχιτεκτονικών αποτυπώνεται στο σχήμα 3, και αποδεικνύει την δυνατότητα επίτευξης της απαραίτητης συνεργασίας και διαλειτουργικότητά τους.

Επιπλέον, επισημαίνεται ότι είναι δυνατή η ταυτόχρονη λειτουργία των δύο αρχιτεκτονικών σε διαφορετικά επίπεδα διαχείρισης (π.χ. η λειτουργία της IEEE προσέγγισης αρχιτεκτονικής για την κεντρική διαχείριση δικτύων στο πλαίσιο κάποιας κοινοπραξίας και η λειτουργία της E3/ETSI προσέγγισης αρχιτεκτονικής στο εσωτερικό κάθε δικτύου για την υλοποίηση της αναδιάρθρωσης των δικτυακών στοιχείων στο πλαίσιο των αποφάσεων του κεντρικού συστήματος διαχείρισης), καθώς και η ενσωμάτωση κάποιων λειτουργιών της E3/ETSI προσέγγισης αρχιτεκτονικής, στην IEEE προσέγγισης αρχιτεκτονική (π.χ. διαχείριση των ραδιοπόρων των δικτυακών στοιχείων στο δίκτυο πρόσβασης μίας περιοχής σε βραχυπρόθεσμη έκταση χρόνου από το n-JRRM). Οι δυνατότητες αυτές καταδεικνύουν την κλιμάκωση, την επεκτασιμότητα και την ευελιξία, τα οποία είναι απαραίτητα χαρακτηριστικά των αρχιτεκτονικών διαχείρισης για ετερογενή περιβάλλοντα ασύρματων επικοινωνιών υψηλών ταχυτήτων 4ης γενιάς.

Η IEEE προσέγγισης αρχιτεκτονική υιοθετήθηκε για την εξέλιξη των επόμενων φάσεων της έρευνάς μου (και στην συνέχεια η IEEE προσέγγισης αρχιτεκτονική θα καλείται αρχιτεκτονική). Είναι προφανές, βάση και της παραπάνω συσχέτισης/αντιστοίχισης των λειτουργιών των δύο αρχιτεκτονικών, ότι η έρευνα θα κατέληγε σε αντίστοιχα αποτελέσματα, αν είχε υιοθετηθεί η E3/ETSI προσέγγισης αρχιτεκτονική.

Για κάθε μονάδα/οντότητα της αρχιτεκτονικής καθορίζεται η ακριβής λειτουργία της, καθώς και η απαιτούμενη πληροφορία για την λειτουργία αυτή. Επιπλέον, καθορίζεται η ελάχιστη ανταλλασόμενη πληροφορία, ανάμεσα στις λειτουργικές μονάδες που συνιστούν την αρχιτεκτονική, όσο και μεταξύ εξωτερικών οντοτήτων και των μονάδων της αρχιτεκτονικής, και αποτυπώνεται με μαθηματική μορφή.

Επιπρόσθετα, καθορίζονται οι συνταγμένες της στρατηγικής που πρέπει να ακολουθηθούν για την εξαγωγή των κανόνων/πολιτικών για την καθοδήγηση των νοημόνων τερματικών στην χρήση των κατάλληλων ραδιοπόρων για την βέλτιστη λειτουργία των δικτύων, την εξυπηρέτηση του κοινού καλού σε ιδιαίτερες συνθήκες αλλά και την ικανοποίηση των αναγκών των χρηστών με τον καλύτερο τεχνοοικονομικό τρόπο, βάση και δικών τους κριτηρίων/επιλογών. Στο πλαίσιο αυτό ορίζεται η βασική μορφή και παράμετροι των κανόνων/πολιτικών.



Σχήμα 3: Συσχέτιση/αντιστοίχηση των λειτουργικών στοιχείων των δύο αρχιτεκτονικών

Η πληροφορία που ανταλλάσσεται στις διασυνδέσεις (interfaces) μεταξύ των διαχειριζόμενων οντοτήτων (δηλαδή των διαχειριζόμενων ασύρματων δικτύων πρόσβασης και των κινητών τερματικών) και των λειτουργιών που συνιστούν το κεντρικό σύστημα διαχείρισης της αρχιτεκτονικής, τυποποιείται και αποτυπώνεται σε βασική μορφή μηνυμάτων (messages), τα οποία συνδυαστικά συνιστούν βασικές πρότυπες διαδικασίες, και δομών δεδομένων, με την βοήθεια του προτύπου ASN.1. Το πρότυπο ASN.1 παρέχει την δυνατότητα αναπαράστασης της μεταδιδόμενης πληροφορίας με απλό και σαφή τρόπο, και επιλέχθηκε αφού επιτρέπει τον καθορισμό των μηνυμάτων ανεξάρτητα από την μέθοδο μετάδοσής τους, αποτελώντας επομένως ένα απλό αλλά ταυτόχρονα ισχυρό εργαλείο με σημαντικό βαθμό ευελιξίας. Επιπλέον, το πρότυπο ASN.1 συνοδεύεται από καθορισμένους κανόνες κωδικοποίησης, οι οποίοι επιτρέπουν την ακριβή μετατροπή των μορφοποιημένης, βάση ASN.1 πληροφορίας, σε κωδικοποιημένη ροή πληροφορίας σε οκτάδες (bytes), κατάλληλη για αποστολή μέσω οποιουδήποτε συνδεδεμένου δικτύου. Για την κωδικοποίηση των μηνυμάτων, από τις οικογένειες των τυποποιημένων κανόνων, επιλέχθηκαν οι Βασικοί Κανόνες Κωδικοποίησης (Basic Encoding Rules) για τον υπολογισμό του αναμενόμενου μεγέθους των μηνυμάτων και το σχετικό φορτίο σηματοδοσίας (signalling load) των προδιαγεγραμμένων διαδικασιών, χωρίς την επιβάρυνση που προκύπτει από την επιλογή συγκεκριμένου πρωτοκόλλου μεταφοράς (transport protocol).

Στην συνέχεια, πραγματοποιείται αξιολόγηση της αρχιτεκτονικής μέσω ενδεικτικών πειραματικών σεναρίων, τα οποία αναδεικνύουν την αποτελεσματική λειτουργία της αρχιτεκτονικής. Τα σενάρια πραγματοποιήθηκαν μέσω εξομοίωσης στην πλατφόρμα Java Agent DEvelopment Framework (JADE), που είναι πλατφόρμα ανοικτού ενδιάμεσου λογισμικού (open-source, middleware platform) βασισμένη σε JAVA. Η πραγματοποίηση των σεναρίων παρείχε ενδεικτικές τιμές του επιπλέον φορτίου στη σηματοδοσία (signaling load), καθώς και του χρόνου καθυστέρησης που εισάγεται με την ενσωμάτωση των λειτουργιών της αρχιτεκτονικής σε πραγματικά δίκτυα, αποδεικνύοντας ότι η προτεινόμενη αρχιτεκτονική πραγματοποιεί τους στόχους της χωρίς να επιβαρύνει σημαντικά και να δυσχεραίνει την λειτουργία του δικτύου. Συγκεκριμένα, το διαχειριστικό φορτίο που προστίθεται στο συνολικό φορτίο είναι χαμηλό και ο χρόνος απόκρισης της αρχιτεκτονικής για την βελτιστοποίηση της λειτουργίας των διαχειριζόμενων δικτύων επιτρέπει την διαχείριση αρκετών ασύρματων τοπικών δικτύων και μεγάλου αριθμού τερματικών σε μία περιοχή.

Για την υλοποίηση των διασυνδέσεων για την μεταφορά της σχετικής πληροφορίας με την λειτουργία της αρχιτεκτονικής και την πραγμάτωση των διαδικασιών που καθορίστηκαν, οι οντότητες της αρχιτεκτονικής αποτυπώνονται σε δικτυακές οντότητες που ανήκουν σε διαφορετικούς τομείς του δικτύου, συγκεκριμένα στο δίκτυο κορμού (core network) και στον τομέα παρακολούθησης λειτουργίας και διαχείρισης δικτύου (operation & management segment). Στο πλαίσιο αυτό, καθορίζονται οι απαιτήσεις της επικοινωνίας και προτείνεται η χρήση ή η εξέλιξη υφιστάμενων πρωτοκόλλων καθώς και πρωτοκόλλων που αναπτύσσονται αυτή την περίοδο από διεθνείς οργανισμούς έρευνας και τυποποίησης. Η υιοθέτηση των παραπάνω πρωτοκόλλων επικοινωνίας για την πραγματοποίηση διαδικασιών της αρχιτεκτονικής, εξασφαλίζει τον συγχρονισμό της με την παρούσα τηλεπικοινωνιακή πραγματικότητα και επιτρέπει την εύκολη και γρήγορη ενσωμάτωσή της στα υπάρχοντα και μελλοντικά δίκτυα.

Η διατριβή ολοκληρώνεται με την παρουσίαση των προκλήσεων που τίθενται από την συγκεκριμένη εργασία και τις δυνατότητες για περαιτέρω εξέλιξη του ερευνητικού αντικειμένου.

Λέξεις–κλειδιά: Δίκτυα 4ης γενιάς, νοήμονα τερματικά, δυναμική αναδιάρθρωση, διαχείριση ραδιοπόρων, αρχιτεκτονική διαχείρισης, πολιτικές/κανόνες, υλοποίηση διασυνδέσεων

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

1.1 Research Area

Wireless telecommunications has undergone dramatic developments in the last decades in all the related fields, including spectrum allocation, transmission methods, network architectures, communications protocols, almost all different segments of management, and network and terminal equipment. These developments affect all the related groups, namely network operators, network and equipment manufacturers, service providers, regulators and users, and gradually lead to a new generation of communications, which constitutes an advancement of current third (3^{rd}) generation of wireless communications, with significant new capabilities.

The next generation wireless communications, referred as 4^{th} generation communications, will consist of reconfigurable Radio Access Networks (RANs), operating at diverse Radio Access Technologies (RATs), such as the Long Term Evolution (LTE) system specified by the 3rd Generation Partnership Project (3GPP) [1], WiMAX [2], mobile 2G/2.5G/3G/3G+ networks (for example, GSM, GPRS, EDGE, UMTS, HSPA) [1][3][4][5][6][7][8] , Wireless Local Area Networks (as

IEEE 802.11 a/b/g/n) [9], Wirelss Sensor Networks [10][11][12], Mobile Broadband Wireless Access (MBWA-IEEE 802.20) [13], Digital Video Broadcasting – Handheld (DVB-H) [14], and multimode and/or multi-homing enabled Mobile Terminals (MTs), in the framework of consortia of operators and providers, as emerges from the results of independent and organized research of the international scientific community [15][16][17][18][19][20][21].

In this radio landscape, MTs will strive to find the most suitable RAN and radio resources to use, in order to satisfy their application's needs with the best possible technological and economical way. Coinstantaneously, network operators will struggle to find the appropriate configuration of their RANs, in terms of operating RATs and frequencies, in order to tackle the limited available spectrum as well as the unstable traffic load. The adoption of cognitive capabilities from network systems and terminals, and the exploitation of advantages of Software Defined Radio Technology, Reconfigurability and Flexible Spectrum Management, seem to be an efficacious response to the accrued complexity from the plethora of continuously new adopted RATs and the augmented services' requirements, as well as a powerful enabler for the accomplishment of both users' and operators' goals.

Cognitive capabilities enables systems to "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" [22]. Essential prerequisites of the cognitive operation are the learning capability that enables the acquisition and accumulation of knowledge via proper processes, and the effectual management of the accumulated knowledge. Cognition capabilities constitute the key enabler for the implementation of a series of functionalities, such as self-configuration, self-planning, self-optimization, self-managing, self-healing, called self-x functionalities altogether [23], which lead to optimization of the overall operation of the network element or the MT.

The exploitation of Software Defined Radio Technology by the concept of Reconfigurability in the context of Cognitive Radio, enables the conformation of the elements (network elements and terminals) to the accrued conditions and needs, via proper software executions, which concern almost all the hardware components that effectuate the element's operation, and all layers of protocol stack [24][25][26][22][17].

Specifically, multimode MTs with the ability to choose among different supported RATs have already become a reality, as many devices offer, for example, operation to second and third generation cellular radio access technologies (RATs), as well as IEEE 802 wireless standards. In the near future, reconfigurable multimode and/or multi-homing enabled MTs will be characterized by cognitive capability, learning functionality and knowledge management in their own ecosystem, independently from their operating technology and their particular operation. These capabilities will give them the potentiality to exploit the advantages of the power infrastructures and the evolution of the telecommunications technologies, to predict or confront problematic situations via proactive or reactive processes respectively, to optimize their aggregate performance, and to use the available services, which will comprise advanced applications for all areas of human activities and content provision. Therefore, future reconfigurable cognitive MTs will support installation of new radio software applications and modification of operating Radio Access Technology and frequency, as well as other radio parameters (such as modulation schemes). Moreover, in order to optimize their operation and satisfy their needs, reconfigurable cognitive MTs will take into consideration context information (e.g. the operating RANs in their vinicity, the available frequencies for secondary usage, traffic conditions, electromagnetic environment conditions - for example, Signal to Noise Ratio), their status (e.g. battery level and necessary power consumption, processing load and available relevant resources, mobility characteristics) and the user's profile (personal preferences, user's contracts and corresponding access rights and service debit).

Nowadays, there are more than three (3) billion mobile phone users. The number of intelligent mobile terminals with demands for high speed services, frequently while they are on the move, is growing exponentially. There are estimations that by 2017, there will be seven (7) trillion wireless devices serving seven (7) billion users [15]. Simultaneously, there are forty (40) different radio services defined in the international Radio Regulations, such as various forms of mobile communications, terrestrial broadcasting, fixed satellite services and radio navigation [27] (The Radio Regulations are developed by the Radiocommunication Sector of the International

Telecommunication Union (ITU-R), the major tasks of which include the management of the international radio-frequency spectrum and satellite orbit resources and the development for radiocommunication systems [28]). Futrthermore, measurements have shown that at specific geographical areas, frequency zones are hardly used or not used at all [29][30]. In this context, in order to be confronted the corresponding demands with the available limited available spectrum, new flexible ways of radio frequencies disposal are necessitated. Flexible Spectrum Management (FSM) [31] comprises dynamic procedures and techniques for obtaining and transferring spectrum usage rights and dynamically changing the usage of specific frequencies. So, Flexible Spectrum Management plays determinant role in exploiting the advantages of cognitive, reconfigurable networks and terminals in order to significantly enhance spectrum efficiency.

In this sphere, there is significant research effort for configuration management in cognitive radio systems (as in [32]), for cooperation between different technologies (for example in [33], two functional architectures are proposed for cooperation of different Radio Access Technologies, and for which the interworking between WiMAX and 3GPP networks is examined as specific case), Radio Resource Management (as in [34][35][36][37][38]) and advanced spectrum management [39][40][41][42][43]. Also, there are enough variant research activities regarding network architectures, which focus on different fields, target to different goals and influence different layers of the protocol stack. For example, in the Personal Router project [44] is proposed a cognitive agent, which is named Personal Router, that selects the suitable wireless network to user's preferences and Mahonen et al. in [45], proposed a cognitive resource manager architecture that enables reconfiguration of parameters in all layers of the protocol stack in any entity that participate in resource management, in order to achieve resource usage optimization. Also, Sutton et al. in [46], proposed a reconfigurable platform for optimized resource management, which exploits device level cognition and consists of reconfigurable wireless nodes.

1.2 Dissertation's Contribution

Despite the described evolution and the advancements that have been effectuated by projects, standardization bodies and independent research in universities and institutes, there is lack of a management architecture, which would tackle the difficulties and challenges in technological, regulatory and business domains all together, in heterogeneous high-speed 4th generation wireless communications environments.

The realization of the presented goals of operators and users expectations, such as pervasive computing, ubiquitous service provision and personalized always-best connectivity in a cost-effective way, in the dynamically alterable 4th generation radio environment, necessitates the adoption of innovative, scalable and reliable architectures for their management. These architectures have to include functions for ubiquitous service provision and seamless mobility, context awareness, personalized and pervasive computing, decision making, knowledge acquisition and policies derivation for optimized operation of network elements and always-best connected terminals. In this framework, this thesis presents a management architecture for heterogeneous high-speed 4th generation wireless communications environments, which achieves improved overall operation of managed entities, comprising Radio Access Networks operating in diverse Radio Access Technologies and multimode/multihoming Mobile Terminals, via combined optimized spectrum and radio resources utilization.

1.3 Dissertation's Structure

The thesis is structured in chapters, a slight description of which is outlined in the sequel.

Chapter 2

In this chapter, the management architecture for heterogeneous high-speed 4th generation wireless communications environments is introduced. The management architecture increases the efficiency of the overall managed system, by optimally exploiting the diversity of the heterogeneous radio ecosystem. The key points for the design of the management architecture, as well as the operational framework of the architecture in the business landscape are presented. In the sequel, two slightly differentiated approaches (IEEE approach architecture and E3/ETSI approach architecture) for the functional architecture are presented analytically. Thereafter, the strong correlation of the functional architectures is displayed. The correlation indicates the scalability and flexibility of the functional architectures, and enables their co-operation and interoperability. Finally, IEEE approach architecture is determined as base for the continuance of the research.

Research in this field resulted in the publications:

- A.Galani, K.Tsagkaris, P.Demestichas, "Information Flow for Optimized Management of Spectrum and Radio Resources in Cognitive B3G Wireless Networks", Journal Of Network and Systems Management, Volume 18, Number 2/June, 2010, DOI 10.1007/S10922-009-9150-4125-149

- A.Galani, K.Tsagkaris, P.Demestichas, "A functional architecture for optimized radio resource and spectrum usage in heterogeneous wireless networks", ICT-mobile summit 2008, Stockholm, June 2008

- K.Tsagkaris, M.Akezidou, A.Galani, P.Demestichas, "Evaluation of Signalling Loads in a Cognitive Network Management Architecture", submitted to International Journal Of Network Management

- 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, vol.4, no.1, pp.42-48, March 2009

- A.Kaloxylos, T.Rosowski, K.Tsagkaris, J.Gebert, E.Bogenfeld, P.Magdalinos, A.Galani, K.Nolte, "The E3 architecture for future cognitive mobile networks", IEEE International Symposium on Personal Indoor and Mobile Radio Communications, Tokyo, 2009

- A.Kaloxylos, K.Nolte, K.Tsagkaris, T.Rosowski, M.Stamatelatos, A.Galani, E.Bogenfeld, P.Magdalinos, J.Tiemman, P.Arnold, J.Gebert, D.Von Hugo, N.Alonistioti, P.Demestichas, W.Koenig, "The E3 architecture: Enabling future cellular networks with cognitive and self-x capabilities", International Journal Of Network Management, 2010, DOI: 10.1002/nem.762

- K.Tsagkaris, M.Akezidou, A.Galani, P.Demestichas, "Signaling load evaluations for policy-driven cognitive management architectures", BROADNETS 2010, 7th International ICST Conference on Broadband Communications, Networks, and Systems, Athens, October 2010, (invited paper)

and:

- A.Galani, K.Tsagkaris, P.Demestichas, "Functional architecture for optimized management and interoperability of radio access networks in Future Internet", Poster presentation, Future Internet Assembly (FIA) 2009, Stockholm, Sweden, 23rd-24th November 2009

Chapter 3

The information flow between the functions that comprise the central management entity of the architecture, as well as the information flow between the central management system and the external entities, are presented in this chapter.

Research in this field resulted in the publications:

- A.Galani, K.Tsagkaris, P.Demestichas, "Information Flow for Optimized Management of Spectrum and Radio Resources in Cognitive B3G Wireless Networks", Journal Of Network and Systems Management, Volume 18, Number 2/June, 2010, DOI 10.1007/S10922-009-9150-4125-149t

- A.Galani, K.Tsagkaris, N.Koutsouris, P.Demestichas, "Design and assessment of functional architecture for optimized spectrum and radio resource management in heterogeneous wireless networks", International Journal Of Network Management, 2010, DOI 10.1002/nem.736

and:

- G.Dimitrakopoulos, P.Demestichas, A.Saatsakis, A.Galani, "Exploitation of Location Awareness in Functionality for Cognitive Wireless Infrastructures", Presentation, Workshop on Localization and Context Awareness, September 28, 2009, Brussels, Belgium
- Z. Feng, Q. Zhang, P. Cordier, B. Mouhouche, C. Le Page, E. Buracchini, P. Goria, A. Trogolo, W. Hau Chin, A. Merentitis, J. Pérez-Romero, R. Agustí, O. Sallent, K. Tsagkaris, A. Galani, P. Demestichas, "Support for heterogeneous standards using Cognitive Pilot Channel (CPC)", White Paper του End-to-End Efficiency (E3) project, July 2009

Chapter 4

Each communication between the central management entity and the managed entities (RANs and MTs) is considered as part of a procedure, consisting of definite messages, and the total of the procedures comprise the corresponding interfaces. The description of the messages that are exchanged in these interfaces is of extremely importance, as it constitutes an essential step for the implementation of the architecture. In this framework, this chapter presents the determination of the included basic parameters in the messages, the specification of the structure of these messages in terms of elementary procedures, and the estimation of the anticipated length of the messages.

Research in this field resulted in the publication:

- K.Tsagkaris, M.Akezidou, A.Galani, P.Demestichas, "Evaluation of Signalling Loads in a Cognitive Network Management Architecture", submitted to International Journal Of Network Management
- K.Tsagkaris, M.Akezidou, A.Galani, P.Demestichas, "Signaling load evaluations for policy-driven cognitive management architectures",

BROADNETS 2010, 7th International ICST Conference on Broadband Communications, Networks, and Systems, Athens, October 2010, (invited paper)

Futhermore, the relevant results of the research are included in publication, which is in final stage for submission in corresponding scientific journal.

Chapter 5

The assessment of the management architecture, regarding the evaluation of the performance of the architecture and the estimation of the management burden which is induced by the incorporation of the described management functionality into the network, is presented in this chapter. The assessment was effectuated based on experimentation and simulation and the assessment criteria, regarding the performance of the management architecture and the management burden, were specific metrics of network operation. Specifically, the assessment is based on measurements of management signaling loads and corresponding prerequisite bandwidth, time delays associated with the operation of the proposed architecture, as well as the reaction time of the management system for the resolution of definite problematic network situation. The measurements were performed for two important scenarios, the operation of the management architecture in normal network conditions and in heavy network conditions.

Research in this field resulted in the publications:

- A.Galani, K.Tsagkaris, N.Koutsouris, P.Demestichas, "Design and assessment of functional architecture for optimized spectrum and radio resource management in heterogeneous wireless networks", International Journal Of Network Management, 2010, DOI 10.1002/nem.736

- K.Tsagkaris, N.Koutsouris, A.Galani, P.Demestichas, "Performance assessment of a spectrum and radio resource management architecture for heterogeneous wireless networks", ICT-mobile summit 2010, Florence, June 2010

Chapter 6

The realization of the interfaces that presented in the previous chapter, neccesitates the determination of proper mechanisms and information exchange protocols for transmition of the corresponding information between the involved entities. The protocols may be legacy or new specified, and may operate in different layers of the OSI model. In this franework, this chapter presents the basic requirements for the effectuation of the interfaces, as well as, candidate solutions.

Chapter 7

The thesis is concluded by recapitulating the main introduced aspects. Furthermore, ongoing challenges and future research steps are presented.

Related research is included in the publication:

- A.Galani, K.Tsagkaris, P.Demestichas, "Functional architecture for optimized management and interoperability of radio access networks in Future Internet", Poster presentation, Future Internet Assembly (FIA) 2009, Stockholm, Sweden, 23rd-24th November 2009

Chapter 2

Functional Architecture

2.1 Introduction

A concise but well-documented image of the needs, the requirements and the potential capabilities of heterogeneous high-speed 4th generation wireless communications, as well as the related research effort, was presented in the previous chapter. In this framework, it is obvious that the optimized spectrum and radio resource utilization will be key factor for the efficient operation of heterogeneous 4th generation wireless networks. For this reason, important efforts have been effectuated in the relevant research fields. Significant steps have been done concerning radio resources utilization for satisfaction of user's needs, as in [47] (in which a new architecture capable of supporting Always Best Connected (ABC) service was proposed), resource management for traffic distribution and resolution of mobility-related problems in heterogeneous networks [48], algorithms for spectrum utilization (as for example in [49], where the proposed algorithm enables users to access spectrum dynamically without disturbing licensed primary radios), etc. Although the existent advancements and innovations, the proposals do not comprise solution for combined optimized spectrum and radio resource usage in complex radio environment, which will oblige the requests of regulators, operators, providers and users. This study presents a solution consisting of appropriate management architecture, which increases the efficiency of the overall managed system by optimally exploiting the diversity of the heterogeneous radio ecosystem. Specifically, two approaches for management architecture of heterogeneous high-speed 4th generation wireless communications environments are presented here, with strong correlation, which enables their co-operation and interoperability. The functional architecture of the management architectures and their correlation are defined thoroughly thereafter.

2.2 IEEE Standard 1900.4™-2009 for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks

The IEEE P1900.4 Working Group is a standardisation group under the supervision of IEEE/SCC41 committee (Standards Coordination Committee 41), which works for standardization of concepts relevant to cognitive radio, dynamic spectrum access networks, interference management, coordination of wireless systems, advanced spectrum management, and policy languages for next generation radio systems [50]. The 1900.4 system approved as a standard on January 2009 and published on February of 2009, under the title “Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks” [51].

The IEEE P1900.4 Working Group defined three general use cases: (i) “Dynamic Spectrum Assignment”, (ii) “Dynamic Spectrum Sharing”, and (iii) “Distributed Radio Resource Usage Optimization”. The “Dynamic Spectrum Assignment” concerns processes and mechanisms, which dynamically assign frequency bands to RANs of the Composite Wireless Network, in compliance with the official regulations, in order to optimize spectrum usage. The term “Composite Wireless Network” is defined in IEEE Std 1900.4 as “a network composed of several radio access networks with corresponding base stations, a packet-based core network connecting these radio access networks, and IEEE 1900.4 entities deployed in this network", with the note that "This definition does not exclude the case where some broadcasting system or future technology system is part of the composite wireless network" [52]. Moreover, the term "base station" is "used to refer to any radio node on the network side from radio interface, independently of its commonly used name in a particular standard. Examples of common name are Base Station in IEEE Std 802.16, Base Transceiver System in cdma2000, Node B in UMTS, Access Point in IEEE Std 802.11, broadcasting transmitter, etc." [52]. The "Dynamic Spectrum Sharing" concerns processes and mechanisms for the type of spectrum access that occurs when different RANs and terminals dynamically access the same frequency bands, enabling opportunistic spectrum usage. Finally, the "Distributed Radio Resource Usage Optimization" refers to processes and mechanisms, by which the optimization of radio resource usage is performed by Composite Wireless Network and terminals in a distributed manner. Based on these use cases, as a result of different contributions and comprehensive discussions, system and functional requirements, system and functional architecture, information model and generic procedures were defined.

The system architecture, as defined in the published IEEE 1900.4 standard [52], is presented in Figure 2-1. The main entities of the IEEE 1900.4 system are the Network Reconfiguration Manager (NRM) and the Terminal Reconfiguration Manager (TRM). The role of NRM is to manage both the Composite Wireless Network and terminals. The TRM has the responsibility to manage the terminal according to its own strategy, but at the same time being in compliance with policies provided by NRM. Policy here, refer to radio resource selection policy which is "a policy generated by the Network Reconfiguration Manager which guides the Terminal Reconfiguration Managers in terms of their radio resource usage optimization decisions" [52] . Furthermore, the entity OSM stands for Operator Spectrum Manager and "enables the operator to control the dynamic spectrum assignment decisions of the NRM" [52].

More analytically, NRM collects context information from its managed RANs and sends reconfiguration commands, in terms of operating RAT and frequency, to them. Context information refers "to any information that together with policies is needed for decision making on radio resource usage optimization in this standard. RAN context information is distinguished from terminal context information" [52]. In general, RAN context may contain information for the radio and transport capabilities of the RAN, RAN measurements etc. Radio resource selection policies as well as context information for the managed RANs, are sent to the TRM from the NRM, whereas terminal related context information is sent to the opposite direction. Similarly with RAN context information, terminal context information may include information such as terminal capabilities, terminal measurements, user preferences, required QoS levels, etc.

The rest four entities that complement the 1900.4 system in Figure 2-1, perform the abovementioned tasks of measurement collection (RMC, TMC) and reconfiguration execution (RRC, TRC). Specifically, RAN Reconfiguration Controller (RRC) and RAN Measurement Controller (RMC) perform these operations in network side, and Terminal Reconfiguration Controller (RRC) and Terminal Measurement Controller (TMC) in terminal side.

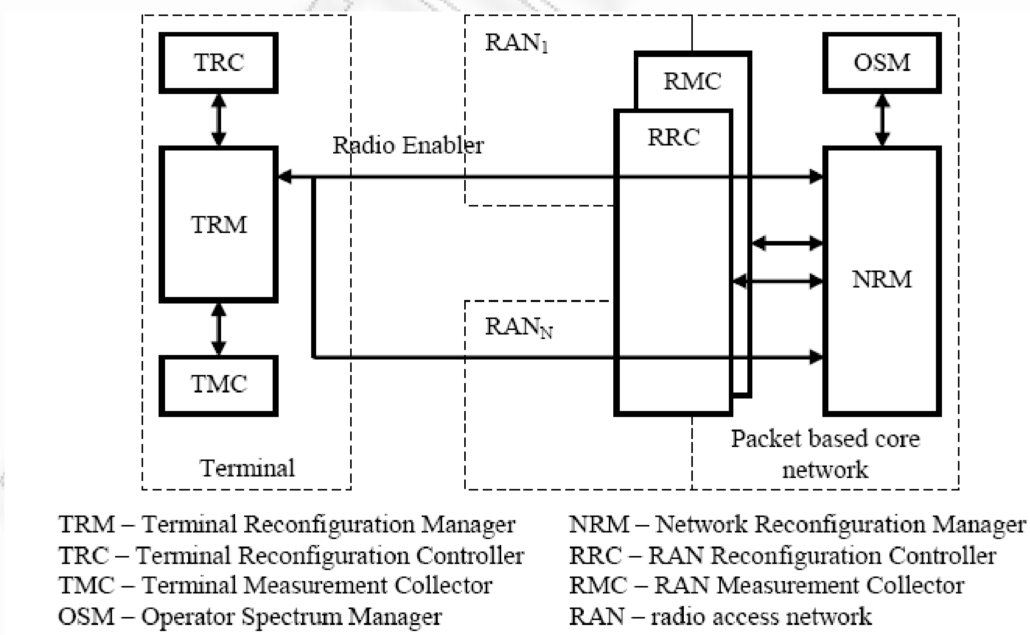

Figure 2-1: IEEE Std 1900.4-2009 System architecture

The logical communication channel between NRM and TRM entities is called Radio Enabler and "may be mapped onto one or several radio access networks used for data transmission (in-band channel) and/or onto one or several dedicated radio access networks (out-of-band channel)"[52].

In the above area, my research interest is placed on the NRM entity and its external interfaces, as it is depicted in Figure 2-2. The functional architecture that will be presented in the sequel, comprises part of a contribution [53] that has been taken into account in part, for the definition of the functional architecture of the 1900.4 system. As my research focuses on NRM, in the following sections I refer to MT for considering the entity that comprises the whole terminal management-related functionality, which is implemented from TRM, TRC and TMC in the framework of 1900.4 system. Similarly, the term RAN thereafter, embraces the operations of reconfiguration control and information collection that are effectuated by RRC and RMC entities respectively, in 1900.4 system. Specifically, my approach for the system architecture in high level is depicted in Figure 2-3, where the entity OSM has been replaced by the entity named Management Authority (MA), which has more extensive scope compared with OSM, and its role will be clearly revealed thereafter.

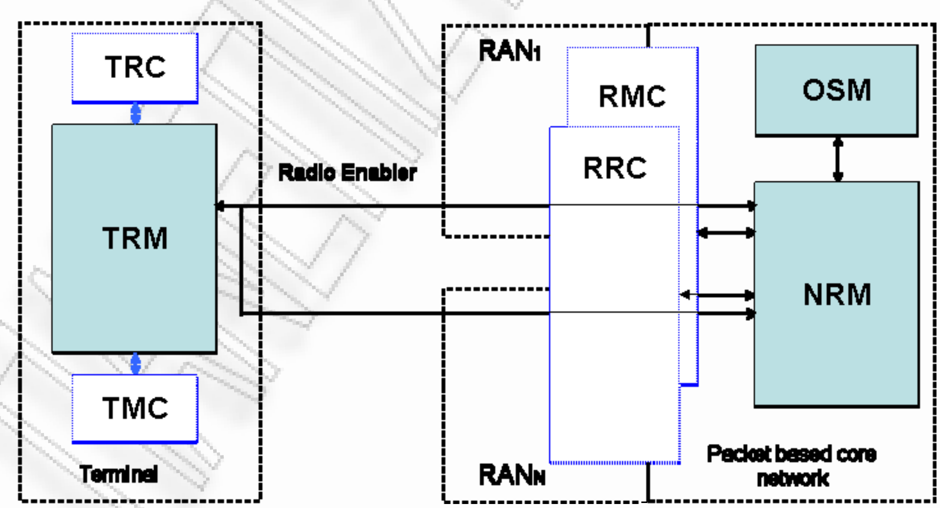

Figure 2-2: My research interest in area of IEEE Std 1900.4-2009

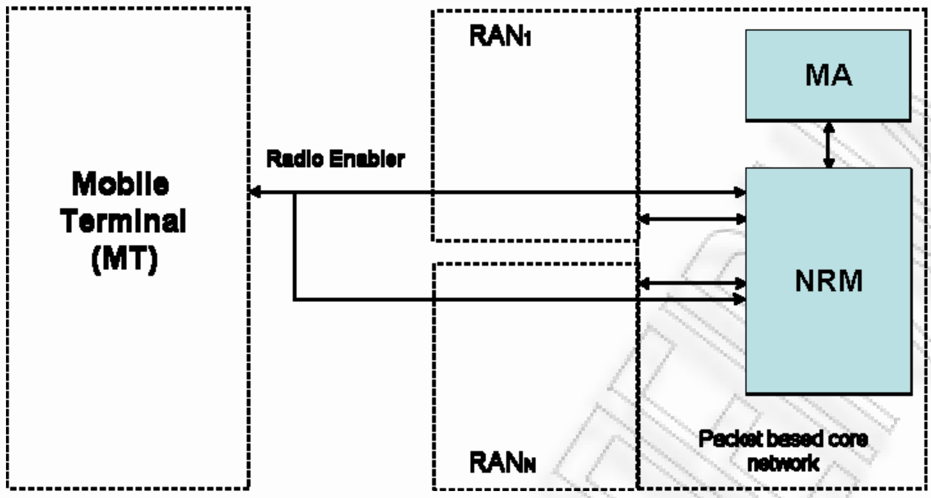

Figure 2-3: High level system architecture

The SCC41 committee decided to recommend to the IEEE Standards Board approving two new Project Authorization Requests (PAR) under the umbrella of the P1900.4 Working Group: The P1900.4.1 project, entitled "Standard for interfaces and protocols enabling distributed decision making for optimized radio resource usage in heterogeneous wireless networks", and the P1900.4a project, which is entitled "IEEE Standard for Architectural building blocks enabling network-device distributed decision making for optimized radio resource usage in heterogeneous wireless access networks – Amendment: Architecture and interfaces for dynamic spectrum access networks in white space frequency bands". From April 2009, 1900.4 Working Group works on these projects. The scope of the first one is to provide detailed description of the interfaces and service access points defined in the IEEE 1900.4 standard, enabling distributed decision making in heterogeneous wireless networks and obtaining context information for this decision making. As it is stated its purpose is to "facilitate innovative, cost-effective, and multi-vendor production of network side and terminal side components of IEEE 1900.4 system and accelerate commercialization of this system to improve capacity and quality of service in heterogeneous wireless networks"[54]. The thorough description of the information that needs to be conveyed on the external interfaces of the designed management architecture, which is presented in Chapter 3 along with the information flow among the functions that comprise the NRM entity, can be seen as the preliminary, but at the same time very important, step, prior to the definition of the description of interfaces defined in the IEEE 1900.4 standard, that will be studied in the framework of P1900.4.1 project. The scope of the P1900.4a project is to amend the IEEE 1900.4 standard to enable mobile wireless access service in white space frequency bands, without any limitation on used radio interface (physical and media access control layers, carrier frequency, etc), by defining additional components of the IEEE 1900.4. Specifically, as it it is stated its purpose is to facilitate cost-effective and multi-vendor production of wireless access system, including cognitive base stations and terminals, capable of operation in white space frequency bands without any limitation on used radio interface, as well as, to accelerate commercialization of this system to improve spectrum usage[55].

2.3 Management Architecture

As it was introduced, the optimized spectrum and radio resource utilization will be key factor for accomplishment of the purposes of both users and operators, namely the satisfaction of user's needs and the augmentation of profit, respectively. In this framework, the role of the designed management architecture is twofold. First, to determine the proper operating RAT and frequencies for each managed RAN (optimized spectrum utilization), and second, to direct MTs to the selection of the appropriate RAN to operate with (optimized radio resource utilization).

The management architecture, regarding the issue of radio resource selection, focuses on the policy-based, distributed decision-making between network and terminals, in the framework of heterogeneous wireless networks and terminals with cognitive capabilities. There are three main approaches in the issue of radio resource selection with yardstick the requirements of the demanded services and the current state of the radio environment: a) the centralised network decision-making, b) the decentralised terminal decision-making and c) the distributed decision-making between network and terminal [56]. In the decentralised terminal decision-making approach, the self-contained terminal decides for the network and resources to use, based on its profile, the characteristics of the desirable services and the information it obtains from the radio environment. That amounts to almost constant pursuit of relevant information from surrounding networks and maybe other neighbouring terminals, which burdens terminal's computational and power resources and is often deficient, due to exhaustive scan of surrounding networks and security constraints. In the centralised network decision-making approach, a management system which has all the appropriate information from the surrounding networks and terminals, determines the "behaviour" of the latter. This calls for a central system with large computational power. Moreover, the effectuation of this approach causes significant signalling load ,which accrues from the collection of all the necessary information from the managed networks and terminals and the transmission of detailed instructions to terminals, and it is not flexible to turnabouts of user's preferences or requests. The aforementioned problems lead to a third, hybrid approach, which is the distributed decision-making between network and terminals. In this approach, a centralised management system directs MTs via policies, under which, MTs take the final decision for the radio resource selection based on their own particular strategies, commonly reflected to specific criteria. Policies are radio resource selection directives, which are used for the guidance of users, and are derived taking into consideration variant types of information, from many possible sources, such as the managed networks, terminals, network operators, regulators. This approach constitutes an effective solution that gathers the most significant merits and simultaneously tackles the majority of the above indicated problems of the two other approaches. For these reasons, the third, hybrid approach was selected for the design of the management architecture.

In this framework, a high level diagram of the management architecture is presented in Figure 2-4, which depicts the kind of information that is exchanged between the management system entity, Network Reconfiguration Manager (NRM), and the external managed entities, namely MTs and RANs. As it is shown in the figure, NRM receives context information from RANs and MTs. The context information includes information that results from operative characteristics of the entities, measurements and requests. This information enables NRM to estimate the existent conditions of the radio environment. In the opposite direction, NRM sends instructions to RANs regarding their operating RAT and corresponding frequency (Reconfiguration Decision), and policies and substantial context information that concerns the surrounding networks to MTs, with goal to assist them to achieve their purposes. MTs, taking into consideration the obtained policies and context information, decide their final behaviour based also on their own strategy, determined for example, by the requirements and constraints of their applications, user's preferences and their hardware and software characteristics.

The functionality of the architecture derives from the requirements and expectations from the management architectures in 4th generation wireless communications environments, as they were presented in chapter 1, and the transformation of legal network and systems management, by the advancements in the fields of cooperation (in all levels of communications), reconfigurability, cognition, and autonomics.

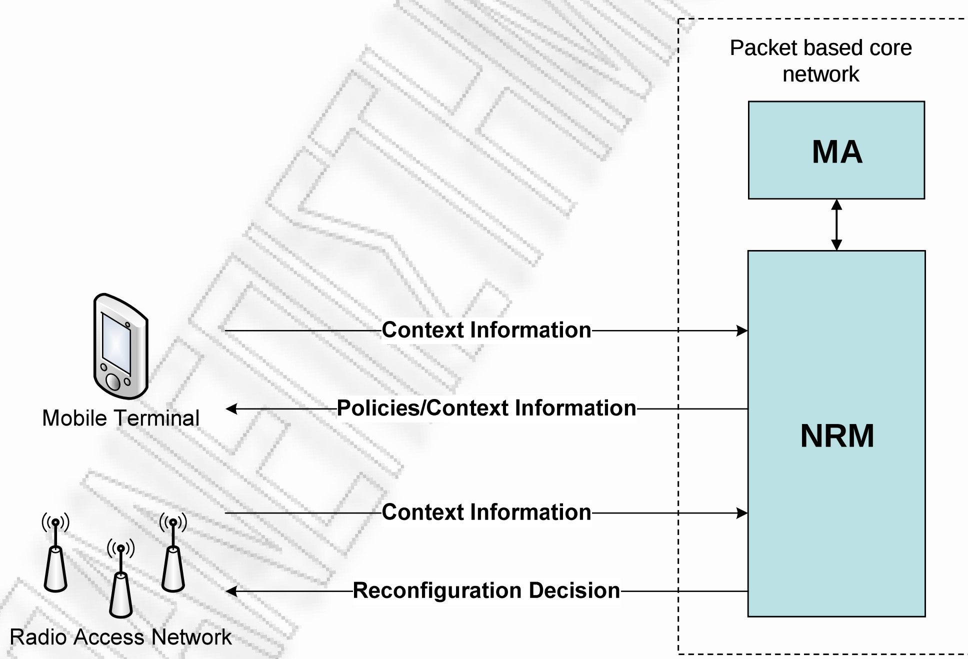

Figure 2-4: High level system architecture with exchanged information between NMR and managed entities

The design of the management architecture was effected taking into consideration the different existent and developable business scenarios, the common features of the envisaged business models in the sphere of 4th generation telecommunications networks, concerning the cooperation and interoperability of the networks, and also, the liberation part of spectrum. The architecture can actively operate in almost all different scenarios, the most significant of which are:

1. The management architecture operates under control of a network operator that is licensed for using definite zones of frequency bands under specific usage rights, in the framework of which operates different Radio Access Networks.

2. The management architecture operates in the frame of a consortium, the members of which may be network operators and virtual network operators, namely network operators that do not have their own licensed frequencies or infrastructure, and offer services to their customers based on resources of other network operators with whom they maintain contractual agreements. Moreover, each member of the consortium may cooperate with Service Providers with corresponding contractual agreements, such as Content Providers, and announce to MTs the characteristics of their offered services through its network. In this scenario, the management architecture operates under strict guide-lines posed by the agreement among the members of the consortium, and the licensed frequencies of the members of the consortium (the sum of all the frequency bands or sections of it) function as one integrated spectrum pool for collective usage [57].

3. The management architecture operates under control of an independent organization in regional or national level, based on specific agreed rules with network operators and regulators.

In the second and third scenario, the existence of an additional external entity is necessitated for the efficacious operation of the management architecture. This entity is the Management Authority (MA), which has already been mentioned, and its role, is the effectuation of the contracts of the co-operated operators in the radio environment. Namely, the translation of the legal conditions of the agreements among the cooperating network operators to rules and constraints, regarding the frequencies and RATs that are allowed to be used by each managed RAN, in compliance with the imposed regulations for Spectrum Usage Rights [58] provided by the relevant official organizations.

The functional decomposition of the management architecture, which is depicted in Figure 2-5, reveals that that the NRM consists of the following functions: Information Collection and Processing Function, Policy Efficiency Function, Policy Derivation Function, RAN Reconfiguration Decision Function, Spectrum Evaluation Function and Repository [59]. The operation and cooperation of these six functions determine the final distribution of RATs and frequencies to RANs, and also provide directives for guidance of terminals in the complex radio environment.

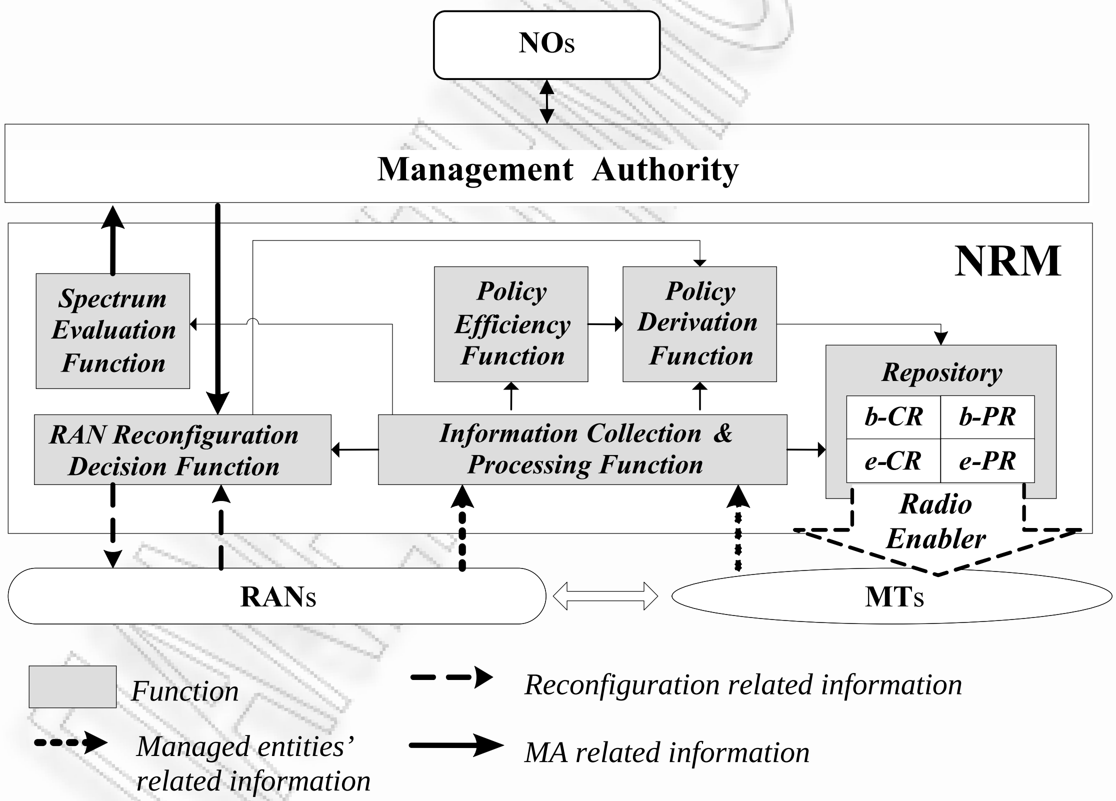

Figure 2-5: Proposed Functional Decomposition for NRM

RANs and MTs send context and configuration information to NRM, which is presented analytically in Chapter 3. Concisely, the information sent from RANs comprises the current configuration of the RANs, the supported services, information about alternative supported RATs and measurements from their operation. The information sent from MTs includes their current configuration, requested services, demanded and measured QoS levels, as well as other measurements. The information is collected by Information Collection and Processing Function, which processes it and extracts the essential information for the operation of the other functions. RAN Reconfiguration Decision Function, having as input data the information that are sent from MA and Information Collection and Processing Function, decides on the final distribution of operating frequencies and RATs to the managed RANs. Spectrum Evaluation Function evaluates current spectrum usage and sends its estimation to MA. Policy Efficiency Function assesses policies' efficiency and forwards its estimations to Policy Derivation Function. Policy Derivation Function derives policies to assist MTs to optimize their operation, based on information from Information Collection and Processing Function and evaluation results for the used policies from Policy Efficiency Function, and sends them to Repository. Repository is the storage unit, which includes all the necessary information for the guidance of MTs to the selection of the optimal RAN, according to their demands.

The propagation of policies and context information of Repository to MTs, necessitates a flexible and effective solution, which points to an appropriate logical channel, called radio enabler. The concept of Cognitive Pilot Channel (CPC) is adopted herewith, as suitable for playing the role of the radio enabler. The CPC has been initiated and defined in the framework of E2RII IST programme [60][61], and it has been through extensive elaboration in the framework of the FP7-EU programme "End-to-End Efficiency (E3)"[62][63]. The characteristics and the possible different realizations of a channel in the framework of the concept of CPC, has also been subject of research in standardisation bodies, such as the Reconfigurable Radio Systems Group of the European Telecommunications Standards Institute (ETSI) [64][65], the Access Network Discovery and Selection Function (ANDSF) specification in 3GPP [66] and the IEEE 802.22 [67], as well as independent research [68] [69].

The information of Repository is differentiated in relevance to geographical areas, which correspond to meshes as prescribed in [70], and time periods. The size and the geographical coordinates of each mesh are determined from Information Collection and Processing Function, based on certain, identified radio commonalities, as it will be presented in the next subsection.

The operation of NRM's functions is described in more detail in the sequel.

2.3.1 Information Collection & Processing Function

The information that is sent from RANs and MTs to NRM, is collected by Information Collection & Processing Function, which processes it, extracts the suitable information in proper format for the operation of the associated functions and then forwards it to them. The role of Information Collection & Processing Function [59] is absolutely elaborative and the function doesn't have the attribute of storing the collective and extracted information. This information may only be stored within other NRM's functions if it is required for the accomplishment of their operation.

Moreover, Information Collection & Processing Function is the competent function for the derivation of meshes [70]. In order to clarify the concept of "mesh", at this point, the term of Access Point *AP* is defined, which will be used thereafter. As Access Point *AP* is stated the network element at the lowest level, independently from its operating RAT, with which the MT has active link for accommodation of its traffic (e.g. Base Station for GPRS, Node-B for UMTS, evolved Node-B for LTE, Access Point for IEEE 802.11). For example, for a Base Station with one Transceiver, the Access Point coincides with the Base Station, whereas for a Base Station with more than one Transceivers, each Transceiver is considered as one Access Point and the served from the Access Point, sector of the cell of the Base Station, is specified as the transmission area of the Access Point. Moreover, the Coverage Area of each ap, CA_{ap}, is defined as the area in which the Signal-to-Interference–plus-Noise Ratio

(SINR) is above a specific pre-agreed, among all the cooperated network operators, threshold, common for all managed RANs of the same RAT.

In order to be implemented the derivation of meshes, the whole managed area of the management architecture is divided into sectors, the size of which is determined by the landscape and human activity. For example, the size of sectors in countryside is bigger than in urban areas, because in cities, the significant amplitude of the demanded traffic load and the considerable interference and noise level necessitate dense population of *AP*s, whereas in countryside, the rather low load and the buildings' structure afford the operation of less *AP*s for the accommodation of traffic, than in previous case. Thereafter, each sector is divided into sections of equal dimensions, which, however, are variable (namely, the size of the sections of two sectors of equal size may be different). The selection of section's dimensions is effectuated with criterion the simplification of the necessary calculations, thence it depends on the topology of the managed networks, the processing method that is used for the extraction of meshes and the amount of information that can be sent through the radio enabler (it is reminded that the information of Repository, which is propagated via the radio enabler, is differentiated based on meshes and time frames, as it will be presented analytically in the sequel). In each section, meshes are defined as each common area of Coverage Areas of the possible maximum number of existent *AP*s.

In the example that is depicted in Figure 2-6, in $section_j$ (that is represented with the rectangle) there are three *AP*s, AP_1, AP_2 and AP_3 (of different RATs and/or Network Operators) with Coverage Areas CA_{AP_1}, CA_{AP_2} and CA_{AP_3} respectively (the outline of which are represented with different line style). The meshes that can be identified, result from the probable nonempty sets of all the possible combinations between the Coverage Areas. Namely, in this example the possible combinations can be:

- $mesh_1 = \left\{(x,y) \in \left(CA_{AP_1} \cap CA_{AP_2} \cap CA_{AP_3}\right)\right\}$

- $mesh_2 = \left\{(x,y) \in \left[\left(CA_{AP_1} \cap CA_{AP_2}\right) / \left(CA_{AP_1} \cap CA_{AP_2} \cap CA_{AP_3}\right)\right]\right\}$

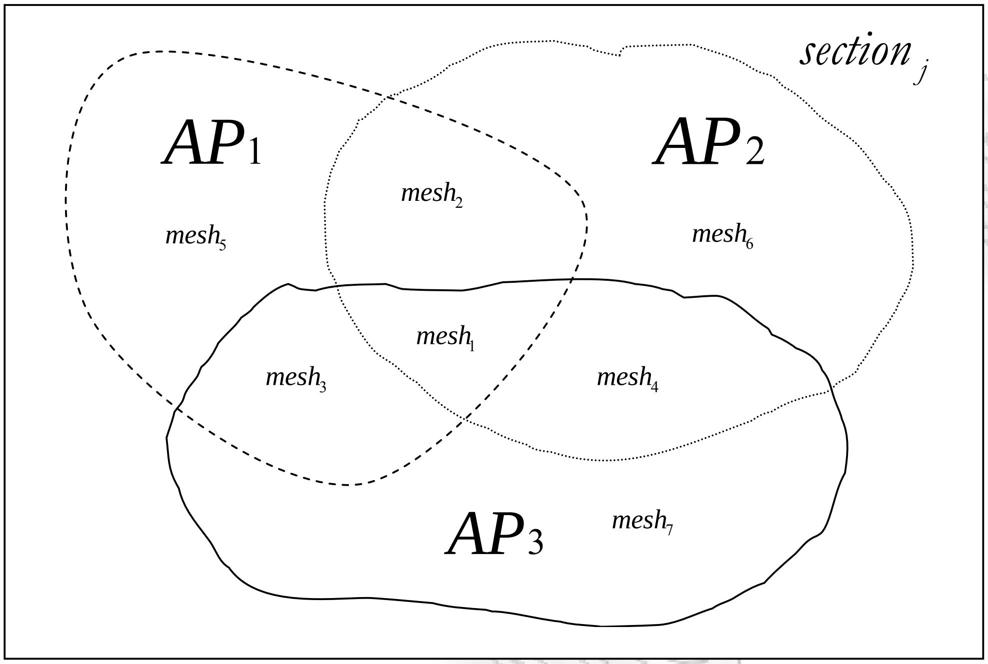

Figure 2-6: Example for derivation of meshes

- $mesh_3 = \left\{(x,y) \in \left[\left(CA_{AP_1} \cap CA_{AP_3}\right) / \left(CA_{AP_1} \cap CA_{AP_2} \cap CA_{AP_3}\right)\right]\right\}$

- $mesh_4 = \left\{(x,y) \in \left[\left(CA_{AP_2} \cap CA_{AP_3}\right) / \left(CA_{AP_1} \cap CA_{AP_2} \cap CA_{AP_3}\right)\right]\right\}$

- $mesh_5 = \left\{(x,y) \in \left[CA_{AP_1} / \left(CA_{AP_2} \cup CA_{AP_3}\right)\right]\right\}$

- $mesh_6 = \left\{(x,y) \in \left[CA_{AP_2} / \left(CA_{AP_1} \cup CA_{AP_3}\right)\right]\right\}$

- $mesh_7 = \left\{(x,y) \in \left[CA_{AP_3} / \left(CA_{AP_1} \cup CA_{AP_2}\right)\right]\right\}$

Obviously, reconfigurations of *AP*s and changes in the electromagnetic environment result in alterations of the size and geographical co-ordinates of meshes. Moreover, as the number of existent *AP*s in a section increases, the number of probable meshes increases exponentially, encumbering the computational process for the derivation of meshes and increasing the size of the necessary information for the derived meshes of a managed area, which has to be transmitted (the exact kind of this information will be presented analytically in the sequel).

The outline of each mesh will most likely have random shape, which makes it extremely difficult to be described by a mathematical function. So, in order to be transmitted in a compact way that can be quickly understandable from MTs, each $mesh_k$ is finally approximated by a "known" mathematical function from MTs, $f_k(x,y)$, where (x,y) represent the geographical coordinates of the spots that constitute the mesh. The function $f_k(x,y)$ may be different for each mesh, in order to embrace the maximum number of spots that satisfy the condition of mesh' definition.

The collected information by the Information Collection & Processing Function and the computed information, which is forwarded to other functions, is presented in the next Chapter.

2.3.2 Policy Derivation Function

Policy Derivation Function [59] derives policies that aim at ensuring profitable operation for both networks and MTs. This goal is implemented by using as prime criterion in policy derivation procedure the combination of effective usage of overall available radio resources and guidance of MTs to the selection of the network, which can satisfy users' needs with the best possible technological and economical way. In this framework, policies are derived based on information that is sent from Information Collection & Processing Function, which reflect the current status of the managed networks and MTs, as well as MTs' demands, and taking into consideration the evaluation for the efficiency of the currently adopted policies, regarding their aforementioned purpose, performed by Policy Efficiency Function. The derived policies are sent to Repository, and specifically to the section of Repository that is named Policy Repository (PR), and then are transmitted to MTs via the Radio Enabler.

The role of the function necessitates suitable cognitive operation. Key factor of the cognitive operation is the learning capability, which enables the acquisition and accumulation of knowledge. This knowledge accrues from exploitation of all the available information from Information Collection & Processing Function and the evaluation results from Policy Efficiency Function, by applying various reasoning paradigms, and constitutes the basis for the process of policies' derivation.

An indispensable attribute of the derived policies is that they have to be easily "understandable", in order to be quickly deployable by MTs, which is very important issue, especially in emergency situations. The label "understandable" for the policies here, denotes that the structure of the policies have to be sufficiently simple. The simple structure of policies (which is presented in section 3.4.3), besides, facilitates and accelerates the policy derivation procedure, which is also significant issue, as derived policies have to be always up to date, in order to be really effectual. For this reason, policies do not usually include detailed information about the characteristics of the transmission behaviour of MTs, e.g. coding schemes. Exception constitutes the transmission power of MTs, in case of policies for secondary usage of definite frequencies. In this case, the limit of MT's transmitted power of secondary users is essential, in order to be ensured the unimpeded operation of primary users and to be reduced, and even eliminated, the risks of secondary spectrum usage.

A substantial parameter is introduced in policies, named "Grade of Obligation (GoO)". The "Grade of Obligation" reflects the degree of importance of each policy for the determination of MT's behavior. Specifically, three values for GoO are determined:

- The value of GoO equal to 1 (GoO = 1), determines that MTs, to which this policy targets, are in duty bound to obey to this policy. This GoO mostly pertains to network conditions of considerable traffic congestion that approximate the borderline of complete crash of the networks, as well as to emergency and public safety situations (for example, for priority of public safety services in natural disasters, e.g. earthquakes, or for blocking the usage of networks by terrorist organizations, in order to be prevented terrorist actions, such as the explosions in trains in Madrid in 2004, which, as it was ascertained, were triggered by mobiles via SMS).

- The value of GoO equal to 2 (GoO = 2) determines that the targeted MTs, have to take into consideration the specific policy, as significant factor for the determination of their behaviour.
- The value of GoO equal to 3 (GoO = 3), determines that the relevant policy has advisory character, and the targeted MTs may ignore it or take it into account, based on their own strategy.

The degree that policies with GoO=2 will affect the determination of the behaviour of a targeted MT, will be defined in user's profile and will consist part of the Service Level Agreement (SLA) of the user with the Network Operator with whom the user has contractual agreement, with probable respective expense. Namely, the user may run into debt her option for more independence from policies and therefore greater degree of autonomy. Consequently, the compliance of a MT with policies with Grade of Obligation 2 and 3, will be finally estimated by the MT based on user's SLA, MT's strategy and the current status of MT, concerning its power and computational resources, e.g, a MT may prefer to connect with a RAN that does not provide the most advantageous offer or does not provide the best Quality of Service (QoS) level for the demanded service, but its operating *AP* is in close distance, and the MT wants to reduce its power transmission because of limited power resources.

Policies are graded according to their scopes to categories (e.g. policies for initial RAN selection, for optimized RAN selection, for secondary spectrum usage, for compulsory handover in critical situations), and specific value of GoO, which has been pre-agreed between the cooperated network operators, correspond to each policy category. Furthermore, network operators may categorize their users per classes, regarding their grade of compliance to policies with value of GoO equal to 2. These distributions may be known to Policy Derivation Function, which might be taken them into consideration in policy derivation. But, this surplus element may delay the corresponding procedure.

Obviously in the process of policy derivation, the materialization of a rule, for example the load counterbalance between the managed RANs or the provision of the best feasible level of QoS to users altogether, may be reflected to different policies for each mesh. Furthermore, in derivation of policies with the same scope, different criteria may be used for each offered service. For example, for evaluation of the service's level provision for derivation of relevant policies, the minimum data rate may be used as criterion for services such as Video On Demand, and the reliability and security level may be used for services like e-banking.

Each policy is valid for specific time frame, which is declared as a parameter in it. Moreover, each policy is identified by a unique identification number pid. The method of assignments of pids to policies will be decided from the operator/operators. For example, it can be selected a range of numbers, and when a new policy is derived, a free number can be assigned to it. Respectively, when a policy is not valid anymore and is removed from the Repository, its pid is freed. Another method for pid generation can use the combination of the time of policy generation and the valid time frame of the policy (for example, if the policy is the second policy that is generated in 9.15.00pm of the 3rd day of June 2010, and is valid for the time frame 10.00-11.30pm, the pid of the policy might be 0221150003062010022002330, where 02 is the ascending number of policy, 211500 is the time of generation, 03062010 is the day of generation and 22002330 is the validity time of the policy). This method for unique identification number generation would facilitate MTs to recognise new policies before examining the content of the policy. Scilicet, if the conditions necessitate the adoption of new derived policies for specific meshes (as in cases that, the evaluation results of Policy Efficiency Function indicate the inefficiency of specific policies, there are unforeseen circumstances in the operation of a RAN such as serious technical problems and rapid alterations in traffic load, or in situations of emergency and public safety), before the expiration of the previous corresponding policies that led the relevant MTs to the adoption of their current behaviour, the MTs will "understand" via the policy identification number of the new policies, the exigency to probably reconsider their behaviour based on the new policies, before examining their content. Furthermore, when a policy is used in MT's behaviour determination, its pid is forwarded to NRM, in order to be taken into consideration in policies' evaluation by Policy Efficiency Function.

2.3.3 Policy Efficiency Function

Policy Efficiency Function [59] evaluates the efficiency of the currently adopted radio resource selection policies, based on the information that is sent from Information Collection & Processing Function, which is presented in section 3.3.

The efficiency of the policies is estimated based on the performance of the overall system, which operates under the guidance of the evaluated policies. The evaluation criteria may be based on various QoS metrics, relevant to network quality e.g. load, throughput, etc., or user satisfaction e.g. blocking, delays, etc. The grade of policies' efficiency, regarding the satisfaction of users, may also be correlated with the perceptible Quality of Experience (QoE) level from users. The augmented processing capabilities of information systems and various methods currently under development, will enable the objective determination of QoE. Namely, each QoE level will correspond to different definite Quality of Service (QoS) level per RAT.

If the evaluation results indicate that the applied policies are ineffective, the Policy Derivation Function must be properly informed in order to proceed to the re-composition of the currently applied policies or the derivation of new policies. It is noted that the results of the operation of Policy Efficiency Function that are forwarded to Policy Derivation Function, enhance its acquired knowledge.

2.3.4. Spectrum Evaluation Function

Spectrum Evaluation Function [59] receives information from Information Collection & Processing Function, which reflects the status of the operation of the managed

RANs. By comparing the received information for different configurations of each RAN, Spectrum Evaluation Function explores if the different implemented configuration of the RANs, in respect of their operating RAT and frequencies, lead to optimization of their operation, as well as to optimized operation of the combined overall system. The evaluation results are sent to MA, which may decide the reallocation of the available frequencies of the spectrum pool to RATs in order to improve the operation of the RANs on the whole, through new potential configurations (via different combinations of operating RAT and corresponding frequency). If the new possible allocation of frequencies does not improve the effectiveness degree of spectrum usage, MA might enlighten the cooperated NOs to extend the common spectrum pool, or in case that it has detected that the current state has strained its possibilities for improvement, to look for new co-operations.

2.3.5 RAN Reconfiguration Decision Function

RAN Reconfiguration Decision Function [59] taking into consideration information, rules and constraints, regarding the frequencies and the respective operating RATs that are allowed to be used by each managed RAN, which are sent from the MA, and suitable information sent from Information Collection & Processing Function, effectuates proper optimization function in order to determine the final allocation of frequencies and RATs to the managed RANs. The optimization procedures are executed in stable time-span and when are triggered by specific alterations of input information sent from MA (e.g. after alteration of frequencies allocation) or Information Collection & Processing Function (e.g. when a RAN's load is over a specific threshold). The framework of the optimization procedures will be distinctly prescribed and will comprise a point of negotiation among the members of the consortium, in case that the management architecture operates in the frame of one. The reconfiguration decisions are sent to the respective RANs, which implement the reconfiguration actions exclusively by their own resources, possibly assisted by software defined radio technology.

A variety of methods and algorithms have been developed, concerning the problem of allocation of frequencies and RATs to RANs. The pertinent procedures will be substantially simplified in the future, through the evolution of WAPECS (Wireless Access Platforms for Electronic Communications Services) by RSPG (Radio Spectrum Policy Group), which is a high-level advisory group that assists the European Commission in the development of radio spectrum policy [71] . In the framework of WAPECS "any electronic communication service (ECS) may be provided in any WAPECS band over any type of electronic communications network. No frequency band should be reserved for the exclusive use of a particular ECS" [72]. Finally, this will gradually lead to spectrum liberation, with the apparent consequences in the aforementioned optimization procedures.

2.3.6 Repository

As stated before, Repository [59] is the storage unit, which includes all the information that is sent from NRM to MTs. This information consists of information for MTs' RAN context and guide-lines for MTs' assistance in order to select the optimal radio resources, namely the optimal RAN. Repository consists of two segments: the Policy Repository (PR) and the Context Repository (CR). Policy Repository includes the policies that are derived from Policy Derivation Function, whereas Context Repository includes information for the status of the managed RANs, which is provided by Information Collection and Processing.

PR is further split into two parts: basic-PR (b-PR) and extended-PR (e-PR). b-PR maintains the simplest, though most important policies that are used by the MT when it is switched on, in order to accomplish its initial RAN selection. Furthermore, b-PR contains all the mandatory policies (namely policies with GoO equal to 1), which aims at assuring efficient and secure operation of the managed RANs under any circumstances. Examples of mandatory policies are policies for obligatory handover in case of traffic congestion and policies for disruption of usage of services with large radio resource claims, in order to be ensured the disposability of the necessary radio resources for safety services in case of natural disasters. e-PR includes policies of secondary importance (policies with GoO equal to 2 and 3), the goal of which is the optimization of both RAN's and MT's operation.

Similarly, CR also consists of two parts: basic-CR (b-CR) and extended-CR (e-CR). b-CR includes the basic information of networks in the vicinity of the MT, in order to accomplish its initial RAN selection, and e-CR includes more detailed information for these RANs, in order MTs to select the appropriate RAN for their demands.

2.4 A second approach for the Management Architecture

In the framework of 4th generation wireless communications environments, as it was depicted in Chapter 1, a slightly differentiated approach for the management architecture of heterogeneous wireless networks from this that was introduced in the previous section, was developed and is presented in this section.

The management architecture has influenced the corresponding architecture that was developed in the context of E3 project [62][73][74][75] (particularly, the architecture in E3 project constitutes a variant structure of the Functional Architecture that was initially proposed within E2R II project [60] and was further developed). The End-to-End Efficiency (E3) project was an FP7 EC Large Scale Integrating Project (IP), which aimed at integrating cognitive wireless systems in the Beyond 3G (B3G) world, evolving current heterogeneous wireless system infrastructures into an integrated, scalable and efficiently managed B3G cognitive system framework, as it is depicted in Figure 2-7 [62].

Specifically, the key objective of the E3 project was to design, develop, prototype and showcase solutions, which guarantee interoperability, flexibility and scalability between existing legacy and future wireless systems, manage the overall system complexity, and ensure convergence across access technologies, business domains, regulatory domains and geographical regions.

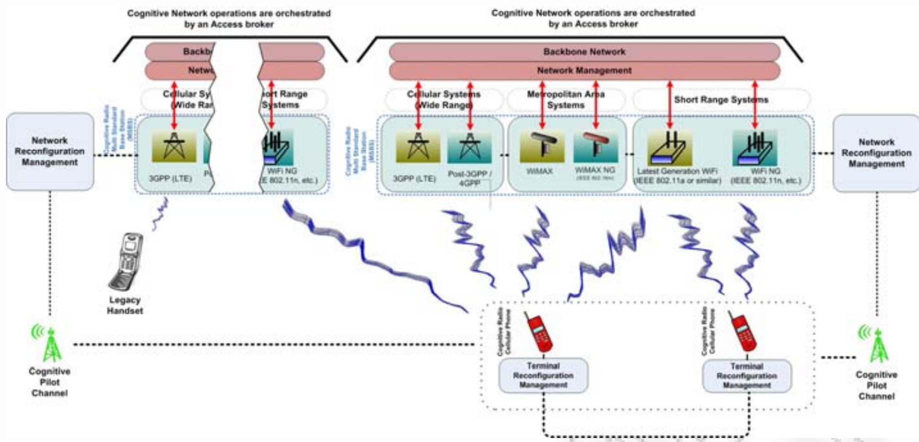

Figure 2-7: E3 Heterogeneous Wireless System Framework

The architecture also comprises a variant of the proposed Functional Architecture that has been elaborated within the Working Group 3 (WG3) of the Reconfigurable Radio Systems Technical Committee (RRS TC), which was created by European Standards Telecommunication Institute (ETSI) Board [64] with the aim to study the feasibility of standardization activities related to reconfigurable radio systems (including software defined and cognitive radios). In May 2009, the ETSI Board approved the respective technical report as ETSI TR 102.682 “Functional Architecture (FA) for the Management and Control of Reconfigurable Radio Systems” [76], which “provides a feasibility study on defining a Functional Architecture (FA) for reconfigurable radio systems, in terms of collecting and putting together all management and control mechanisms that are targeted for improving the utilization of spectrum and the available radio resources”.

The Functional Architecture (FA) of the management architecture is depicted in Figure 2-8. It consists of four functional blocks: (i) the Dynamic Spectrum Management (DSM) (ii) the Dynamic, Self-organising Planning and Management (DSNPM), (iii) the Joint Radio Resource Management (JRRM), and (iv) the Configuration Control Module (CCM) [77], which cater for different operational needs and goals. These functional blocks exchange proper information via the depicted interfaces in Figure 2-8.

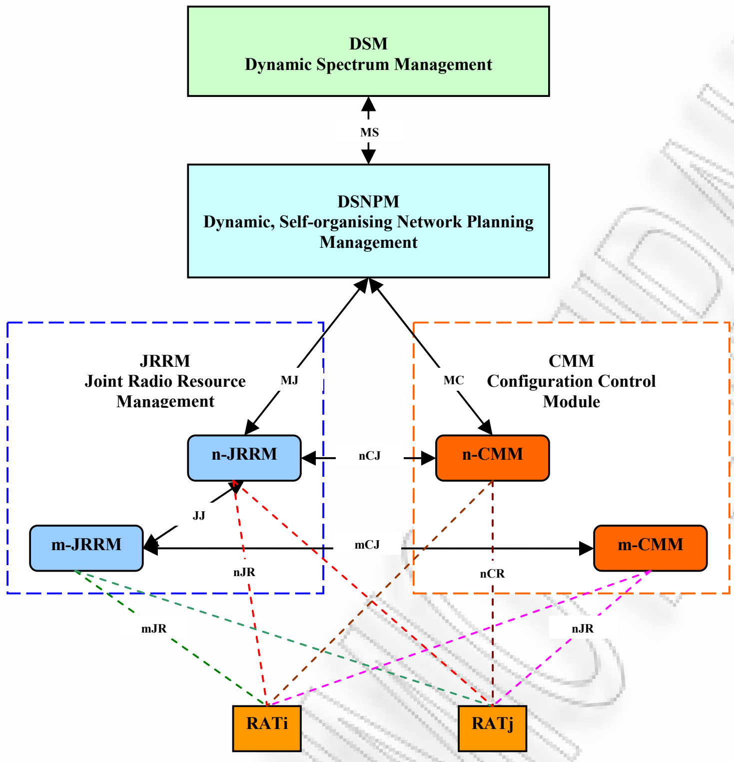

Figure 2-8: Functional Architecture of the Management Architecture

The FA encompasses network elements in all levels of network's structure/hierarchy, independently from the innate architecture of each Radio Access Technology, as well as MTs. In the sequel, the term RAT, correspondingly to E3 and ETSI approach, comprises the set of network elements operating at specific radio access technology, with the exclusion of their functional part that is encompassed in the functional architecture. Scilicet, the term RAT in this management architecture coincides with the term RAN (Radio Access Network) in the previous one, with the defined exclusion.

In summary, the main function of DSM concerns the spectrum management in medium and long term. The function of DSNPM concerns the management of the network elements, regarding their configuration, and the MTs' guidance for achievement of best connectivity. JRRM effectuates joint management of the radio resources of the different managed RATs in short term, in the framework of DSNPM decisions and directives. Finally, CCM is restricted to the implementation of the decisions of DSNPM and JRRM.

The operation of both DSM and DSNPM necessitates central processing of information that is sent from the lower functional blocks of FA (DSNPM for DSM and JRRM for DSNPM, respectively). This fact entails centralized-like operation of them in the upper level network elements (for example in GPRS systems, DSNPM might operate in GGSN – Gateway GPRS Support Node). In contrast with DSM and DSNPM, the function of JRRM and CCM calls for distributed-like operation in both network and terminals. In CCM, the distributed operation is demanded in order to ensure the implementation of the decisions of the functional blocks in network elements and terminals. Besides, the overall operation of the FA presumes the collection of various information, which is a task being accomplished by the complementary operation of JRRM in network and terminal sides. Specifically, JRRM and CCM functions in the network are called n-JRRM and n-CCM respectively, whereas the corresponding functions in MTs, are the m-JRRM and m-CCM. n-CCM principally effectuates the decisions of DSNPM regarding all the possible different actions of the reconfiguration process in network elements and m-CCM effectuates all the respective actions that are determined from n-JRRM and m-JRRM in terminal side, correspondingly.

In the corresponding ETSI FA [76], DSNPM is named DSNOPM, the m-JRRM and m-CCM are called JRRM-TE and CCM-TE and n-JRRM and n-CCM are named JRRM-NET and CCM-NET, respectively. Moreover, DSNPM performs an expanded operation with respect to the one defined in the framework of E3 architecture [74][75], which comprises the operation of another entity named “Self-x for RAN”, and CCM effectuates the operation of corresponding entity RCM [74][75].

2.4.1 Dynamic Spectrum Management (DSM)

DSM, the operation of which is depicted in Figure 2-9, is responsible for the:

- Assignment of operating frequencies to the different Radio Access Technologies in specific time periods and definite geographical areas, and determination of corresponding directives for final allocation of frequencies to RATs per region and time scale, based on:

  - constraints imposed by the relevant official organizations (e.g. the spectrum usage rights for the licensed operating frequencies),
  - spectrum utilization metrics, and
  - spectrum assignment policies, which are predefined rules that have been designated by the network operator based on techno-economical criteria and constraints.

- Detection of long-term available frequency bands for sharing or trading with other network operators, in the framework of a consortium in the former case and in free co-operation in the latter case.

- Derivation of economical parameters for spectrum trading.

- Bargaining in spectrum sharing/trading with other network operators.

DSM determines spectrum's assignment to Radio Access Technologies, but the final allocation of frequencies to RATs, based on DSM's directives, is accomplished by DSNPM. DSNPM collects the necessary information from the lower level's functional block JRRM and effectuates proper optimization algorithms, with outcome the definition of operating frequencies and configuration parameters for the reconfigurable network elements, as it will be presented in the following section.

The spectrum utilization metrics that are used by DSM for spectrum assignment, are calculated in DSNPM and are sent to DSM. These metrics correspond to Grade of Usage of the operating frequencies in specific time frame for each managed section of the whole managed area. The Grade of Usage results after elaboration of the information sent from JRRM, such as measurements of signal strength for each operating frequency combined with data about the load of the RATs operating on the corresponding frequencies, and may be defined differently for each network based on

Network Operator's strategy. Furthermore, DSNPM determines the dimensions of the managed sections, which are used by DSM (and other functional blocks) for its operation, and sent the corresponding geographic coordinates of each managed section to DSM. All the necessary information between DSM and DSNPM is exchanged via interface MS.

Specifically, based on:

- The set of the operating frequencies with the relevant Spectrum Usage Rights,
- The structure of managed sections,

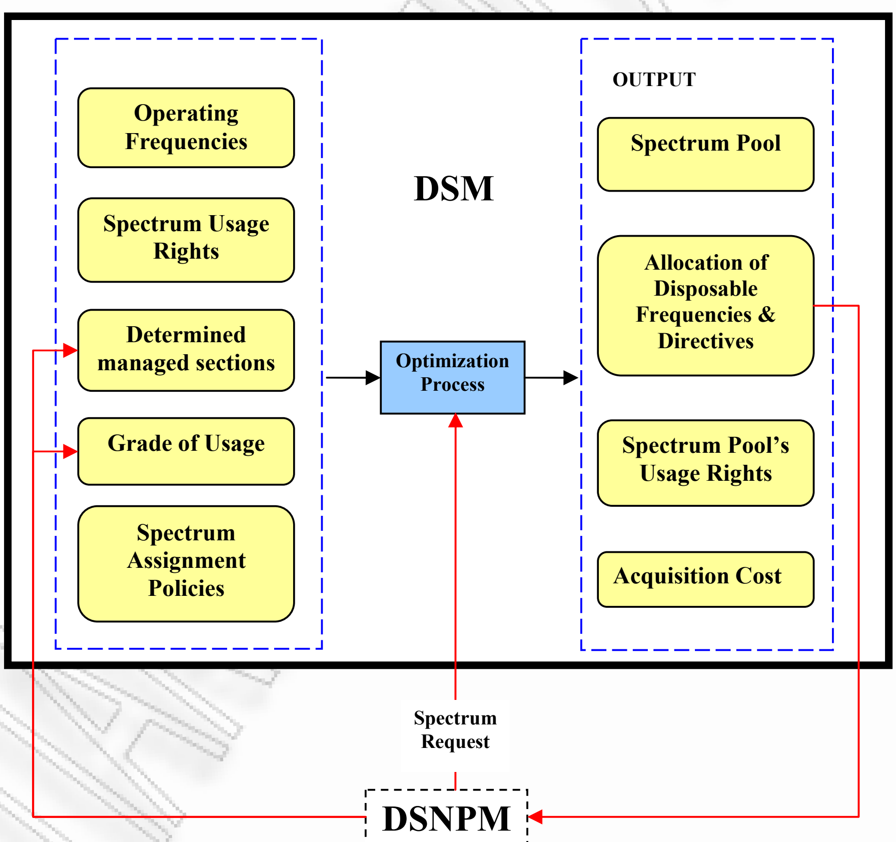

Figure 2-9: DSM overview

- The Grade of Usage of each managed section,

- The Spectrum Assignment Policies,

DSM constructs (for definite geographical areas, consisting of a variable number of managed sections, and time periods) the following:

- The set of long-term available spectrum for sharing/trading (for example in order of hours), which is named Spectrum Pool, with the corresponding Spectrum Usage Rights (Spectrum Pool's Usage Rights).

- The permissible Allocation of Disposable Frequencies to operative RATs in the framework of specific directives (for example that a specific frequency can be assigned to two different radio access technoloigies, but not in adjacent managed sections) .

- The set of Acquisition Costs of the available frequencies of Spectrum Pool for definite time period. The cost of different frequencies bands is determined based on conjunction of technological and economical factors, and maybe variant for different time periods.

The procedure of determination of frequencies' Acquisition Cost is complex and requires appropriate level of cognition, in order to forecast the needs of spectrum market, to detect the opportunities that arise from different situations and to adjust properly the offered bandwidth price.

The elements, which are derived in the framework of optimization process in DSM, are reconstructed each time there is an alteration in any of the input data, or whenever there is explicit demand from DSNPM (Spectrum Request), as it will be presented in the operational example of section 2.4.6, and is depicted in Figure 2-9.

Algorithms that may be utilized in the effectuation of DSM's goals have been developed in the framework of research relevant to spectrum management such as [78][79][80][81].

2.4.2 Dynamic, Self-organising Planning and Management (DSNPM)

DSNPM, the main function of which is depicted in Figure 2-10, is concisely responsible for:

- Determination of operating radio access technology, frequency and respective operational parameters of the managed network elements (namely, the operating *AP*s, as it were defined in section 2.3.1), plus the mode of their interconnection, under the directives of DSM.

- Determination of the framework for efficient operation of the overall network, as this is reflected to derived rules, such as the allocation of services to operating radio access technology (as order of accommodated services per radio access technology) and the allocation of applications to Quality of Services (QoS) levels. The target of these rules is the realization of users' and operator's purposes.

- Derivation of radio resources directives and constraints for the managed MTs.

- Provision of suitable information to MTs for initial network connection, via proper mechanisms of propagation.

These objectives are accomplished by applying optimization functionality, enhanced with learning capabilities that enable the acquisition and accumulation of knowledge via proper processes, based on context and profiles information, in a specific Rules' Framework, as depicted in Figure 2-10. Relevant algorithms that might be used for accomplishment of DSNPM's objectives have already been developed, for instance in [82].

The context and profiles information, existent in Context & Profiles related Info Management of DSNPM, illustrates network's status and user's demands. Specifically:

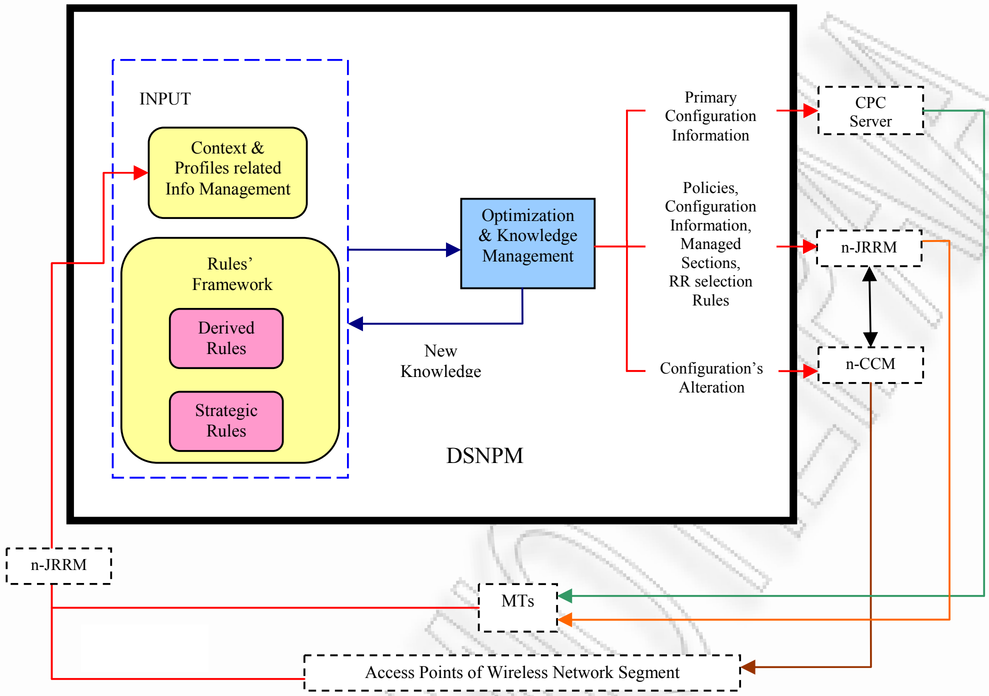

Figure 2-10 : DSNPM Main Function

Context information: It comprises information of the current status of network elements and MTs, statistics on the traffic (such as MTs' demand per service), and mobility and interference conditions (such as the supported mobility mechanisms from each RAT).

Profiles information: It encompasses system aspects, such as the possible alternative configurations of network elements (*AP*s) and MTs, user's classes and preferences, and services' characteristics.

The Rules' Framework comprises:

- The Strategic Rules.

- The Derived rules.

Strategic Rules: They illustrate the strategy of the Network Operator, always in compliance with the official regulations. The Strategic Rules are determinant rules for the operation of the network, which are designated in the uppermost level of network administration, probably in non-automatic way.

Derived rules: They are rules that are designated in DSNPM, in order to assist the utilization of context and profiles related information in Optimization Phase. The rules are altered based on accumulated knowledge from the Knowledge Phase of Optimization & Knowledge Management Function, as it is presented below. Derived rules may include for example, rules for preferred QoS per service, order of preferred RAT per accommodated traffic, etc.

DSNPM obtains primary (non-processed) and secondary (calculated) information from JRRM (namely from n-JRRM) via interface MJ. This information comprises cumulative context and profile information. The obtained information from n-JRRM and significant information for each RAT , which is known to DSNPM from the introduction phase of each RAT, is kept and further elaborated in Context & Profiles related Information Management function of DSNPM. The Context & Profiles related Information Management consists of all the procedures and actions, which are related to procession of the abovementioned information, the extraction of proper information depending on DSNPM operation's requirements, its storage and supply to Optimization & Knowledge Management Function, according to the specific case/event.

The Optimization & Knowledge Management Function of DSNPM (Figure 2-11) operates in three phases:

- The Optimization Phase.

- The Decision-Making Phase.

- The Knowledge Phase.

Optimization Phase: Congruent methods and algorithms, medium-term applicable, are executed for the accomplishment of DSNPM's purposes (which are presented analytically below) in Optimization Phase, under the aforementioned rules of the Rule's Framework, using as input data the information sent from Context & Profiles related Information Management.

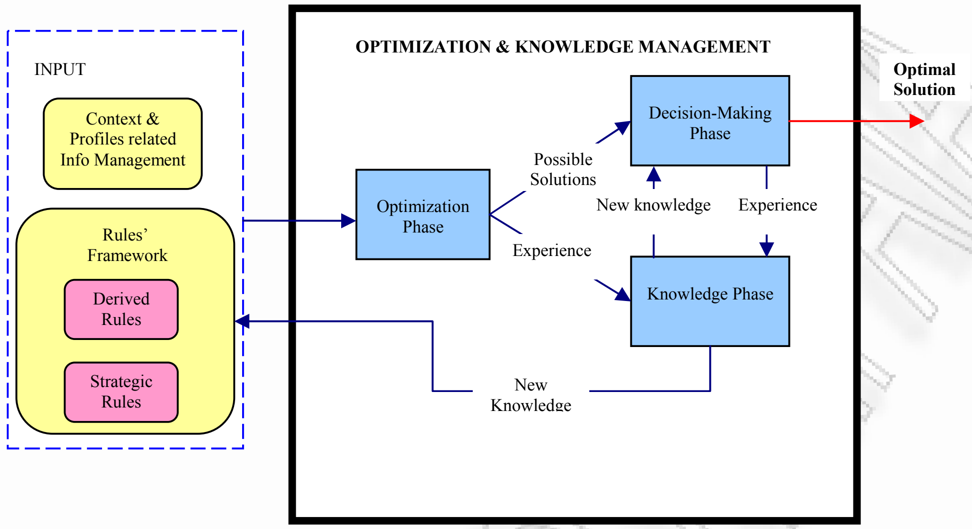

Figure 2-11: Optimization & Knowledge Management Function of DSNPM

Decision-Making Phase: From the possible solutions that result from the Optimization Phase, the optimal solution is chosen, taking into consideration the system's knowledge.

Knowledge Phase: The aforementioned system's knowledge accrues from elaboration of the experience that is sent from the Optimization Phase and the Decision–Making Phase, by the Learning Functionality of the Knowledge Phase. This process, which is based on definite reasoning schemes, may lead to derivation of new knowledge. New knowledge might be used for future commensurate network conditions, eventuating in rapid solution of problems and optimized operation of network via proactive actions, in order to be confronted the predicted problems. The acquisition of new knowledge enriches the knowledge base of the Decision-Making Phase and the corresponding knowledge for derivation of new rules in Rule's Framework.

Analytically, the Optimization & Knowledge Management Function of DSNPM:

- Assists MTs in initial RAT selection, by provisioning them with the essential configuration information of the managed RATs in MT's vicinity. The transmission of this information may be accomplished by an external entity, which will take the responsibility to broadcast the relevant information for all the network operators in a certain area. The role of this entity can be successfully accomplished by the Cognitive Pilot Channel (CPC), respectively with the prior management architecture. In this occasion, the aforementioned Primary Configuration Information of the network is sent to the respective database server, which is the CPC Server, as it is represented in Figure 2-10.

- Divides the total network's coverage area into managed sections, for which proper calculations for the estimation of the current and prospective status of the network are implemented. Based on these calculations, a set of determinative decisions for the operation of the network are made. The dimensions of the managed sections are variable and depend on the network's topology. Each managed section is determined by its geographic coordinates, as these are approximated by a "known" mathematical function, which embrace the spots that constitute the managed section and is understandable from network entities and MTs. It may be designated "managed sections" to correspond to "meshes" as have been prescribed in the framework of CPC, which would simplify the procedures for derivation of the suitable information that should be forwarded to CPC Server. After the determination of the managed sections of the network's coverage area, DSNPM forwards this information to JRRM (namely to n-JRRM), in order to carry out the necessary calculations for the operation of the FA, and to DSM.

- Detects harmful interference within licensed frequencies and unlicensed frequencies of common usage.

- Specifies the Final Allocation of frequencies to RATs per region and time scale, in the framework of the decisions and directives of DSM.

- Determines the configuration of the managed network elements (*AP*s) for accommodation of the traffic, scilicet their operating radio access technology and frequency as well as respective operational parameters (e.g., transmission power per carrier, tilt, etc). In case of reconfiguration of elements, DSNPM informs both n-JRRM and n-CCM (via interfaces MJ and MC respectively) in order to proceed to the proper actions.

- Detects the necessity of commissioning new elements in specific geographical regions with definite operational characteristics.

- Determines the mode of interconnection of network elements (backhaul or mesh).

- Derives rules for optimization of radio resource selection (RR selection), that concern for example, accommodation of specific service traffic from specific radio access technologies, minimum QoS level per application, etc. These rules are sent to n-JRRM and constitute the framework for its decisions for the most suitable access selection for each MT.

- Derives policies for MTs, which act as directives and constraints for their behaviour. The scope of these policies is to assist MTs to achieve best connectivity according to user's preferences. The derived policies are forward to n-JRRM, which is responsible for provision of them to the corresponding MTs.

- Calculates the Grade of Usage of the used frequencies in specific time frame for each managed section and sends it to DSM, as it has been presented.

2.4.3 Joint Radio Resource Management (JRRM)

JRRM, as already mentioned, is a functional block that operates in a distributed manner in both network and MTs, with distinct and simultaneously supplementary functions.

n-JRRM (JRRM on network side) is responsible for:

- The access selection for the managed MTs, based on user's demands and preferences and network's status in the framework of DSNPM decisions.

- The provision of proper information to MTs for all alternative available accesses of the network in their neighbourhood. This information is an extended version of the information that is provided to MTs from DSNPM, via the responsible entity (CPC), for assistance in initial RAN selection, and may include information for each RAT such as the supported QoS levels per service with the corresponding potential costs.

- The provision of policies (resource management directives and constraints), obtained from DSNPM, to the addressed MTs.

- The provision of context and profile information to DSNPM, necessary for its operation.

m-JRRM (JRRM on mobile terminal side) is responsible for:

- The initial access selection, based on the suitable information forwarded from DSNPM and MT's needs. m-JRRM uses MT's cognitive capabilities and knowledge accrued from former decisions, to select the RAN to connect to.

- The co-operation with n-JRRM for implementation of access selection, and reconfiguration procedures.

- The access selection for a requested service based on MT's strategy and the neighborhood information sent from n-JRRM, in compliance with policies sent from n-JRRM and derived in DSNPM, when this potentiality is provided from the network.

- The retrieval, from the different operative functions of the MT, suitable information for the aggregate operation of JRRM. This information includes the MT's capabilities and its determinant operational characteristics, its requests and assessment of its active links.

Relevant algorithms to n-JRRM operation have been proposed in [83][84][85] and to m-JRRM in [86][87], respectively.

2.4.3.1 Co-operative operation of n-JRRM and m-JRRM in access selection

When a MT m via m-JRRM demands a service with specific QoS level, n-JRRM based on the known attributes of the supported network services, the collected information for the status of the managed network elements (*AP*s) and the relative specified policies from DSNPM, estimates the short-term status of the *AP*s, and :

- decides MT's access connection with the *AP* ap_l with specific characteristics of QoS,
- commands the *AP* ap_l for reservation of the necessary radio resources and
- sends the appropriate instruction to m-JRRM function in MT side.

The access selection with specific QoS level per offered service for MTs, is performed with target the combination of the load counterbalance between the *AP*s and the satisfaction of user's needs. The aforementioned scope may lead n-JRRM, after elaboration of *AP*'s status information and calculated estimations, to command a set of MTs with active interfaces to connect to other *AP*s. In this occasion, if a MT is going to be connected to a new *AP* of the same RAT, then the procedure is analogical of the corresponding process in legal systems, with the difference that the exact moment of handover between the two *AP*s is determined from the m-JRRM. Particularly, after estimation of the aforementioned data, n-JRRM may decide that a group of MTs have to connect from the prior *AP* ap_{pl} to the subsequent *AP* ap_{sl}. Then, the *AP* ap_{sl} reserves the necessary radio resources for the accommodation of the traffic of the specified group of MTs, but the final selection of the right time for handover is accomplished by the m-JRRM of each MT, in order to ensure uninterrupted operation of its services. However, the exact moment of handover is inside a default time frame, which is determined in the handover command of n-JRRM.

If the MT has to be connected to an *AP* of different RAT, there is a slight difference in the implementation procedure of the command. Specifically, the stages, which are illustrated in Figure 2-12, are the following:

- n-JRRM decides MT's handover connection from *AP* ap_{pl} of rat_i to the *AP* ap_{sl} that operates rat_j, with specific characteristics of QoS for its services,
- n-JRRM commands the *AP* ap_{sl} for reservation of the necessary radio resources,
- n-JRRM sends the appropriate instruction to m-JRRM via interface JJ,
- m-JRRM determines the specific moment of reconfiguration and commands m-CCM, via interface mCJ, to implement the reconfiguration procedure for the specific RAT,
- m-CCM supervise the reconfiguration procedure, as it is presented more analytically in the following section, and when it is successfully effectuated informs m-JRRM,
- m-JRRM decides the exact moment of handover, which is inside the definite time frame from n-JRRM.

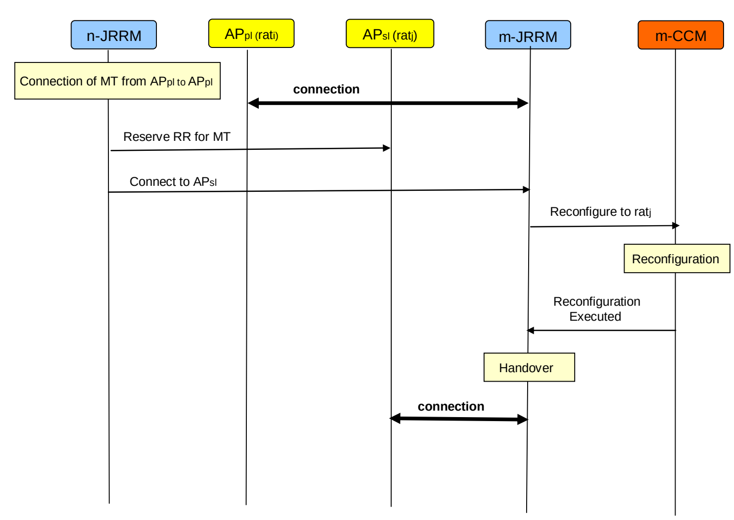

Figure 2-12: Handover procedure between *AP*s of different RATs

2.4.4 Configuration Control Module (CCM)

CCM implements the decisions of DSNPM and JRRM in network elements and of JRRM in MTs, in all layers of their operation.

Specifically, CCM, for both network elements and MTs, is responsible for:

- The implementation of all stages of reconfiguration and all possible related actions (e.g. software download).

- The control of specific operational parameters and the effectuation of proper measurements. This information is forwarded to JRRM entity, in order to supply processes of the FA and to evaluate the efficient operation of the operating entity (MT or network element).

Moreover, m-CCM (CCM on mobile terminal side), particularly, implements the decision for access selection, taken from JRRM functional block.

In order to clarify the operation of CCM, and especially the cooperation of JRRM and CCM, we consider the case that DSNPM, after optimization procedure, decides reconfiguration of a number of *AP*s (Figure 2-13).

DSNPM requests the reconfiguration of the abovementioned *AP*s by n-CCM (message: Reconfiguration Request), and simultaneously informs n-JRRM for the required reconfigurations (message: Reconfiguration Notification), in order to ensure the uninterrupted operation of the mobile terminals which are currently connected with the *AP*s that will be reconfigured. n-JRRM and n-CCM cooperate for the reconfiguration of the *AP*s. Specifically, n-JRRM determines the suitable moment at which n-CCM initiates the execution of the *AP*s reconfiguration (message: Reconfiguration Initiation).

n-CCM enforces and controls all the stages of the reconfiguration procedure and afterwards, informs n-JRRM for the successful reconfiguration execution (message: Reconfiguration Execution). Then, n-JRRM informs DSNPM for the new status of the reconfigured *AP*s (message: Configuration Status).

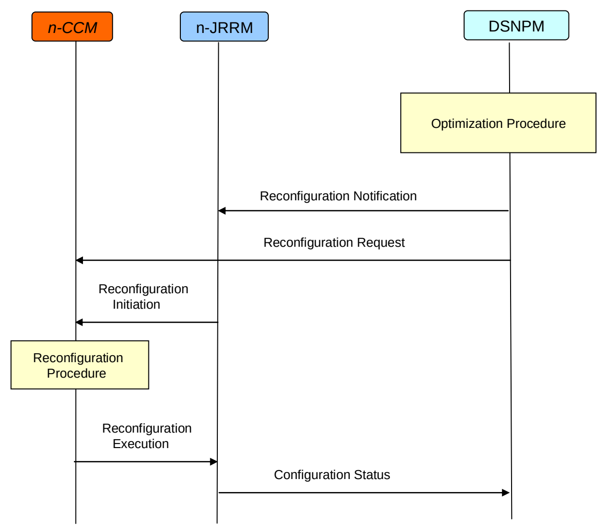

Figure 2-13: Co-operation of n-JRRM and n-CCM for *AP*s' reconfiguration execution

2.4.5 Operation of the FA in the framework of collaboration with other NOs with respective management architectures

The proposed FA can actively and efficiently operate in different multi-operators scenarios, with goal the satisfaction of the customers and the augmentation of network's profit. In this context, a set of interfaces between the corresponding functional blocks of different operators is defined and represented in Figure 2-14. The exact information that is exchanged between the corresponding functional blocks via the proper interfaces depends on the distinctiveness of each business case.

DSM of different operators may share information about the long-term available frequencies and the permissible Radio Access Technologies for these frequencies, plus the acquisition costs for them for definite time period in case of spectrum trading.

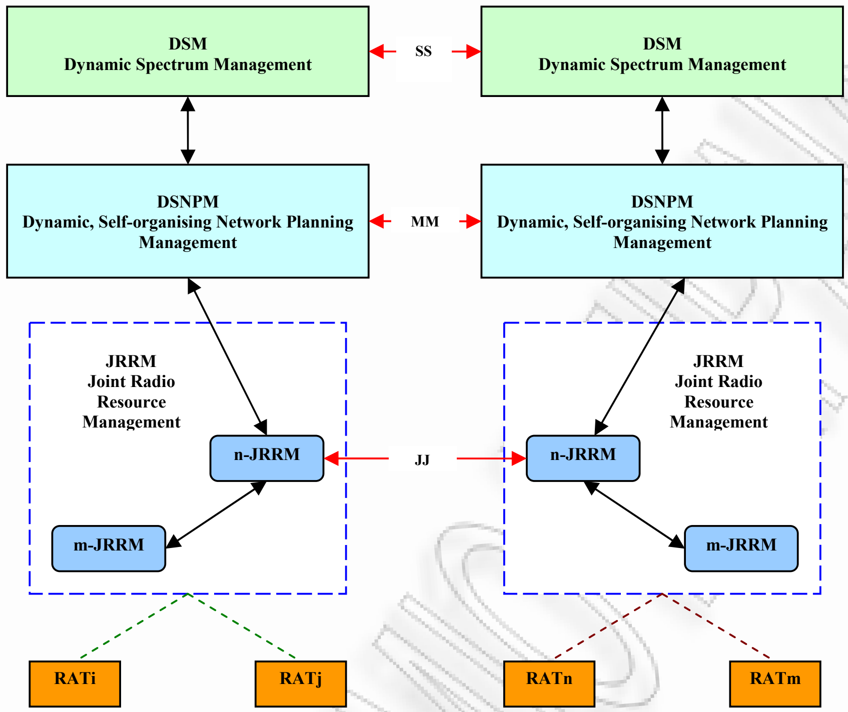

Figure 2-14: FA operation in multi-operator scenario

For instance, if there is request from another network operator's DSM for bandwidth for specific RAT, DSM after examining the Spectrum Pool's Usage Rights, it sends to the corresponding DSM the appropriate set of pairs Frequency-Acquisition Cost, namely the offered frequencies with the corresponding costs. Moreover, if the Network Operator is member of a consortium, where licensed frequencies of its independent members function as one integrated spectrum pool for collective usage under the control of a central management system, the network operator may send via interface SS to the management system the Spectrum Pool and the corresponding Spectrum Pool's Usage Rights.

DSNPM functional blocks (via MM interface) may share primary information for their network configuration, in order to facilitate initial network selection from terminals and simplify roaming procedures, or when there isn't an external entity with operation respective to CPC. This information may include their *AP*s with their operating frequencies and the corresponding Radio Access Technologies for specific regions and time periods, their offered services with the corresponding minimum QoS level, etc. Also, they may exchange information for impermanent available frequencies for secondary spectrum usage.

JRRM functional blocks (via JJ interface) may share spatial and time dependent information about network status (e.g. traffic load), in order to be examined the potentiality of traffic accommodation of cooperated networks.

2.4.6 Operational example

A simple operational example of the FA, which illustrates the cooperation of different functional blocks and the corresponding sequence of messages, is presented in this section. Namely, there is alteration of network status because of rapid alterations of traffic in specific regions or because of unexpected situations (e.g. destroyed segment of network from earthquake). DSNMP, as it is depicted in Figure 2-14, captures the accrued situation from the context information sent from n-JRRM (via message: Context Notification). DSNMP "comprehends" the necessity of enhanced usage of some RATs (augmentation of usage of alternate safe networks and self-organized networks in case of the previous example of destroyed networks), and executes proper procedures to determine the suitable reconfigurations in order to meet the new requirements.

If the procedures eventuated in unsatisfactory results, DSNPM requests from DSM new resources for specific time period, managed sections and RATs (via message: Spectrum Request), and updates the determined managed sections, due to probable alterations, and corresponding the Grade Of Usage. The structure of the new managed sections and their corresponding Grade Of Usage is sent to DSM with messages: Managed Sections and Spectrum Usage Metric, respectively.

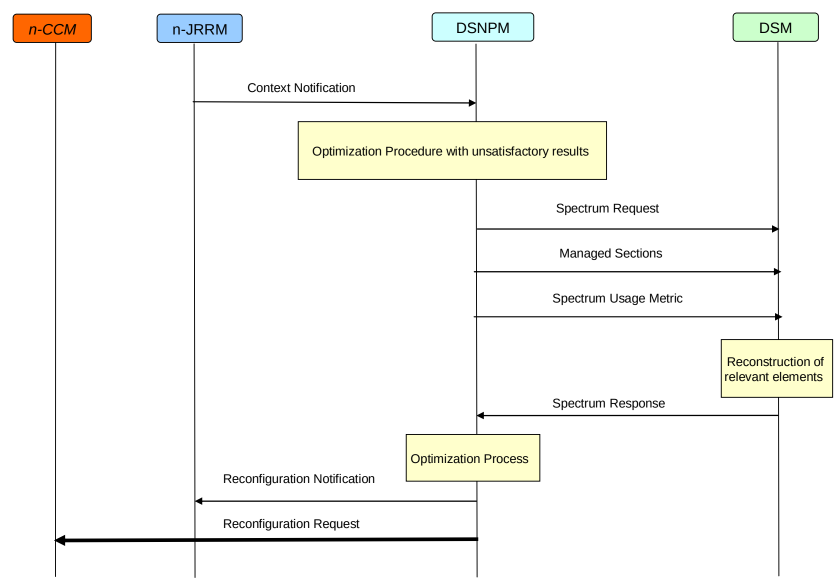

Figure 2-15: Operational Example

DSM based on the new conditions, reconstructs the elements presented in section 2.4.1 and sends the reconstructed permissible Allocation of Disposable Frequencies to operative RATs, to DSNPM (message: Spectrum Response). DSNPM re-executes optimization process, with result the decision of reconfiguration of a number of APs. The reconfiguration information is sent to n-JRRM (message: Reconfiguration Notification) and the reconfiguration command to n-CCM (message: Reconfiguration Request), in order to control the corresponding procedure (as it was presented in section 2.4.4).

2.5 Correlation of the Functional Architectures

The second management architecture (E3/ETSI approach architecture) encompasses deeper analysis level in relation to the former architecture, regarding the network configuration, as it enables the determination of operational parameters of the network elements in the level of radio access network. In essence, the latter architecture effectuates in a second level of analysis, the operation of RAN Reconfiguration Decision Function of the prior architecture. Furthermore, in the first architecture (IEEE approach architecture), the final selection of radio access from MT according to its own strategy, but always in accordance with the policies that are sent from the management system, had determinant role in design and development of the architecture and provides significant degree of autonomy to MTs. The E3/ETSI approach architecture permits the final radio resource selection from MTs in the frame that is determined from the operation of the FA, but this capability has subordinate role in the strategy of the architecture design. Moreover, the E3/ETSI approach architecture essentially focuses on operation of the architecture in the network of a network operator which operates different radio access networks, and secondly, in the cooperation of networks that belong to different network operators. This is revealed also by the fact that the architecture proceeds to determination of operational parameters of the network elements in the level of radio access network, plus the operating radio access technology and the corresponding frequency, which necessitates significant degree of transparency in the operating level of network. This degree of transparency cannot exist in case of managed networks of different network operators due to reasons of security as well as reasons of antagonism. In occasion of the operation of the architecture in the framework of collaboration with other NOs with respective FA, which presented in section 2.4.5, the information that is exchanged between the corresponding functional blocks is defined among the network operators and does not need the abovementioned degree of transparency.

There is strong correlation between the functional blocks of the the E3/ETSI approach architecture and the functions, as well as the entity MA, of the IEEE approach architecture. Specifically, DSM effectuates the role of MA, regarding the determination of the Spectrum Pool that will be used for the different RATs (RANs in the IEEE approach management architecture), the assignment of the frequencies that comprise the Spectrum Pool to radio access technologies per region and time scale, and the bargaining with other network operators. In case of spectrum bargaining, MA takes the responsibility to suggest to cooperated NOs (in case of consortium) to look for new co-operations (as it was mentioned in section 2.3.4) or even to bargain with other independent network operators or other consortiums, the frequencies of the Spectrum Pool that are not currently used from the managed RANs, and foresee, from the relative statistics measurements and the cumulative information from the profiles of the active users (namely the users that are currently connected to a managed RAN), that they will not be used for a minimum time frame.

DSNPM implements the operation of RAN Reconfiguration Decision Function concerning the final allocation of frequencies and access technologies to radio access networks, the operation of Policy Derivation Function and Policy Efficiency Function concerning the derivation of radio resource selection policies for MTs and their evaluation, the operation of Spectrum Evaluation Function regarding the evaluation of current spectrum usage, and the operation of Information Collection & Processing Function regarding the derivation of managed sections that corresponds to meshes in the IEEE approach.

JRRM effectuates the operation of Information Collection & Processing Function concerning the procession of the information sent from RATs (n-JRRM in E3/ETSI approach architecture) and MTs (m-JRRM in E3/ETSI approach architecture), and the extraction of proper information for the operation of DSNPM, as well as the operation of Repository, as it is responsible for the provision of policies and suitable context information to the addressed MTs.

There is not corresponding function of CCM in IEEE approach management architecture, as it comprises internal operation of the managed radio access networks and MTs. In Figure 2-15, the correlation between the functional blocks of E3/ETSI approach architecture and MA and the NRM's function of IEEE approach architecture is depicted.

The correlation of the functional elements demonstrates the possibility of the necessary cooperation and interoperability of the two architectures. It is noted, that it is also possible the simultaneously operation of the architectures in different levels of management (e.g. the operation of IEEE approach architecture for the central management of the networks in the frame of a consortium and the operation of the E3/ETSI approach architecture in the inner operation of each managed network for the implementation of the reconfiguration decision for the network elements, in the framework of the decisions of the central management system). These capabilities of the architectures demonstrate their scalability and flexibility, which is essential characteristics for the management architectures for heterogeneous high –speed 4th generation wireless communications environments.

Moreover, the correlation of the functional elements of the two architectures enables the incorporation of the functions of E3/ETSI approach architecture in IEEE approach architecture (e.g. the management of radio resources of network elements in short-term in a specific area from n-JRRM) when the IEEE approach architecture operates under the control of a network operator for his different operating RANs.

The IEEE approach architecture is adopted as base for the continuance of my research. Obviously, based on the above correlation, corresponding results in the research would be generated if the E3/ETSI approach architecture was adopted.

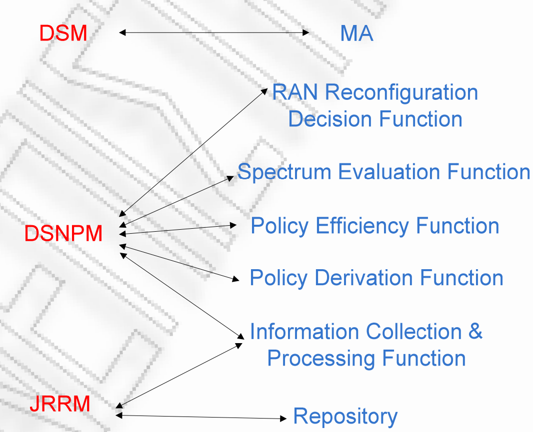

Figure 2-16: The correlation of the functional elements of the two architectures

Chapter 3

Information Flow between the NRM's functions, and NRM and the external entities

3.1 Reference Scenario for Information Flow Specification

In order to be depicted the information flow between the functions of the central management entity (NRM), and the information flow between NRM and the external entities (the MA as well as the managed entities - RANs and MTs), the scenario of operation of the proposed management architecture in the framework of a consortium of Network Operators, from the scenarios that was presented in section 2.3, is adopted, as the most general and most probable to be materialized. The information flow in realization of every other scenario, can easily be extracted from the corresponding defined information flow in this scenario, with alternation of a small number of details.

In this framework, we consider a consortium of p members, comprising the set of Network Operators NO.

3.2 Information flow from external entities to NRM

3.2.1 Information from Management Authority

Each member of the consortium $no_i \in NO$, $i = 1, 2 \ldots p$, reports the following elements to MA [59]:

- The set RAN_{no_i}, which consists of the Radio Access Networks (RANs), ran_j, $j = 1, 2 \ldots w$, that belong to no_i. Each ran_j of operator no_i consists of a number of operating elements with distinct operation.

- The set RAT_{no_i, ran_j} of the feasible operating RATs of each RAN $ran_j \in RAN_{no_i}$ ($RAT_{no_i, ran_j} \subseteq R$, where R is the set of all the different existent RATs). The feasible operating RATs of each RAN are determined by Network Operators, taking into consideration the existent reconfiguration capabilities of its network elements and the estimated cost of each possible reconfiguration. The set is reconsidered when a new RAT is introduced in the network of the no_i or there is alteration in the factors of its determination.

- The set of its licensed frequencies $F_{no_i} = F^b_{no_i} \cup F^d_{no_i}$, where $F^b_{no_i}$ contains the bound frequencies for proprietary usage by the no_i and $F^d_{no_i}$ contains the frequencies that are dispensed for spectrum sharing with the other members of the consortium.

- The Spectrum Usage Rights $SUR = \left\{ \left(f, r \right) \mid f \in F_{no_i}, r \in R \right\}$, which consist of the allowed operating RAT per frequency, for their licensed frequencies. Each frequency f may be available to more than one RATs. These rules are imposed by the relevant international and local official organizations/authorities.

From the corresponding aggregate information of all the NOs, MA extracts:

- The Spectrum Pool $SP = \sum_i F^{d}_{no_i}$, $i = 1, 2 ... p$, which is the sum of all NO's frequencies that are dispensed for collective usage from all the members of the consortium.

- The Allocation of frequencies of Spectrum Pool to RATs, $ASP = \{(f, r) \mid f \in SP, r \in R\}$, which is determined based on the Spectrum Usage Rights of the licensed frequencies of each NO, network management principles, pre-agreed rules among the network operators and the status and needs of the managed RANs.

MA sends to RAN Reconfiguration Decision Function the following information (that is derived by all the above information):

- For each ran_j, the possible operating RATs of the RAN, RAT_{no_i, ran_j} and the corresponding bound frequencies for these RATs, $f^{b}_{r} \in F^{b}_{no_i}$.

- The Allocation of frequencies of Spectrum Pool to RATs ASP.

- A set of rules, which constitute the framework for RAN Reconfiguration Decision Function's operation concerning the final allocation of frequencies to RANs (e.g. the period of time after which, a frequency band can be considered unused and be dispensed for secondary usage).

The operation of the MA in the framework of a consortium of three Network Operators (NO_1, NO_2, NO_3), two of which cooperate with other Service Providers (SP_a, SP_b, SP_c), is illustrated in Figure 3-1.

3.2.2 Information from RAN(s) to NRM

Each ran_j of operator no_i sends to NRM information for its status, containing information for its radio and transport capabilities, measurements, etc.

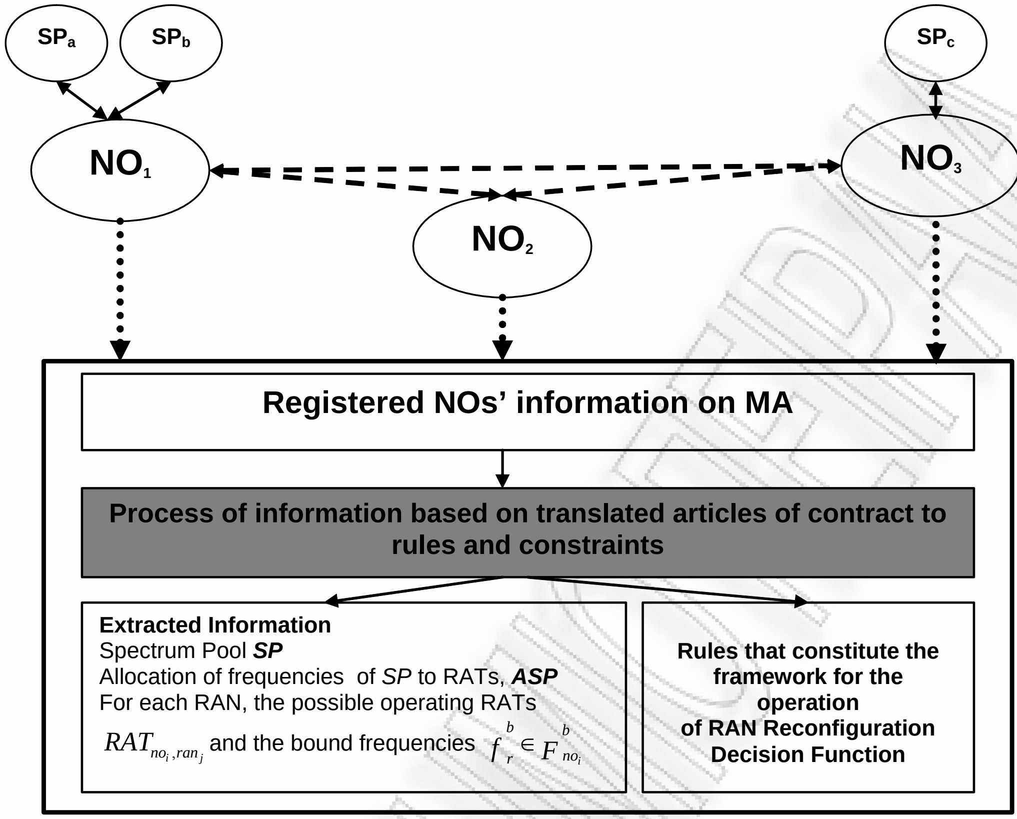

Figure 3-1: Operation of Management Authority

Large amount of information about RAN's status, collected from the operating elements and processed properly in order to depict a comprehensive illustration of it, requires considerable time, having as result to be already outdated when sent to NRM. Besides, large amount of information for a big number of RANs would encumber NRM's operation. For the aforementioned reasons, we consider that the information that is sent from RAN to NRM have to be both precise and concise. In this framework, the information that each ran_j of no_i sends to NRM comprises [59]:

- Its current configuration $c_{ran_j,no_i}^{cur} = \left\{ (r, f) \mid r \in RAT_{no_i,ran_j}, f \in \left(F_{no_i}^{b} \cup SP \right) \right\}$, namely the operating RAT in the corresponding frequencies.

- The set of its operating *AP*s, AP_{no_i,ran_j}, and specifically for each $ap_l \in AP_{no_i,ran_j}$ ($l = 1,2...L$, where L is the total number of *AP*s of ran_j of the Network Operator no_i):
  - Its operating frequency f_{ap_l} ,where $f_{ap_l} \in \left(F_{no_i}^{b} \cup SP\right)$.
  - The bandwidth allocated to uplink and downlink $\left(BW_{UL_{ap_l}}, BW_{DL_{ap_l}}\right)$.
  - Its geographical position given in x-y coordinates $\left(x_{ap_l}, y_{ap_l}\right)$.
  - Its coverage area CA_{ap_l} (as defined in section 2.3.1).
  - The current load $CL_{ap_l}\left(t_1\right)$ e.g. at time t_1. The current load of each *AP* is defined as the percentage of the aggregate current active users in relation with the possible maximum number of connected users, with specific minimum QoS level (the relevant minimum QoS level is definite for each service and is determined in the framework of the operation of the management system among the network operators).
  - The predicted load for the time period $Dt = \left(t_1, t_2\right]$, $PL_{ap_l}\left(Dt\right)$. The Predicted Load is defined as the percentage of the aggregate predicted connected users in relation with the possible maximum number of active users, with specific minimum QoS level.
  - Its Mean level of Signal Strength $mSINR_{ap_l}$, which is the Mean level of Signal Strength for all the connected terminals to it.
  - Its Aggregate Throughput AT_{ap_l}, which is defined as the sum of the throughputs of all the connected terminals.
  - Its Spectral Efficiency SE_{ap_l}. The Spectral Efficiency is the Aggregate Throughput of the connected terminals divided by the sum of the allocated bandwidth to uplink and downlink.

- The set of supported services, S_{no_i,ran_j}, and for each service $s_n \in S_{no_i,ran_j}$ ($n = 1, 2...N$, where N is the total number of supported services in ran_j of no_i) its corresponding QoS indicators $QoSI_{s_n}$ and cost C_{s_n}. Different costs C_{s_n}, which are estimated based on techno-economical factors, might be sent for different levels of QoS indicators. The supported QoS levels with corresponding costs are sent to users for their enlightenment, enabling the satisfaction of their wishes, if they are willing to pay for possible higher QoS, different from their SLA or their usual preferences. The QoS indicators may be different for each service, according to its special characteristics, and may include the mean bit-rate, the bit-rate variance, the mean and maximum bandwidth, the mean delay, the delay variance, mean error rate, etc. It is noted that a simple general classification of services, such as this of UMTS QoS classes (conversational, streaming, interactive, background), with common QoS Indicators for the services of the same class, would simplify the procedures for calculation of the relevant indicators.

- Its mobility mechanism mm_{no_i,ran_j}.

- Its authentication method am_{no_i,ran_j}.

- Its security mechanisms sm_{no_i,ran_j}.

- The spectrum holes $Sh_{no_i,ran_j,f}$ in terms of frequency ranges for specific geographical areas. For each frequency range, a minimum time frame T at which frequencies of this range are disposed for secondary usage and maybe the maximum power level $P_{SU,max}$, at which secondary MTs are permitted to transmit, are also declared.

This information is forwarded to NRM from each managed RAN:

- the first time of its operation,

- in periodic time intervals (that are determined from the NRM and may be altered according to the requirements of its operation),

- if there is alteration in the RAN's status,
- if it is asked by NRM.

The aggregate aforementioned information from all the managed RANs, is enough to ensure efficient operation of NRM and beneficial results for both network operators and users. Obviously, more data can be sent to NRM as indicators of RAN's status and criteria for its performance evaluation, for example Connection Setup Latency, if the number of the members of the consortium is rather small or the processing capability of the system is extremely large (as result of the way of materialization of the architecture), enabling the processing of the total information from NRM.

3.2.3 Information from MT(s) to NRM

The information that is sent from MT to NRM has to be sufficient to support NRM's functions but not excessively large, because the prerequisite operation of MT for procurement and processing, would burden its computational and power resources. Furthermore, significant augmentation of the information, such as detailed information about MT's hardware and software characteristics (e.g. device model and version, power consumption and power saving schemes, total size of memory, supported coding schemes) and the criteria that constitute the deciding factors of user's strategy, may lead to optimization of NRM's operation, regarding the definition of proper operating RAT and corresponding frequency for each RAN and the policy derivation for MTs, but simultaneously, it will considerably complicate the procedures and the computational approaches of these two functions. The comprehensive information for MT's status will be used for the determination of MT's behaviour in the framework of its own strategy, in its internal function.

The MT context information, which is sent via the current RAN with which the MT is connected, includes information for its status and its capabilities, location information, the requested services, measurements, user's preferences, etc. Specifically, the aforementioned information of MT m comprises [59]:

- Its Reconfiguration Capability RC_m. The parameter Reconfiguration Capability may have two values to express if the MT is reconfigurable or not, and allows NRM to estimate the demanded radio resources for legacy MTs in the managed RANs. This is important as, especially in the first period of 4th generation networks deployment, MTs of different kinds and generations will coexist. The effectuation mode of reconfigurability of MT (static, via different existent interfaces, or dynamic, via over the air software defined radio technology) is not information of the first mportance and is not sent to NRM.

- Its current Configuration $c_m = (r, f)$, in RAT $r \in R$ and frequency $f \in F$, where *R*, as presented in section 3.2.1, is the set of all the different existent RATs, and F is the sum of all NO's licenced frequencies ($\sum_i F_i$) plus the probable unlicensed frequencies that may also used by NOs (members and not members of the consortium). In case of MTs with multihoming capabilities (i.e. MTs that can maintain simultaneous different links via different RATs and/or frequencies), the configuration of each active interface *if*, $c_{m,if} = (r, f)$, is sent to NRM. It holds that $c_m \in C_m$, where C_m is the set of the total possible configurations in which MT *m* can operate, comprising both the alternative existent configurations and the possible prospective configurations with the assistance of software defined radio technology, if the MT is reconfigurable.

- Its Geographic Coordinates (longitude, latitude) at time point t $GC_m(t) = (lo, la)$.

- Its Priority of Communication pr, $pr \in P = \{0,1,...\}$, where P is the set of different grades of priority, which would constitute indispensable part of user's profile. Based on their Priority of Communication, specific MTs, which are used by professionals working in public safety services e.g. police forces, fire brigades, health services, and government agencies, will have priority over all the other MTs in situations of emergency and public safety.

- Its Mobility Profile $MP_m = (v, d, mvp)$, where v is the velocity, d is the direction and *mvp* is the moving pattern of the MT. The moving pattern *mvp* defines a specific behaviour of the MT, in terms of moving behaviour for specific recorded routes, in conjunction with information for user preferences. For example, a specific record of moving pattern in mobility profile can be the fact that the user travels by train going to her office every morning (definite track with known average speed and speed variance), and during the ride she reads her emails through the cheapest RAN, independently of the service data rate, and she downloads music files being connected to the RAN with the higher data rate and cost less in value than a specific price.

- The RAN ran_j with which, each interface *if* of MT has active link. In case of ad-hoc connection, the MT sends information for the neighbouring MT (e.g. an identification number for the MT or most probably its IP address, as 4th generation networks will be part of Future Internet, which will be an integrated global network that will consist of smaller interconnected networks [88]), with which has active link and employs it as relaying node.

- The measured level of Signal Strength for every active interface of MT $SINR_{m,if}$, as this reflects of SINR (Signal-to-Interference-plus-Noise Ratio).

- The requested service $s \in S_m$, where S_m is the set of services that can be requested by MT *m*. It holds that $S_m = S_{m_{sub}} \cup S_{m_{nsub}}$, where $S_{m_{sub}}$ is the set of services in which user subscribes in and $S_{m_{nsub}}$ is the set of services, of her network operator or co-operated network operators, which user can use without being a subscriber to them, and $S_m \subseteq S$ (S is the set of all the possible services).

- The demanded QoS level for each requested service s, which is comprised of a set of specific QoS Indicators $QoSI_s$. The values of the indicators may be constant, and constitute component of Service Level Agreement in user's subscription, or dynamically alterable and negotiable from both sides, user and network (in any case, the offered values from each network will always be upper from a specific level, different for each service and agreed between the network operators).

- The measured QoS level of each operative service s, which is comprised of a set of specific QoS Metrics $QoSM_s$. QoS Metrics illustrate the conditions in several communication layers, for example in physical layer by means of the physical rate or Bit Error Rate, in MAC sublayer by means of the access delay, in network layer by means of throughput or blocking probability, etc.

- The policy identification number pid, which has been taken into consideration for MT's current operation and behaviour.

This information may be sent to NRM, when the MT is switch on, in stable time-span, when there is alteration in any of them, or when it is asked from NRM. Other information can also be extracted by MT's measurements, according to NRM's demands, the contract of the user with her network operator and her personal preferences, and sent to NRM. It could be claimed, for example, from MTs, to send SINR measurements for all RANs in their vicinity (this is relatively easy, because MTs know the operating frequencies of these RANs from b-CR - as it will be presented in the sequel - and they simply have to switch to these frequencies, perform corresponding measurements and then switch to their preferred RAN in order to send the measurements to NRM). Furthermore, NRM can request feedback by the user herself, in settled interval of time, in order to assess user's perception for QoS, asking for example to mark the perception of specific services with a grade from 1 to 10.

Ii is noted that the operation of the management architecture under control of a network operator, would lead to extension of the presented information, because the total number of managed MTs and RANs is significant smaller than this in the previous case of the operation of NRM in the framework of a consortium, and respectively smaller is the requisite processing power. Consequently, information from user and terminal profile, such as user's preferences, MT's hardware and software capabilities and detailed handoff history records (for example, when she downloads movies –"service video on demand" – she always prefers to connect to the RAN with altogether the best QoS Indicators), could be sent to NRM. Moreover, in this case there is no restriction of the information that is announced to the external central management system, because of security reasons.

3.3 Information flow inside NRM (between NRM functions)

As already mentioned, the information that is sent from RANs and MTs to NRM, is collected from Information Collection & Processing Function, which extracts the suitable information in proper format, in order to support the operation of the associated functions [59]. Specifically, Information Collection & Processing Function uses the Geographic Coordinates $GC_m(t)$ and the Mobility Profile MP_m of MTs, plus the geographical positions of the operating *AP*s, in the process of estimation of the most probable meshes, in which each MT will be in time frame $\Delta t = [t_a, t_b]$. Approaches for relative estimations have already been developed [89][90]. From the estimated position of MTs in relation to meshes, Information Collection & Processing Function computes the probable population of each $mesh_k$ for the specific time frame Δt, $POP_{meshk,\Delta t}$.

For the probable population $POP_{meshk,\Delta t}$ of $mesh_k$ for the specific time frame Δt, Information Collection & Processing Function estimates:

- The distribution of MTs to RANs $dn_{meshk,\Delta t}(RAN)$, from the RANs with which MTs have active links.
- The distribution of all active links of MTs to RATs and corresponding operating frequencies $dc_{meshk,\Delta t}(r, f)$, from configuration of MTs c_m.
- The probable population of reconfigurable MTs $RPOP_{meshk,\Delta t}$ and the probable population of non-reconfigurable MTs $nRPOP_{meshk,\Delta t}$, from Reconfiguration capability of MTs RC_m.

- The distribution of MTs to different values of Priority $dp_{meshk,\Delta t}\left(pr\right)$, from Priority of Communication values pr.

- For each service *s*:

  - the distribution of applicant MTs to demanded QoS Levels $dqd_{s,meshk,\Delta t}\left(QoSI_{s}\right)$, and

  - the distribution of active MTs to measured QoS Levels $dqm_{s,meshk,\Delta t}\left(QoSM_{s}\right)$,

  from QoS Indicators $QoSI_s$ and QoS Metrics $QoSM_s$, respectively.

For each ran_j, for the specific time frame Δt, Information Collection & Processing Function estimates:

- The population of non-reconfigurable MTs $nRPOP_{ran_j}$, from identification indicator of RANs with which MTs are connected and reconfiguration capability of MTs RC_m.

- The distribution of MTs to measured QoS Levels $dqml_{sn,RAN,\Delta t}\left(QoSM_{sn}\right)$ for each service s_n.

The aforementioned computed information in Information Collection & Processing Function, after the derivation of meshes, which is forwarded to NRM's functions is depicted in Figure 3-2.

The above information is the minimum information that ensures efficient operation of the management architecture. More calculations maybe accomplished in order to assess the networks' status, according to management system strategy. Furthermore, the time frame Δt is variable and its determination depends on the implementation of the FA. For example, if the FA operates in a radio environment that is characterized by periods of relatively high variability, the NRM will demand high frequency of provided measurements from RANs and MTs in these periods, and will shorten the time frame Δt for which Information Collection & Processing Function calculates the aforementioned information, in order the relevant estimations to coincide with the real networks' conditions. Consequently, new information is forwarded more frequently to other functions, which proceed to relative actions with higher frequency correspondingly.

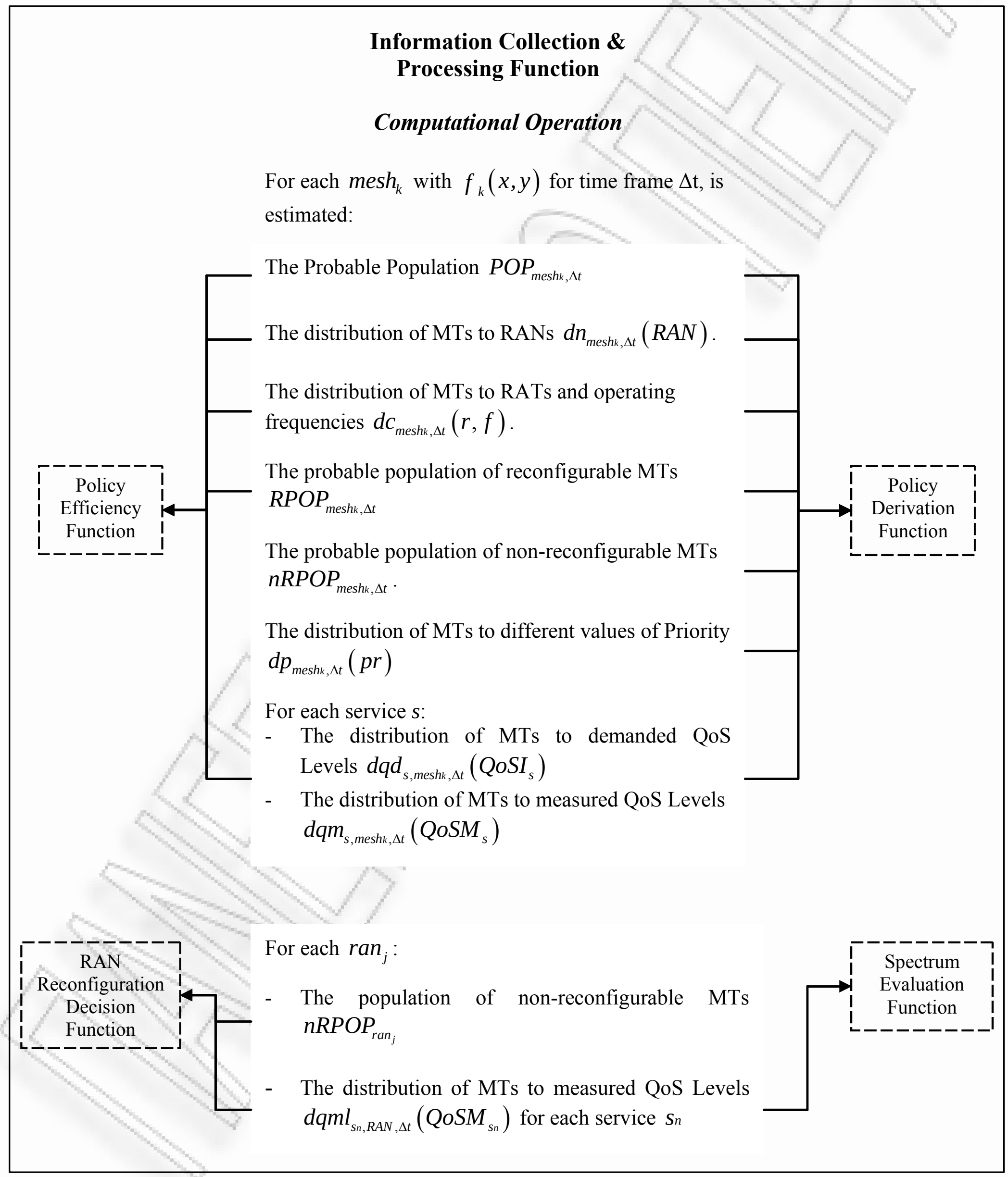

Figure 3-2: Computed information in Information Collection and Processing Function after derivation of meshes

The proper collected and calculated information in Information Collection & Processing Function is forwarded to each function, according to its operation. So, the forwarded information to Policy Derivation Function is represented in Table 3-1, and correspondingly, to Policy Efficiency Function in Table 3-2, to RAN Reconfiguration Decision Function in Table 3-3, to Context Repository Table 3-4 and to Spectrum Evaluation Function in Table 3-5.

$f_k(x,y)$	The geographical coordinates of each $mesh_k$
For each RAN ran_j of each no_i of $mesh_k$:	
$CL_{ap_l}(t_1)$	The current load at time t1 for its operating *AP*s ap_l in $mesh_k$
$PL_{ap_l}(Dt)$	The predicted load for time period $Dt=(t_1,t_2]$ for its operating *AP*s ap_l in $mesh_k$
$mSINR_{ap_l}$	The Mean level of Signal Strength for its operating *AP*s ap_l in $mesh_k$
AT_{ap_l}	The Aggregate Throughput for its operating *AP*s ap_l in $mesh_k$
For each $mesh_k$ for a specific time frame Δt ($\Delta t \subseteq Dt$):	
$POP_{mesh_k,\Delta t}$	The probable population of MTs.
$RPOP_{mesh_k,\Delta t}$	The probable population of reconfigurable MTs.
$nRPOP_{mesh_k,\Delta t}$	The probable population of non-reconfigurable MTs.
$dn_{mesh_k,\Delta t}(RAN)$	The distribution of MTs to RANs.
$dc_{mesh_k,\Delta t}(r,f)$	The distribution of MTs to RATs and corresponding operating frequencies.
$dp_{mesh_k,\Delta t}(pr)$	The distribution of MTs to different values of Priority.
$dqd_{s,mesh_k,\Delta t}(QoSI_s)$	The distribution of MTs to demanded QoS Levels for service *s*
$dqm_{s,mesh_k,\Delta t}(QoSM_s)$	The distribution of MTs to measured QoS Levels for service *s*

Table 3-1: Forwarded Information from Information Collection and Processing Function to Policy Derivation Function

It is noted that the data that will be included in b-CR and e-CR respectively, depend on the amount of information that can be transmitted to MTs from CR, as more data amounts to more demanded bandwidth for transmission. Therefore, the way of materialization of radio enabler is the key issue in determination of the exact content of b-CR and e-CR.

Furthermore, the way of utilization of the information that is forwarded to NRM's functions, depends on the strategy in the framework of which the management architecture operates and which has determined from its operator(s), as well as the mode that this strategy is reflected to specific procedures and methods.

For each RAN ran_j of each no_i of $mesh_k$:	
$CL_{ap_l}(t_1)$	The current load at time t1 for its operating APs ap_l in $mesh_k$
$PL_{ap_l}(Dt)$	The predicted load for time period $Dt=(t_1,t_2]$ for its operating APs ap_l in $mesh_k$
s_n	The supported service
$QoSI_{s_n}$	The QoS indicators of service s_n
C_{s_n}	The costs of service s_n
For each $mesh_k$ for a specific time frame Δt ($\Delta t \subseteq Dt$):	
$POP_{mesh_k,\Delta t}$	The probable population of MTs
$dn_{mesh_k,\Delta t}(RAN)$	The distribution of MTs to RANs
$dc_{mesh_k,\Delta t}(r,f)$	The distribution of MTs to RATs and corresponding operating frequencies.
$RPOP_{mesh_k,\Delta t}$	The probable population of reconfigurable MTs
$nRPOP_{mesh_k,\Delta t}$	The probable population of non-reconfigurable MTs
pid	The policy identification number of the policies that the populated MTs of $mesh_k$ have taken into account for their behavior
$dqd_{s,mesh_k,\Delta t}(QoSI_s)$	The distribution of MTs to demanded QoS Levels for service *s*
$dqm_{s,mesh_k,\Delta t}(QoSM_s)$	The distribution of MTs to measured QoS Levels for service *s*

Table 3-2: Forwarded Information from Information Collection and Processing Function to Policy Efficiency Function

For each ran_j of no_i:	
$c^{cur}_{ran_j,no_i}$	The current configuration
f_{ap_l}	The operating frequency f_{ap_l} of its operating APs ap_l
$\left(x_{ap_l}, y_{ap_l}\right)$	The geographical position of its operating APs ap_l
CA_{ap_l}	The coverage area CA_{ap_l} of its operating APs ap_l
$CL_{ap_l}\left(t_1\right)$	The current load at time t1 for its operating APs ap_l
$PL_{ap_l}\left(Dt\right)$	The predicted load for time period $Dt=\left(t_1,t_2\right]$ for its operating APs ap_l
$mSINR_{ap_l}$	The Mean level of Signal Strength for its operating APs ap_l
AT_{ap_l}	The Aggregate Throughput for its operating APs ap_l
SE_{ap_l}	The Spectral Efficiency for its operating APs ap_l
s_n	The supported services
$QoSI_{s_n}$	The QoS indicators of service s_n
$\left[Sh_{no_i,ran_j,f}, T, P_{SU,max}\right]$	The spectrum holes $Sh_{no_i,ran_j,f}$, with the corresponding minimum time frame of frequencies dispensation T and maximum power level $P_{SU,max}$, for specific geographical areas
$nRPOP_{ran_j}$	The population of non-reconfigurable MTs
$dqml_{s_n,RAN,\Delta t}\left(QoSM_{s_n}\right)$	The distribution of MTs to measured QoS Levels for service s_n
$\left[GC_m\left(t\right), SINR_{m,if}\right]$	The pair of geographic coordinates and the Signal-to-Interference-plus-Noise Ratio for the connected MTs m

Table 3-3: Forwarded Information from Information Collection and Processing Function to RAN Reconfiguration Decision Function

For example, in an approach of the optimization problem in RAN Reconfiguration Decision Function, the "state" of each ran_j may be characterized as "satisfactory", "unsatisfactory", "dangerous" or "congested", based on the current load $CL_{ap_l}\left(t_1\right)$, the predicted load $PL_{ap_l}\left(Dt\right)$ and the distribution of MTs to measured QoS Levels $dqm_{s,mesh_k,\Delta t}\left(QoSM_s\right)$ for each service s. For example, the "state" of a RAN may be characterized a) as “satisfactory” if the current and predicted load is under a specific threshold, and for each service the 75% of the users are experienced the highest QoS level, b) as “unsatisfactory” if the current and predicted load is under the specific threshold and for each service the 50% of the users are experienced the highest QoS level, c) as “congested” if the current and predicted load is near the specific threshold independently from the percentage of users that experience the highest QoS level and d) as “dangerous” if the current load is near the threshold and the predicted load is higher from the threshold. The different states may activate different actions and procedures. The limits between the above states and the relevant actions and procedures, which will comprise a point of negotiation among the members of the consortium, will be definitely prescribed and may change according the conditions.

$f_k(x,y)$	The geographical coordinates of each $mesh_k$
For each RAN ran_j of each no_i of $mesh_k$:	
$c^{cur}_{ran_j,no_i}$	The current configuration
s_n	The supported service
$QoSI_{s_n}$	The QoS indicators of service s_n
C_{s_n}	The costs of service s_n
mm_{no_i,ran_j}	The mobility mechanism.
am_{no_i,ran_j}	The authentication method
sm_{no_i,ran_j}	The security mechanisms
$\left[Sh_{no_i,ran_j,f},T,P_{SU,max}\right]$	The spectrum holes $Sh_{no_i,ran_j,f}$ with the corresponding minimum time frame of frequencies dispensation T and maximum power level $P_{SU,max}$, for specific geographical areas

Table 3-4: Forwarded Information from Information Collection and Processing Function to Context Repository

For each ran_j of each no_i :	
$c^{cur}_{ran_j,no_i}$	The current configuration
$CL_{ap_l}(t_1)$	The current load at time t1 for its operating *AP*s ap_l
$PL_{ap_l}(Dt)$	The predicted load for time period $Dt = (t_1, t_2]$ for its operating *AP*s ap_l
$dqm_{s,meshk,\Delta t}(QoSM_s)$	The distribution of MTs to measured QoS Levels for each service s

Table 3-5: Forwarded Information from Information Collection and Processing Function to Spectrum Evaluation Function

3.4 Information flow from NRM to external entities

3.4.1 Information from NRM to Management Authority

NRM, namely Spectrum Evaluation Function, sends to MA evaluation results for the efficiency of frequencies allocation to specific RATs, in periodic time intervals (which are altered according the conditions of the managed RANs) and whenever the evaluation procedure indicates that there is necessity for re-allocation of the available frequencies. The information that is sent to MA may comprise the status of each RAN in regard of traffic load. Namely, based on the information sent from Information Collection and Processing Function, Spectrum Evaluation Function, for the existent configuration of each ran_j, and for time period T_{ev} ($\Delta t \subseteq Dt \subset T_{ev}$), may extract the Percentage of its *AP*s $Plap_{ranj}$ of which the load is under a specific threshold lth and the Percentage of its *AP*s $Phap_{ranj}$ of which the load is over a specific threshold hth, and send them to MA, along with instances of the distribution of MTs to measured QoS Levels for each service s during the time period T_{ev}. The aforementioned evaluation results are proposed as metrics for spectrum evaluation, but the exact type of evaluation results will be determined from the cooperated network operators, in case of operation of the management architecture in the framework of a consortium, or from the independent organization that operates the central management sytem in regional or national level, after deliberations with all the network operators.

3.4.2 Information from NRM to RAN(s)

NRM sends to managed RANs reconfiguration decisions in terms of operating frequencies, RAT or both, when it is necessitated for the optimization of their operation and of the overall managed system. When the operation of RAN Reconfiguration Decision Function results in reconfiguration decision for some of the managed RANs, these RANs are informed with a reconfiguration command which may have the form:

{rcid= x

ran_j **Reconfigure to** (r, f) **in Time Period** $\left[t_{i-1}, t_i\right]$**}**

In this example of reconfiguration command with identification number rcid equal to x, the ran_j of operator no_i is commanded to reconfigure its elements in RAT $r \in RAT_{noi,\, ranj}$ and corresponding frequency $f \in \left(F^{b}_{no_i} \cup SP\right)$ in a time frame $\left[t_{i-1}, t_i\right]$, $i \in N$. After the successive implementation of the reconfiguration procedure, ran_j informs RAN Reconfiguration Decision Function about it, which forwards the new status of ran_j to Policy Derivation Function, in order to derive new policies for the MTs (this information is also included in the information that Policy Derivation Function gets from Information Collection and Processing Function. The surplus forwarding of information aims at expediting and facilitating the derivation of new policies).

If in time $t_{conf} \geq t_i$, RAN Reconfiguration Function has not received confirmation for reconfiguration from the corresponding RAN, it requests from the RAN enlightenment for the reasons that prevented the reconfiguration' execution, and accordingly with the response proceeds to suitable actions e.g. re-execution of allocation algorithm with new input data.

3.4.3 Information from NRM to MT(s)

The information that is sent from NRM to MTs is included in Repository. As presented, CR segment of Repository, which is split in b-CR and e-CR, maintains information for the MT's RAN context, which is provided by Information Collection and Processing Function. PR segment is respectively split into b-PR and e-PR, and maintains the policies, which are derived and provided by Policy Derivation Function.

More analytically, b-CR includes the basic information of networks in the vicinity of MTs, such as the specific RANs with their operating RAT, frequency, authentication method, security mechanisms and the Network Operator (NO) in which they belong to, plus frequency bands available for secondary usage, for MT's assistance in initial RAN selection. The authentication method is important because MTs should already have the necessary credentials in order to connect when powered on. The security mechanism may also be important for the user, according to the demanded service (for instance, for applications like e-banking, the user may prefer to be connected to the RAN with the most advanced and stringent security framework). That is to say, the information may have the form:

$$for\ mesh_k,\ [mesh_k\ with\ f_k(x,y)\ ]$$

$$\left[no_j, ran_m, rat_{no_j,ran_m}, f_m, am_{no_j,ran_m}, SU\ f_m, sm_{no_j,ran_m}\right]$$

$$\left[no_j, ran_n, rat_{no_j,ran_n}, f_n, am_{no_j,ran_n}, SU\ f_n, sm_{no_j,ran_n}\right]$$

$$\left[no_k, ran_l, rat_{no_k,ran_l}, f_l, am_{no_k,ran_l}, SU\ f_l, sm_{no_k,ran_l}\right]$$

where, for example in $mesh_k$, which covers the area with geographical coordinates stated by $f_k(x,y)$, the network operator no_j operates two RANs ran_m and ran_n with corresponding RATs $rat_{no_j,ran_m} \in RAT_{no_j,ran_m}$ and $rat_{no_j,ran_n} \in RAT_{no_j,ran_n}$ in operating frequencies f_m and f_n, authentication methods $am_{noj,ranm}$ and $am_{noj,rann}$, available frequencies for secondary usage SU_{f_m} and SU_{f_n} and security mechanisms $sm_{noj,ranm}$ and $sm_{noj,rann}$. It holds that $SU_{f_m} \subseteq Sh_{noj,ran_m,f}$ and $SU_{f_n} \subseteq Sh_{noj,ran_n,f}$.

e-CR includes more detailed information for the managed RANs, in order MTs to select the appropriate RAN for their needs. Therefore e-CR comprises information such as the supported QoS levels per service for each RAN and corresponding cost. Moreover, an important feature of each RAN, which is included in e-CR, is its mobility mechanisms. This information is taken under consideration by MTs, as a significant factor for handover decision. For example, MIP mobility mechanisms fit with connection oriented applications, such as TCP applications, whereas SIP mobility mechanisms fit with connectionless applications, such as UDP applications. Namely, the information that is sent from e-CR to MTs may have the form:

$for\ mesh_k$

$\{ran_m,$

$[s_x(QOS\,\mathrm{I}_{sx}, c_x)]$

$[mm_{noj,ranm}]\}$

$\{ran_n,$

$[s_y(QOS\,\mathrm{I}_{sy}, c_y)]$

$[s_z(QOS\,\mathrm{I}_{sz}, c_z)]$

$[mm_{noj,rann}]\}$

$\{ran_l,$

$[s_a(QOS\,\mathrm{I}_{sa}, c_a)]$

$[s_b(QOS\,\mathrm{I}_{sb}, c_b)]$

$[mm_{nok,ranl}]\}$

where, for example in $mesh_k$, ran_n provides services s_y and s_z with corresponding QoS Indicators $QOSI_{sy}$ and $QOSI_{sz}$, and costs c_y and c_z respectively and supports mm_{noj,ran_n} mobility mechanism in vertical handover procedure. The geographical coordinates $f_k(x,y)$ of $mesh_k$ and the network operator no_j, that operates ran_n are already known to MTs from the information that is sent from b-CR.

On the other hand, the PR segment of repository refers to policies that are sent from NRM to MTs. As it was presented, b-PR includes the most important policies that are used by MTs in order to accomplish their initial RAN selection and e-PR includes policies of less importance, which may have more parameters relatively to the policies that are included in b-PR, used for optimizing the final selection of RAN by MTs. A general example of policy of b-PR is displayed in Table 3-6, where in policy with identification number (pid) x and Grade of Obligation y, is suggested to MTs in with priority *pr* in time period $(t_{i-1},t_i), i \in N$, to select ran_j as first choice for operating RAN, ran_m as second choice etc. In critical situations, access of all MTs to any RAN may be prohibited, as it is depicted in the corresponding example in Table 3-6. Two examples of e-PR policies are displayed in Table 3-7. In the second example, in policy for secondary spectrum usage with identification number (pid) e.g. equal to x and Grade of Obligation e.g. equal to y, it is suggested to MTs in $mesh_k$ with priority *pr* in time period $(t_{i-1},t_i), i \in N$, which are interested for *service s,* to use frequency SU_f, which is available in this area for secondary usage, with Power Transmission $P_t \leq P_{SU_f,max} . mesh_k$.

From the above structure of the policies, as well as the policy derivation procedures that presented in Section 2.3.2, it is obvious that the adoption of a localization method which provides also time awareness to MTs would be very helpful, as it would assist a common time adoption from the MTs.

Structure of Policies of b-PR	
General Policy	Policy for Critical Situations
pid x with GoO = = y **IF** { *mesh*$_k$ **AND** [*priority==pr*] **AND** [*TimePeriod==* (t_{i-1}, t_i)]} **THEN** {*1= ran*$_j$ *,2= ran*$_m$ *, 3= ran*$_n$ …}	**pid x with GoO = = 1** **IF** { *mesh*$_k$ **AND** [*priority==any*] **AND** [*Time Period==* (t_{i-1}, t_i)] } **THEN** *No Access*

Table 3-6: Examples of structure of policies of b-PR

Structure of Policies of e-PR	
General Policy	Policy for Spectrum Secondary Usage
pid x with GoO = = y **IF** { *mesh*$_k$ **AND** [*priority==pr*] **AND** [*TimePeriod==* (t_{i-1}, t_i)] **AND** [*service ==s*] } **THEN** {*1= ran*$_j$ *,2= ran*$_m$ *, 3= ran*$_n$ …}	**pid x with GoO = = y** **IF** { *mesh*$_k$ **AND** [*priority==pr*] **AND** [*TimePeriod==* (t_{i-1}, t_i)] **AND** [*service ==s*] } **THEN** SU_f with $P_{SU_f,max}$ }

Table 3-7: Examples of structure of policies of e-PR

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΑ

Chapter 4

Interfaces between NRM and RAN(s) and NRM and MT(s)

4.1 Introduction

Each communication between NRM and RAN(s)/MT(s) can be considered as part of a procedure, and the total of the procedures comprises the corresponding interfaces. The procedures consist of definite messages. The description of the messages that are exchanged in the interfaces between NRM and the managed RANs, as well as the connected MTs, is of extremely importance, as it constitutes an essential step for the implementation of the architecture. In this framework, this chapter presents the determination of the included basic parameters, the specification of the structure of these messages in terms of elementary procedures, and the estimation of the anticipated length of the messages.

The physical entities that are involved in the information interchange between NRM and RAN(s)/MT(s) (as well as among NRM functions), depend on the mode of implementation of the architecture. The way of materialization of NRM is determined by the framework of its operation and the strategy of the network operator(s) of the managed RANs (in the sequel of this chapter, the network operators of the managed RANs by NRM, are just called operators). NRM may be materialised in a fully centralised way or in hybrid way (especially in the operation of the management architecture under the control of one operator), where some operations of NRM may be effectuated in different physical entities. For reasons of generality, and as the abovementioned different implementations do not affect the transmitted information between RANs/MTs and NRM, we consider that NRM is materialised in a fully centralised way.

The messages between NRM and RANs/MTs consist of the presented information in the previous chapter. In order to be enabled the independency of the messages from the transmitted method that it will be selected from the operator(s), it is necessitated a clear specification of the information type that is contained in the relevant messages. Abstract Syntax Notation One (ASN.1) was selected for this role, among others corresponding choices (for example [91]). ASN.1 is a notation "for defining the syntax of information data. It defines a number of simple data types and specifies a notation for referencing these types and for specifying values of these types" [92]. Specifically, "a data type (or type for short) is a category of information (for example, numeric, textual, still image or video information)", "a data value (or value for short) is an instance of such a type", and ASN.1 "defines several basic types and their corresponding values, and rules for combining them into more complex types and values" [92]. ASN.1, except of the potentiality of describing the data type of the exchanged information (which is known with the term "abstract syntax"), enables the precise transformation of the formatted data into bit-stream, prior to being transmitted into the network. Specifically, "ASN.1 is supplemented by the specification of one or more algorithms called encoding rules that determine the value of the octets that carry the application semantics (called the transfer syntax). ITU-T Rec. X.690 | ISO/IEC 8825-1, ITU-T Rec. X.691 | ISO/IEC 8825-2 and ITU-T Rec. X.693 |ISO/IEC 8825-4 specify three families of standardized encoding rules, called Basic Encoding Rules (BER), Packed Encoding Rules (PER), and XML Encoding Rules (XER)" respectively [92].

In this context, ASN.1 enables the representation of the format and type of the exchanged information between the entities, without reference to the transmitted method, the programming language, the operating system of the entities, etc. This independence facilates the implementation of the presented functions of the management architecture that pertain to communication with RANs and MTs via different technologies (subject which will be decided based on technoeconomical critera by the network operators), as well as the determination of the information exchange protocols (legacy or new specified) for the transmittion of the corresponding information between the involved entities.

From the aforementioned standardized encoding rules, namely Basic Encoding Rules (BER) [93], Packed Encoding Rules (PER) [94], and XML Encoding Rules (XER) [95], the Basic Encoding Rules were selected for the calculations of the anticipated value of the messages. BER were adopted, as they constitute a simple but simultaneously powerful tool, which enable high degree of flexibility.

4.2 Data type specification of messages' parameters

The specification of the type of each of the parameters, which are included in the messages exchanged in the interfaces between NRM and RAN(s)/MT(s), in ASN.1, is based on their presumable value, according to their definition in the previous chapter.

The INTEGER type in ASN.1 stands for any positive or negative integer, whatever its length, namely the set Z in mathematics [96]. In this context, as INTEGER type are defined the parameters that are presented in Table 4-1.

The BOOLEAN type have two possible values, which are TRUE and FALSE. The BOOLEAN type was selected for the essential parameter "reconfigurationCapability". As it was defined in paragraph 3.2.3, the parameter "reconfigurationCapability" may have two values to express if the MT is reconfigurable or not. In this framework, existent reconfiguration capability of a MT can be represented with the value TRUE and the absence of this capability can be represented with the value FALSE. Furthermore, the BOOLEAN type was selected for the parameter "ok" of the Acknowledgement messages. The selection of the BOOLEAN type, instead of the common usage of null type for this kind of messages, provides an accessional confirmation of the correct receipt of the content of the message.

The REAL type in ASN.1 stands for any real number. So, as REAL type are defined the parameters that are presented in Table 4-2.

The character string types in ASN.1 consist of strings of characters from some specified character repertoire [92]. The characters that can appear in the PrintableString type comprise latin capital letters (A, B, ... Z), latin small letters (a, b, ... z), digits (0, 1, ... 9), space, apostrophe ('), left parenthesis (**(**), right parenthesis (**)**), plus sign (+), comma (,), hyphen-minus (-), full stop (.), solidus (/), colon (:), equals sign (=) and question mark (?). The parameters that are defined as PrintableString type are presented in Table 4-3.

Parameters of INTEGER type	
RanId	Identification number of RAN
XxxFreq	Frequency (which is differentiated form the other frequencies in the same message by the characters “xxx”)
secondsTimeFrameValidity	Duration in seconds of minimum time frame of frequencies dispensation for secondary usage
secondsTimePeriod	Duration in seconds of time period of valid predicted load of specific *AP*
accessPointId	Identification number of *AP*
secDurationReconfigurationTimeFrame	Duration of time frame in seconds for execution of specific reconfiguration action
ErrorCode	Code of error
connectedRanId	Identification number of the RAN with which an interface of a MT has active link
Pid	Policy Identification number
GoO	Grade of Obligation
secDurationTimePeriod	Duration in seconds of the time period in which a specific policy is valid
Priority	Priority of Communication

Table 4-1: Messages’ Parameters of INTEGER type

Parameters of REAL type	
maximumPowerLevel	The maximum power level at which secondary MTs are permitted to transmit
xGeograpicalCoordinate	x coordinate of a geographical position
yGeograpicalCoordinate	y coordinate of a geographical position
currentLoad	The current load of an *AP*
predictedLoadValue	The predicted load of an *AP* for definite time period
meanSignalStrength	The Mean level of Signal Strength of an *AP*
aggregatedThroughput	The Aggregate Throughput of an *AP*
spectralEfficiency	The Spectral Efficiency of an *AP*
signalStrength	The Signal Strength for the active interface of a MT

Table 4-2: Messages' Parameters of REAL type

It is noted that for *AP*'s Coverage Area and mesh's determination, PrintableString type was selected for their representation, because from their definition (that it was presented in Chapter 2), they both most likely have random shape, so the mathematical function that is used for their description is different for each case. The same applies to parameter "geographicalArea" that determines a specific area, where is permitted the secondary usage of definite frequencies.

For specification of time, the GeneralizedTime type was selected. GeneralizedTime type enables the representation of time by means of a character string conforming to OSI standard [97]. Specifically, a value of type GeneralizedTime consists of the calendar date with four digits for the year, two for the month and two for the day, and the time with an hour, minute or second precision (or even fractions of a second). Furthermore, the GeneralizedTime type enables the indication of a possible time lag. Namely, the letter `Z' after the digits for time denotes the universal time coordinate (UTC), otherwise, the time digits are followed by a positive or negative time lag, which expresses in hours and minutes whether it is ahead or behind the universal time coordinate [96]. The parameters of time, which are defined as GeneralizedTime type, are presented in Table 4-4.

Parameters of PrintableString type	
NetworkOperator	Network Operator's name
mobilityMechanism	RAN's mobility mechanism
authenticationMethod	RAN's authentication method
securityMechanisms	RAN's security mechanisms
OperatingRAT	RAN's operating RAT
CoverageArea	*AP*'s Coverage Area
GeographicalArea	Geographical Area where is permitted secondary spectrum usage
mobileTerminlalId	MT's Identity
MobilityProfile	MT's Mobility Profile
Mesh	Mesh's determination
XxxService	Name of a service (the label of the service, for example "supported" for a RAN and "demanded" from a MT, is determined from the characters "xxx")
xxxServiceQoSIndicators	QoS indicators of each specific service
XxxServiceCost	Cost for each specific service
ErrorDescrition	Description of specific error

Table 4-3: Messages' Parameters of PrintableString type

<table>
<tr><th colspan="2">Parameters of GeneralizedTime type</th></tr>
<tr><td>Time</td><td>Time instance</td></tr>
<tr><td>timeFrameValidityInitiation</td><td rowspan="2">Initiation and expiration time of the determined time frame for which specific information is valid</td></tr>
<tr><td>timeFrameValidityExpiration</td></tr>
<tr><td>timePeriodInitiation</td><td rowspan="2">Initiation and expiration time of a determined time period</td></tr>
<tr><td>timePeriodExpiration</td></tr>
<tr><td>reconfigurationTimeFrameInitiation</td><td rowspan="2">Initiation and expiration time of the determined time frame for a reconfiguration procedure</td></tr>
<tr><td>reconfigurationTimeFrameExpiration</td></tr>
</table>

Table 4-4: Messages' Parameters of GeneralizedTime type

4.3 Procedures of the interface between NRM and RAN

4.3.1 Procedure RAN Context & Configuration Information Provision

The Procedure **RAN Context & Configuration Information Provision** consists of the *Context&ConfigurationNotification* message that is sent from RANs to NRM and *Context&ConfigurationNotificationAck* message that is sent conversely. The messages are depicted in Table 4-5. The transmission of *Context&ConfigurationNotification* message is effected by each RAN the first time of its operation, in periodic time intervals and if there is alteration in RAN's status. The information that is included in the procedure, as it was presented in Chapter 3, may be extended, according to the framework of the operation of the management architecture. The transmission of *Context&ConfigurationNotificationAck* message is not compulsory. The final decision for its transmission is made by the operator(s) of NRM, and it might be different for each situation. For example, it may be decided that *Context& ConfigurationNotificationAck* message is transmitted only when the *Context&ConfigurationNotification* message is sent from the RAN thereupon the initiation of its operation.

RAN Context & Configuration Information Provision	
Message	**Content Parameters**

Context & Configuration Notification (RAN→ NRM)	**networkOperator** :: = PrintableString
	time ::= GeneralizedTime
	ranGenericInfo :: = SEQUENCE {
	ranlId INTEGER,
	operatingRAT PrintableString,
	operatingFrequency SEQUENCE {
	lowFreq INTEGER,
	highFreq INTEGER },
	supportedServices SEQUENCE OF PrintableString,
	SupportedServicesQoSindicators
	SEQUENCE OF PrintableString,
	SupportedServicesCosts
	SEQUENCE OF PrintableString,
	mobilityMechanism PrintableString,
	authenticationMethod PrintableString,
	securityMechanisms PrintableString}
	spectrumHolesInfo:: = SEQUENCE OF SEQUENCE {
	frequencyRange SEQUENCE {

	lowFreq INTEGER,
	highFreq INTEGER},
	geographicalArea PrintableString,
	timeFrameValidityInitiation GeneralizedTime,
	timeFrameValidityExpiration GeneralizedTime,
	secondsTimeFrameValidity INTEGER OPTIONAL,
	maximumPowerLevel REAL}}
	accessPointsInfo :: = SEQUENCE OF SEQUENCE {
	accessPointId INTEGER,
	uplinkBandwidth SEQUENCE {
	lowFreq INTEGER,
	highFreq INTEGER },
	downlinkBandwidth SEQUENCE {
	lowFreq INTEGER,
	highFreq INTEGER },
	xGeograpicalCoordinate REAL,
	yGeograpicalCoordinate REAL,
	coverageArea PrintableString,
	currentLoad REAL,
	predictedLoad SEQUENCE {
	predictedLoadValue REAL,
	timePeriodInitiation GeneralizedTime,
	timePeriodExpiration GeneralizedTime,
	secondsTimePeriod INTEGER OPTIONAL},
	meanSignalStrength REAL,
	aggregatedThroughput REAL,
	spectralEfficiency REAL }

Context & Configuration Notification Ack
(NRM→ RAN)
	networkOperator :: = PrintableString
	ranlId :: = INTEGER
	resultType ::= CHOICE {
	ok BOOLEAN,
	nok SEQUENCE {
	errorCode INTEGER OPTIONAL
	errorDescrition PrintableString }}

Table 4-5: Procedure **RAN Context & Configuration Information Provision**

The Content Parameters of *Context&ConfigurationNotification* message include the information presented in paragraph 3.2.2. This information is shaped into the types that were determined in the previous paragraph. Specifically, in *Context& ConfigurationNotification* message, the RAN with identification number “ranId” of the network operator “networkOperator”, sends the determined information, consisting of generic information for the RAN (“ranGenericInfo”), information for its

*AP*s (“accessPointsInfo”) and particular information for secondary spectrum usage (“spectrumHolesInfo”).

In “ranGenericInfo**”,** the operating frequency of the RAN is prescribed as a sequence that contains the lower and the higher level of the operating frequency.

The content parameter “spectrumHolesInfo**”** is stated as a sequence of sequences. The sequence types are “types defined by referencing a fixed, ordered list of types (some of which may be declared to be optional); each value of the sequence type is an ordered list of values, one from each component type” and sequence-of types are “types defined by referencing a single component type; each value in the sequence-of type is an ordered list of zero, one or more values of the component type” [92]. Namely, the SEQUENCE OF type is equivalent to dynamic arrays, where all the elements are of the same type but the number of the elements is not necessarily known beforehand [96]. In this case, each sequence of the sequences contains the relevant definite information for a specific set of frequency range and geographical area. Furthermore, for the determination of the minimum time frame at which frequencies of this range are disposed for secondary usage, it is stated the instance of the initiation of the time frame (“timeFrameValidityInitiation”), the instance of the expiration of the time frame (“timeFrameValidityExpiration”), as well as the duration of the time frame in seconds (“secondsTimeFrameValidity”). The duration of the time frame is surplus information, which is not mandatory, and may be used for verification of the precision of this determinant information element. For this reason, the last parameter “secondsTimeFrameValidity” is stated as OPTIONAL. The term “OPTIONAL” indicates that the parameter “secondsTimeFrameValidity” is not necessarily transmitted.

Finally, it is noted that all the content parameters which are defined in relation to time (for example, the current load of the *AP*s), are referred to instance “time”, except in case that is stated differently (namely, the time frame validity for secondary spectrum usage and the time period of predicted load).

The arbitral *Context&ConfigurationNotificationAck* message includes in its content parameters the ASN.1 constructor type “CHOICE” for the parameter “resultType”. The CHOICE types are “types defined by referencing a list of distinct types; each value of the choice type is derived from the value of one of the component types" [92]. Namely, the CHOICE type gives the choice between several alternatives and in essence, it models two pieces of information: the chosen alternative and the value associated with this alternative [96]. The component "ok" has a BOOLEAN type (and its anticipated value is TRUE when NRM has obtained correctly the corresponding message), and the "nok" component is a sequence which includes two elements, the code of the error (which is OPTIONAL) and the corresponding description.

4.3.2 Procedure RAN Context & Configuration Information Request

The Procedure **RAN Context & Configuration Information Request** is accomplished when NRM decides that it needs updated information for the status of a RAN. The procedure consist of the *Context&ConfigurationRequest* message that is sent from NRM to the RAN, with which is asked the transmission of specific information for its status, and the *Context&ConfigurationResponse* message from the RAN to NRM, which contains the corresponding requested information. The procedure is presented in Table 4-6. The messages in the table contain the whole essential information that may be asked by NRM (presented analytically in 3.2.2 paragraph). As mentioned, a subset of this information, which is determined from the accrued situation that NRM needs to confront, may be requested.

RAN Context & Configuration Information Request	
Message	**Content Parameters**

Context & Configuration Request (NRM→ RAN)	**networkOperator** :: = PrintableString
	ranlId :: = INTEGER
	requestedData ::= SEQUENCE {
	requestedRanGenericInfo SEQUENCE OF ENUMERATED {
	operatingRAT,
	operatingFrequency,
	supportedServices,
	supportedServicesQoSindicators,
	supportedServicesCosts,
	mobilityMechanism,
	AuthenticationMethod,

	securityMechanisms},
	requestedSpectrumHolesInfo SEQUENCE OF ENUMERATED {
	frequencyRange,
	geographicalArea,
	timeFrameValidityInitiation,
	timeFrameValidityExpiration,
	secondsTimeFrameValidity OPTIONAL,
	maximumPowerLevel},
	accessPointsInfo SEQUENCE OF SEQUENCE {
	accessPointId,
	requested SEQUENCE OF ENUMERATED {
	uplinkBandwidth,
	downlinkBandwidth,
	xGeograpicalCoordinate,
	yGeograpicalCoordinate,
	coverageArea,
	currentLoad,
	predictedLoad,
	meanSignalStrength,
	aggregatedThroughput,
	spectralEfficiency}}}

Context & Configuration Response (RAN→ NRM)	**networkOperator** :: = PrintableString
	ranId :: = INTEGER
	time ::= GeneralizedTime
	contentData :: = SEQUENCE {
	operatingRAT PrintableString,
	operatingFrequency SEQUENCE {
	lowFreq INTEGER,
	highFreq INTEGER },
	supportedServices SEQUENCE OF PrintableString,
	supportedServicesQoSindicators
	SEQUENCE OF PrintableString,
	supportedServicesCosts
	SEQUENCE OF PrintableString,
	mobilityMechanism PrintableString,
	authenticationMethod PrintableString,
	securityMechanisms PrintableString,
	spectrumHolesInfo SEQUENCE OF SEQUENCE {
	frequencyRange SEQUENCE {
	lowFreq INTEGER,
	highFreq INTEGER},
	geographicalArea PrintableString,
	timeFrameValidityInitiation GeneralizedTime,
	timeFrameValidityExpiration GeneralizedTime,
	secondsTimeFrameValidity INTEGER OPTIONAL,
	maximumPowerLevel REAL },
	accessPointsInfo SEQUENCE OF SEQUENCE {
	accessPointId INTEGER,
	uplinkBandwidth SEQUENCE {

	lowFreq INTEGER,
	highFreq INTEGER },
	downlinkBandwidth SEQUENCE {
	lowFreq INTEGER,
	highFreq INTEGER },
	xGeograpicalCoordinate REAL,
	yGeograpicalCoordinate REAL,
	coverageArea PrintableString,
	currentLoad REAL,
	predictedLoad SEQUENCE {
	predictedLoadValue REAL,
	timePeriodInitiation GeneralizedTime,
	timePeriodExpiration GeneralizedTime,
	secondsTimePeriod INTEGER OPTINAL},
	meanSignalStrength REAL,
	aggregatedThroughput REAL,
	spectralEfficiency REAL } }

Table 4-6: Procedure **RAN Context & Configuration Information Request**

The definition of the parameters in the messages *Context&ConfigurationRequest* and *Context&ConfigurationResponse*, is the same with those in *Context&ConfigurationNotification* message of the Procedure **RAN Context & Configuration Information Provision**. It is noted that for the construction of the *Context&ConfigurationRequest* message, the ENUMERATED type was used. The ENUMERATED types, as defined in [92], are "simple types whose values are given distinct identifiers as part of the type notation" and "the values themselves are not expected to have any integer semantics". Namely, the type is used in order to inventory objects, as in the relevant message.

4.3.3 Procedure Reconfiguration Command

The Procedure **Reconfiguration Command** is accomplished when NRM decides that it is necessitated reconfiguration of specific RAN(s). The procedure consist of the *ReconfigurationRequest* message that is sent from NRM to each of the RANs that

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΑ

need to be reconfigured, and with which the RAN is asked to change its operating frequencies, RAT or both, and the *ReconfigurationRequestAck* message that is sent conversely. The *ReconfigurationRequestAck* message constitutes the acknowledgment for the correct reception of the *ReconfigurationRequest* message or the enlightenment for problematic reception of the message and the description of the relevant error. M The procedure that is displayed in Table 4-7, presents the case in which, it is asked from the RAN to reconfigure its operating RAT and frequency. The *ReconfigurationRequest* message includes the time frame, in the duration of which, the reconfiguration have to be executed. The time frame is declared with the instance of the initiation of the time frame ("reconfigurationTimeFrameInitiation"), the instance of the expiration of the time frame ("reconfigurationTimeFrameExpiration"), and the duration of the time frame in seconds ("secDurationReconfigurationTimeFrame"). The duration of the time frame in seconds is surplus information, which is not mandatory, and may be used for verification of the precision of the relevant information element. For this reason, the last parameter "secDurationReconfigurationTimeFrame" is stated as OPTIONAL, accordingly with parameter "secondsTimeFrameValidity" in *Context&ConfigurationNotification* message. Furthermore, as in case of *Context&ConfigurationNotificationAck* message, the *ReconfigurationRequestAck* message is optional and the final decision for its transmission is taken by the operator(s).

Reconfiguration Command	
Message	**Content Parameters**

Reconfiguration Request (NRM→ RAN)	**networkOperator** :: = PrintableString
	ranlId :: = INTEGER
	reconfiguredElements ::= SEQUENCE {
	operatingRAT PrintableString,
	operatingFrequency SEQUENCE {
	lowFreq INTEGER,
	highFreq INTEGER },
	reconfigurationTimeFrameInitiation GeneralizedTime,
	reconfigurationTimeFrameExpiration GeneralizedTime,
	secDurationReconfigurationTimeFrame INTEGER OPTIONAL}

Reconfiguration Request Ack (RAN→ NRM)	**networkOperator** :: = PrintableString
	ranlId :: = INTEGER
	resultType ::= CHOICE {
	ok BOOLEAN,
	nok SEQUENCE {

	errorCode INTEGER OPTIONAL errorDescrition PrintableString }

Table 4-7: Procedure **Reconfiguration Command**

4.3.4 Procedure Reconfiguration Execution

The Procedure **Reconfiguration Execution** (which is presented in Table 4-8) is performed when the reconfigured RAN informs the NRM for the execution of the requested action. The *ReconfigurationExecutionNotification* message includes only the reconfigured elements, which may be the operating RAT, frequency or both. For reasons of generality and completeness, the *ReconfigurationExecutionNotification* message contains the whole possible relevant information. Respectively with previous messages, in the *ReconfigurationExecutionNotificationAck* message, the component value "ok" is a BOOLEAN type and the "nok" component is a sequence containing the code of the error and the corresponding description.

Reconfiguration Execution	
Message	**Content Parameters**

Reconfiguration Execution Notification
(RAN→ NRM)
	networkOperator :: = PrintableString
	ranlId :: = INTEGER
	reconfiguredElements ::= SEQUENCE {
	operatingRAT PrintableString,
	operatingFrequency SEQUENCE {
	lowFreq INTEGER,
	highFreq INTEGER } }

Reconfiguration Execution Notification Ack
(NRM→ RAN)
	networkOperator :: = PrintableString
	ranlId :: = INTEGER
	resultType ::= CHOICE {
	ok BOOLEAN,
	nok SEQUENCE {
	errorCode INTEGER OPTIONAL
	errorDescrition PrintableString OPTIONAL}

Table 4-8: Procedure **Reconfiguration Execution**

4.3.5 Procedure Reconfiguration Failure Report

The Procedure **Reconfiguration Failure Report** (presented in Table 4-9) is performed when the specific time frame for reconfiguration execution has expired, and the NRM has not received confirmation for the requested reconfiguration from the corresponding RAN. The *ReconfigurationFailureReportRequest* message utilizes the ASN.1 constructor "SEQUENCE OF ENUMERATED", in order to request the necessary data, which depict the exact problem that led to reconfiguration's failure. The *ReconfigurationFailureReportResponse* message includes the requested data with the determined type. The "errorCode" is OPTIONAL as the significant element of the information is the precise description of the problem, which is not always feasible to be classified to specific categories.

Reconfiguration Failure Report	
Message	**Content Parameters**
Reconfiguration Failure Report Request (NRM→ RAN)	**networkOperator** :: = PrintableString **ranlId** :: = INTEGER **requestedData ::=** SEQUENCE OF ENUMERATED{ errorCode OPTIONAL errorDescrition }
Reconfiguration Failure Report Response (RAN→ NRM)	**networkOperator** :: = PrintableString **ranlId** :: = INTEGER **reportedData ::=** SEQUENCE { errorCode INTEGER OPTIONAL errorDescrition PrintableString }

Table 4-9: Procedure **Reconfiguration Failure Report**

4.4 Procedures of the interface between NRM and MT

4.4.1 Procedures affined with transmission of information from MTs to NRM

4.4.1.1 Procedure MT Status Notification

The Procedure **MT Status Notification** takes place when a MT is switch on, in stable time-span (which is determined from NRM and is designated based on the state of the overall managed RANs), and when there is alteration in any of the information elements that denote the MT's status. The procedure consists of the *StatusNotification* message and the *StatusNotificationAck* message, which are presented in Table 4-10. The *StatusNotification* message includes the information that was presented in paragraph 3.2.3, and which may be extended, according to the framework of the operation of the management architecture. The transmission of *StatusNotificationAck* message is not compulsory. The final decision of its transmission is made by the operator(s) of NRM, and it might be different for each situation. For example, it may be determined that *StatusNotificationAck* message is transmitted only when the *StatusNotification* message is sent from a MT that has altered a significant specific parameter of its operation, for example its reconfiguration capability, or when a MT initiates the operation of a new service.

MT Status Notification	
Message	**Content Parameters**

Status Notification (MT→ NRM)	**mobileTerminlalId** :: = PrintableString
	time ::= GeneralizedTime
	statusData :: = SEQUENCE {
	reconfigurationCapability BOOLEAN,
	activeInterface SEQUENCE OF SEQUENCE{
	operatingRAT PrintableString,
	operatingFrequency SEQUENCE {
	lowFreq INTEGER,
	highFreq INTEGER },
	connectedRanId INTEGER,
	signalStrength REAL },
	xGeograpicalCoordinate REAL,
	yGeograpicalCoordinate REAL,
	priority INTEGER,
	mobilityProfile PrintableString,

	operatingServices [1] SEQUENCE OF PrintableString, operatingServicesQoSMetrics [2] SEQUENCE OF PrintableString, demandedServices [3] SEQUENCE OF PrintableString, demandedServicesQoSIndicators [4] SEQUENCE OF PrintableString, pid INTEGER}

Status Notification Ack (NRM → MT)	**mobileTerminlalId** :: = PrintableString
	resultType ::= CHOICE {
	ok BOOLEAN,
	nok SEQUENCE {
	errorCode INTEGER OPTIONAL
	errorDescrition PrintableString }

Table 4-10: Procedure **MT Status Notification**

For reasons of generality and completeness, in Table 4-10 is represented the case that the MT has more than one active interface, it uses more than one service and simultaneously requests the usage of more than one offered services. The tags [1]–[4] are optional, and can be used for the four consecutive sequences of printable string of the parameters “operatingServices”, “operatingServicesQoSMetrics”, “demandedServices” and “demandedServicesQoSIndicators”, as surplus precaution against any ambiguity during decoding and interpreting from the recipient.

4.4.1.2 Procedure MT Status Request

The Procedure **MT Status Request** is accomplished when NRM decides that it needs updated information for the status of a MT (or commonly, when it needs updated information from the MTs that exist in a specific geographic area). The procedure consist of the *StatusRequest* message that is sent from NRM to the MT, with which is asked the transmission of specific information for its status, and the *StatusResponse* message from the MT to NRM, which contains the corresponding requested information. The procedure is presented in Table 4-11. The messages in the table contain the whole essential information that may be asked by NRM. As mentioned, a subset of this information may be requested.

MT Status Request	
Message	**Content Parameters**
Status Request (NRM→ MT)	**mobileTerminlalId** :: = PrintableString **time** ::= GeneralizedTime **requestedData** :: = SEQUENCE OF ENUMERATED{ reconfigurationCapability, activeInterface, xGeograpicalCoordinate, yGeograpicalCoordinate, priority, mobilityProfile, operatingServices, operatingServicesQoSMetrics, demandedServiceS, demandedServicesQoSIndicators, pid }

Status Response (MT → NRM)	**mobileTerminlalId** :: = PrintableString
	time ::= GeneralizedTime
	statusData :: = SEQUENCE {
	reconfigurationCapability BOOLEAN,
	activeInterfaceId SEQUENCE OF SEQUENCE{
	operatingRAT PrintableString,
	operatingFrequency SEQUENCE {
	lowFreq INTEGER,
	highFreq INTEGER },
	connectedRanId INTEGER,
	signalStrength REAL },
	xGeograpicalCoordinate REAL,
	yGeograpicalCoordinate REAL,
	priority INTEGER,
	mobilityProfile PrintableString,
	operatingServices [1] SEQUENCE OF PrintableString,
	operatingServicesQoSMetrics [2] SEQUENCE OF PrintableString,
	demandedServices [3] SEQUENCE OF PrintableString,
	demandedServicesQoSIndicators [4] SEQUENCE OF PrintableString,
	pid INTEGER}

Table 4-11: Procedure **MT Status Request**

For the *StatusRequest* message, the constructed type SEQUENCE OF ENUMERATED was utilized. Regarding the parameter “activeInterface”, is known to MTs that when this specific parameter is asked from NRM, the response has to comprise the sequence of parameters “operatingRAT”, “operatingFrequency” (stated as sequence of low and high frequency), “connectedRanId” and “signalStrength”.

4.4.2 Repository’s messages

4.4.2.1 Context Repository’s messages

The information of basic and extended Context Repository is transmitted via proper messages. The messages contain the specified parameters in paragraphs 3.4.3, and they are not followed from acknowledgment messages from the receiver, as it is considered superfluous.

The messages that include the **Context Repository Information** for an area, may comprise information for one or more meshes. The number of meshes for which the relevant information have to be trasmitted in a geographical area, depends on the networks topology and may vary in relation to time. Namely, in urban areas, where the number of meshes will be large, the characteristics of mobility behavior of a number of MTs may lead to frequently transmission among different meshes’ areas (for example, in transfer of a user with metropolitan railway), so the transmision of the corresponding information in one message may accelerate the decisions that are related with the relevant information. Simultaneously, the corresponding number of meshes for which the relevant information can be trasmitted in one message, depends on the available bandwidth and the technology that will finally be selected for the transmission (namely, the technology that will be selected for the implementation of the relevant operation of the Radio Enabler). Conclusively, the number of meshes for which the **Context Repository Information** is transmitted in one message, is determined by the operator(s) of NRM taking into considerations the aforementioned factors.

The messages in Tables 4-12 and 4-13 depict the **basic and extended Context Repository Information** for one mesh respectively, and the messages in Tables 4-14 and 4-15 depict the **basic and extended Context Repository Information** for more than one mesh correspondingly. It is noted that the information in the message that contains **extended Context Repository Information** does not encompass the operator of the included RANs, as it is already known to MTs from the messages comprising **basic Context Repository Information.**

basic Context Repository Information of a mesh

```
mesh :: = PrintableString
contextData :: =  SEQUENCE OF SEQUENCE{
networkOperator  PrintableString,
ranlId  INTEGER,
operatingRAT PrintableString,
operatingFrequency SEQUENCE {
    lowFreq INTEGER,
    highFreq INTEGER },
authenticationMethod PrintableString,
securityMechanisms PrintableString,
secondaryUsageFrequencies SEQUENCE{
    lowFreq INTEGER,
    highFreq INTEGER }}
```

Table 4-12: Message with **basic Context Repository Information for a mesh**

extended Context Repository Information of a mesh

```
mesh :: = PrintableString
contextData :: =  SEQUENCE OF SEQUENCE{
ranlId  INTEGER,
providingService SEQUENCE OF SEQUENCE{
    service PrintableString,
    serviceQoSIndicators PrintableString,
    serviceQost PrintableString },
mobilityMechanism PrintableString }
```

Table 4-13: Message with **extended Context Repository Information for a mesh**

basic Context Repository Information

```
basicContextRepositoryData:: = SEQUENCE OF
SEQUENCE{
mesh :: = PrintableString
contextData :: =  SEQUENCE OF SEQUENCE{
    networkOperator  PrintableString,
    ranlId  INTEGER,
    operatingRAT PrintableString,
    operatingFrequency SEQUENCE {
        lowFreq INTEGER,
        highFreq INTEGER },
    authenticationMethod PrintableString,
    securityMechanisms PrintableString,
    secondaryUsageFrequencies SEQUENCE{
        lowFreq INTEGER,
        highFreq INTEGER }}}
```

Table 4-14: Message with **basic Context Repository Information for a number of meshes**

extended Context Repository Information

```
extendedContextRepositoryData:: = SEQUENCE OF
SEQUENCE{
mesh :: = PrintableString
contextData :: =  SEQUENCE OF SEQUENCE{
    ranlId  INTEGER,
    providingService SEQUENCE OF SEQUENCE{
        service PrintableString,
        serviceQoSIndicators PrintableString,
        serviceQost PrintableString },
    mobilityMechanism PrintableString }}
```

Table 4-15: Message with **extended Context Repository Information for a number of meshes**

4.4.2.2 Policy Repository's messages

The policies, the structure of which was presented in the previous chapter, are formatted as rules that adopt Condition-Action format. Namely, policies are actually statements of the type:

IF

<Condition>

THEN

<Action>

The <Condition> include the prerequisites, the satisfaction of which, signals the execution of the corresponding <Action>.

This format comprises part of the known Event-Condition-Action (ECA) type, which is actually a statement of the type:

ON

<Event>

IF

<Condition>

THEN

<Action>

The simplified format of the policies accelerate the compliance of the MTs with policies, as MTs have to examine less factors in order to decide on their probable adoption. Simultaneously, the processing operation of the MT is not burdened with superfluous procedures. Furthermore, for reasons of security, the reason/event that activated specific operation of the management system, which led to derivation of the corresponding policies, should not be transmitted.

In this framework, the structure of the message that comprises the example of a general policy of b-PR, is represented in Table 4-16. Every other policy is structured respectively, slightly modified, based on its content.

General policy of basic Policy Repository
pid :: = INTEGER **goO** :: = INTEGER

conditionData :: = SEQUENCE {
mesh :: = PrintableString
priority :: = INTEGER
timePeriod :: = SEQUENCE {
timePeriodInitiation GeneralizedTime,
timePeriodExpiration GeneralizedTime,
secDurationTimePeriod INTEGER OPTIONAL}

actionData :: = PrintableString

Table 4-16: Message with example of **General Policy of Basic-Policy Repository**

The parameter "actionData" can be translated by the cognitive MTs to the corresponding actions for implementation. For this translation, methods and mechanisms of artificial intelligence may be used (for example, transformation of this printable string to directives for specific actions, based on a semantic model and assistance of proper software, built in suitable logic programming language, e.g. prolog language).

4.5 Information Encoding

As already mentioned, the Basic Encoding Rules (BER) were selected for the calculations of the anticipated value of the messages. In BER, the encoding of a data value consist of four components [93]:

a) The identifier octets,

b) The length octets,

c) The contents octets, and

d) end-of-contents octets.

The end-of-contents octets are present only when the value of the length octets requires them to be present.

The identifier octets (Bytes), usually called simply Tag, encode the ASN.1 tag of the type of the data value, identifying it unambiguously. A Tag is a couple of a tagging class and a number, which is is a positive integer. For tags with a number ranging from zero (0) to thirty (30), the identifier octets comprise a single octet, whereas for tags with a number greater than or equal to 31, the identifier octets consist of a leading octet followed by one or more subsequent octets. There are four tagging classes: universal, context-specifc, application and private. This categorization enables the determination of the context, where each tag must be unique. In a given context, two tags are considered to be diffeerent if they are of different classes or if their respective numbers are different [96]. The universal class is reserved for the ASN.1 standard designers, who allocate a tag of this class to all new standardized types. Context-specific tagging is frequently applied in an algorithmic manner to all components of a SET, SEQUENCE, or CHOICE type. Application class tagging is used in order to identify a type that finds wide usage within an application. Private class aims at definition of a data type within a particular organization or country, which have to be distinguishable from all other data types used by the organization or country.

For the length octets, usually called simply Length, are specified two forms in [93], the definite form and the indefinite form. In the definite form, the length octets consist of one or more octets, which represent the number of octets in the contents octets. In the indefinite form, there is one octet that indicates that the contents octets are terminated by end-of-contents octets. The indefinite form has to be used when the encoding is constructed and is not all data immediately available, and may be used, if the encoding is constructed and is all data immediately available (constructed encoding is defined a data value encoding, in which the contents octets are the complete encoding of one or more data values [93]).

The contents octets, usually called simply Value, consist of zero, one or more octets, which comprise the encoding actual information. If there are end-of-contents octets, these follow the contents octets and consist of two zero octets.

Every ASN.1 value is transmitted along with the identifier tag and the length of the value. The tag is determined by the type of the ASN.1 parameter and identifies a value for the type. So, the receiver obtains both the tag and the value and can interpret the value as belonging to a particular type.

If the type of a parameter is a structured type, then the value will contain all the other types. For instance, SEQUENCE OF INTEGER would contain a tag for the sequence, a length that includes the entire sequence of integers and a value consisting of a sequence of identifier-length-value triples, one for each integer in the sequence.

The calculations are made by taking into account only the encoding overheads that result from the encoding of the defined parameters (in the calculations are not included any overheads due to the selection of a specific transport protocol). The values of the parameters are defined based on estimations for their possible range.

If the tag number is smaller than or equal to 30, the tag is encoded on a single octet. Also, if the length of the Value is shorter than 127 (for definite form of the Length type [93]), the Length can be decoded in one octet. These limits are not exceeded from the types that are defined for the messsages' parameters presented in Tables 4-1, 4-2, 4-3 and 4-4. So, the Tag field and the Length field of these types extend the Value field of the aforementioned parameters of two Bytes (octets). The Length field of the constructed parameters is determined for each of them according to the size of its components.

Based on [93], for a BOOLEAN value (which has "UNIVERSAL 1" tag), "the contents octets shall consist of a single octet". So, the Value field for a BOOLEAN value equals to 1Byte and the total size of all parameters of BOOLEAN type is 3 Bytes.

Based on [93], for an INTEGER value (which has "UNIVERSAL 2" tag), "the contents octets shall consist of one or more octets". The number of octets for the parameters that presented in Table 4-1, based on their possible range of value, are defined as 1Byte for "priority" and "goO" and 2Bytes for "ranId", "xxxFreq", "accessPointId", "errorCode", "connectedRanId "secondsTimeFrameValidity", "secondsTimePeriod", "secDurationReconfigurationTimeFrame", "secDurationTimePeriod" and "pid". Consequently, the size of the former is 3Bytes and of the latter is 4Bytes.

The non-zero values of a REAL type (which has tag "UNIVERSAL 9") can be specified by the formula $M \times B^E$, which involves three integers, M (called the mantissa), B (called the base) and E (called the exponent) [92]. The real type for value definition has the associated type:

```
SEQUENCE {
        mantissa INTEGER,
        base INTEGER (2|10),
        exponent INTEGER
        -- The associated mathematical real number is "mantissa"
        -- multiplied by "base" raised to the power "exponent"
        }
```

In the above definition, the base B equals to 2 or 10. Furthermore, if the real value equals zero, there are no contents octets in the encoding.

In this framework, the mantissa, base and exponent are considered as integer types with 2Bytes each and as a result, the whole sequence corresponds to a declaration of a REAL type with a size of 14Bytes.

The value of the GeneralizedTime type (which has "UNIVERSAL 24" tag) is a character string which may have a form "AAAAMMJJhh[mm[ss[(.|,)ffff]]]" (the square brackets indicate the optional characters and the round brackets and the vertical bar stand for the possible alternatives). In this form, as presented in paragraph 4.2, the first four digits represents the year, and then follow, two for the month, two for the day, two for the hour (the value 24 is forbidden), two for the minutes and two for the seconds if it is required. Thereafter, if it is needed considerable precision, a dot (or a comma) is set after the digits for seconds, which is followed by a number for the fractions of second (the maximum precision depends on each application). The form "AAAAMMJJhhmmss.fff" of GeneralizedTime type is selected for the calculations and the string is encoded as if it is octet string [96]. In this framework, every parameter of GeneralizedTime type of Table 4-4, has a value of 18Bytes (1Byte for each of the 18 characters), and totally size of 20Bytes.

Also, the string of type PrintableString (which has "UNIVERSAL 19" tag) is encoded as if it is octet string [96]. Based on estimations for the possible range of values of the parameters with PrintableString, the value of 48Bytes was selected for the parameters "networkOperator", "mobilityMechanism", "authenticationMethod", "securityMechanisms", "operatingRAT", "mobileTerminlalId", "supportedService", "supportedServiceQoSIndicators", and "supportedServiceCost", which is approximately a middle value of the corresponding permissible values of PrintableString type. Therefore, the total size of these parameters is 50Bytes. The value of 68Bytes was selected for the parameters "coverageArea", "geographicalArea", "mobilityProfile", "mesh", and "errorDescription" and the total size of them is 70Bytes, respectively. Finally, the value of 98Bytes (100Bytes with Tag and Length fields) was selected for the parameter "actionData" of the policies (which constitutes the <Action> in the policy's structure that described previously), in order to satisfy even the cases for which is necessitated the transmission of significant size of directional information in case of meshes that are occupied of a large number of managed RANs.

The size of the determined parameters altogether is presented in Table 4-17.

Parameter	Size
reconfigurationCapability	3 Bytes
ok	3 Bytes
ranId	4 Bytes
xxxFreq	4 Bytes
secondsTimeFrameValidity	4 Bytes
secondsTimePeriod	4 Bytes
accessPointId	4 Bytes
secDurationReconfigurationTimeFrame	4 Bytes
errorCode	4 Bytes

ConnectedRanId	4 Bytes
Pid	4 Bytes
GoO	3 Bytes
SecDurationTimePeriod	4 Bytes
Priority	3 Bytes
MaximumPowerLevel	14 Bytes
XGeograpicalCoordinate	14 Bytes
YGeograpicalCoordinate	14 Bytes
CurrentLoad	14 Bytes
PredictedLoadValue	14 Bytes
MeanSignalStrength	14 Bytes
AggregatedThroughput	14 Bytes
SpectralEfficiency	14 Bytes
SignalStrength	14 Bytes
NetworkOperator	50 Bytes
MobilityMechanism	50 Bytes
AuthenticationMethod	50 Bytes
SecurityMechanisms	50 Bytes
OperatingRAT	50 Bytes
CoverageArea	70 Bytes
geographicalArea	70 Bytes
mobileTerminlalId	50 Bytes
MobilityProfile	70 Bytes
Mesh	70 Bytes
SupportedService	50 Bytes
supportedServiceQoSIndicators	50 Bytes
SupportedServiceCost	50 Bytes
ErrorDescrition	70 Bytes
TimeFrameValidityInitiation	20 Bytes
TimeFrameValidityExpiration	20 Bytes
TimePeriodInitiation	20 Bytes
TimePeriodExpiration	20 Bytes
reconfigurationTimeFrameInitiation	20 Bytes
reconfigurationTimeFrameExpiration	20 Bytes
ActionData	100 Bytes

Table 4-17: Size of the determined parameters

As specified in [93], the encoding of an enumerated value is that of the integer value with which it is associated.

The encoding of a sequence value consists of the complete encoding of the data value for each of the types listed in the ASN.1 definition of the sequence type, in the order of their appearance in the definition, unless the type is referenced with the keyword OPTIONAL [93]. Respectively, the contents octets in the encoding of a sequence-of value consist of zero, one or more complete encodings of data values from the type listed in the ASN.1 definition, the order of which is the same as the order of the data values in the sequence-of value to be encoded [93].

The encoding of a choice value is the same as the encoding of the value of the chosen type, and the tag that is used in the identifier octets is the tag of the chosen type as specified in the ASN.1 [93].

4.6 Anticipated length of the messages

Based on the, presented in the previous paragraph, size of the determined parameters and the rules of BER, the anticipated length of the messages that constitute the specified procedures is calculated. For the calculations, it is considered that:

- s is the number of the offered services of a RAN,
- h is the number of the different frequencies that are disposed for secondary spectrum usage from a RAN,
- L is the number of the operating *AP*s of a RAN,
- l is the number of the operating *AP*s of a RAN for which definite information is requested from NRM,
- a is the the number of the active interfaces of a MT,
- os is the number of the operating services of a MT,

- *ds* is the number of the demanded services of a MT,

- *m* is the number of meshes for which relevant information is included in a message, and

- *r* is the number of RANs that are included in a mesh, and

- r_m is the number of RANs of the m^{th} mesh.

As already mentioned, the value of the parameters that are OPTIONAL is not taken into account to the calculations. The decision for their usage is from the operator(s) in relation to the framework of the operation of the management architecture, as well as the available bandwidth for the transmission of the messages that constitute the specified procedures.

4.6.1 Anticipated length of the messages of Procedure RAN Context & Configuration Information Provision

The calculation of the length of the messages *Context&ConfigurationNotification* and *Context&ConfigurationNotificationAck*, which comprise the Procedure **RAN Context & Configuration Information Provision**, is presented analytically as paradigm for the respective calculations for all messages.

The length of the *Context&ConfigurationNotification* message is the sum of its content parameters "network operator", "time", "ranGenericInfo", "spectrumHolesInfo" and "accessPointsInfo". The size of the parameter "network operator" is 50Bytes, of the parameter "time" is 20Bytes and the size of the other parameters result from the combination of the size of their components, as the type of the parameters "ranGenericInfo", "spectrumHolesInfo" and "accessPointsInfo" is constructed.

The parameter "ranGenericInfo" is type of SEQUENCE, so its size is the sum of the size of the listed types. The size of the components and their sum that comprise the "ranGenericInfo", are presented in Table 4-18. The "operatingFrequency" is SEQUENCE type, so its size is the sum of the "lowFreq" and "highFreq", which have size 4Bytes each, plus 2Bytes for the Tag and Length field. So, the size of the "operatingFrequency" is 10Bytes. The parameters "supportedServices", "supportedServicesQoSIndicators" and "supportedServicesCost" have type "SEQUENCE OF PrintableString". So, the size of each of them is $(50 \times s)$Bytes (where s is the number of the offered services form the RAN), which result from adding 50Bytes (which is the size of the parameters "supportedService", "supportedServiceQoSIndicators" and "supportedServiceCost") for each of the supported services. Finally, 4Bytes are added, 1Byte for the Tag field and 3Bytes for the Length field.

The parameter "spectrumHolesInfo" is type of SEQUENCE OF SEQUENCE, so its size is the sum of the size of each of the contained sequences. The size of each contained sequence is 134Bytes (its size along with the sizes of its components is depicted in Table 4-19). It is noted that size of "secondsTimeFrameValidity" is not added as it is OPTIONAL. Furthermore, the "frequencyRange" is SEQUENCE type, so its size is the sum of the "lowFreq" and "highFreq", which have size 4Bytes each, plus 2Bytes for the Tag field and Length field. Finally, the size of the content parameter "spectrumHolesInfo" is the product of the number of dispoded frequencies for secondary spectrum usage and the size of each of the contained sequences, plus 4Bytes, 1Byte for the Tag field and 3Bytes for the Length field. Therefore, the size of "spectrumHolesInfo" is $\left[(134 \times h)+4\right]$Bytes (where h is the number of the different frequencies).

The parameter "accessPointsInfo" is SEQUENCE OF SEQUENCE, so its size is also the sum of the size of the contained sequences. The size of each contained sequence is 234Bytes (its size along with the sizes of its components is depicted in Table 4-20). The size of each of the parameters "uplinkBandwidth" and "downlinkBandwidth" is 10Bytes, as it is the sum of the parameters "lowFreq" and "highFreq", which have size 4Bytes each, plus 2Bytes for the Tag field and Length field (1Byte for each). The size of the "predictedLoad" as SEQUENCE type is the sum of the sizes "predictedLoadValue", "timePeriodInitiation" and "timePeriodExpiration", which are

14Bytes, 20Bytes and 20Bytes respectively (the size of the parameter "secondsTimePeriod" is not added as the parameter is OPTIONAL). Finally, the size of the "accessPointsInfo" is $\left[(234 \times L)+4\right]$Bytes (where L as defined is the number of the operating *AP*s of the specific RAN and 4Bytes are added for the Tag and Length fields).

Conclusively, the size of *Context&ConfigurationNotification* message is: $S_{Context\&ConfigurationNotification} = \left\{296+(150 \times s)+(134 \times h)+(234 \times L)\right\}$ Bytes.

Parameter	Size (Bytes)
RanId	4
OperatingRAT	50
OperatingFrequency	10
SupportedServices	50 x s
supportedServicesQoSIndicators	50 x s
SupportedServicesCost	50 x s
MobilityMechanism	50
AuthenticationMethod	50
SecurityMechanisms	50
RanGenericInfo	$218+(150 \times s)$

Table 4-18: Size of the parameter "ranGenericInfo" and its components

Parameter	Size (Bytes)
FrequencyRange	10
geographicalArea	70
TimeFrameValidityInitiation	20
TimeFrameValidityExpiration	20
MaximumPowerLevel	14
SpectrumHolesInfo	$\left[(134 \times h)+4\right]$

Table 4-19: Size of the parameter "spectrumHolesInfo"and of the parameters of each contained sequence

Parameter	Size (Bytes)
accessPointId	4
uplinkBandwidth	10
downlinkBandwidth	10
xGeograpicalCoordinate	14
yGeograpicalCoordinate	14
coverageArea	70
currentLoad	14
predictedLoad	56
meanSignalStrength	14
aggregatedThroughput	14
spectralEfficiency	14
accessPointsInfo	$\left[(234 \times L) + 4\right]$

Table 4-20: Size of each of the sequences (and their components) that constitute the parameter "accessPointsInfo"

The length of the *Context&ConfigurationNotificationAck* message is the sum of its content parameters "network operator", "ranId" and "resultType". The size of the parameter "network operator" is 50Bytes and the size of the parameter "ranId" is 4Bytes. But, the size of the "resultType" is not constant and depends on the chosen type. So, if the "resultType" has the value "ok", the size of the "resultType" is 3Bytes and if it has the value of "nok", the size of the "resultType" is the size of the parameter "errorDescription", namely 70Bytes (the size of the parameter "errorCode" is OPTIONAL), plus 2Bytes for the Tag field and Length field. Therefore, the size of the *Context&ConfigurationNotificationAck* message is 57Bytes if the *Context&ConfigurationNotification* message has received correctly from NRM, and 126Bytes if the received message contains error. Finally, in order to be assessed the necessary bandwidth for the procedure, the larger value of load for the *Context&ConfigurationNotificationAck* message is used for the corresponding estimation, namely $S_{Context\&ConfigurationNotificationAck} = 126$ Bytes.

The total size of the Procedure **RAN Context & Configuration Information Provision** is:

$$S_{RANContext\&ConfigurationInformationProvision} = \{422 + (150 \times s) + (134 \times h) + (234 \times L)\} \text{ Bytes}$$

We consider a RAN, operating under the control of NRM, which offers 3 services (for example, Telephony, Web Service and Video on Demand), has one frequency range that can be disposed for secondary spectrum usage and operates 40 *AP*s. For this RAN, for which applies that *s*=3, *h*=1 and *L*=40,

- the size of *Context&ConfigurationNotification* message is $S_{Context\&ConfigurationNotification} = 10240$ Bytes,

- the size of *Context&ConfigurationNotificationAck* message is $S_{Context\&ConfigurationNotificationAck} = 126$ Bytes, and

- the total size of the Procedure **RAN Context & Configuration Information Provision** is $S_{RANContext\&ConfigurationInformationProvision} = 10366$ Bytes.

4.6.2 Anticipated length of the messages of Procedure RAN Context & Configuration Information Request

The anticipated length for the messages is calculated correspondingly to the previous analytical example. It is noted that for the ENUMERATED type of our application 1Byte for the number of octets of the related INTEGER value is sufficient. So, the size of each of the parameters of the SEQUENCE OF ENUMERATED is 3Bytes.

The length of the *Context&ConfigurationRequest* message is the sum of its content parameters "network operator", "ranId" and "requestedData". The size of the parameter "network operator" is 50Bytes and of the parameter "ranId" is 4Bytes. The size of the "requestedData" is the sum of its parameters "requestedRanGenericInfo", "requestedSpectrumHolesInfo" and "accessPointId", plus 4Bytes for Tag and Length fields. The size of the "requestedRanGenericInfo" is 26Bytes, 3Bytes for each of the 8 contained parameters plus 2Bytes for the Tag and Length fields. Respectively, the size of "requestedSpectrumHolesInfo" is 17Bytes. The size for the "requested SEQUENCE OF ENUMERATED" for each "accessPointId" from the requested number l of *AP*s, is 32Bytes. Therefore, the size of "accessPointsInfo" is $\left[(36\times l)+4\right]$Bytes ($(36\times l)$ Bytes for the Value field, 1Byte for the Tag field and 3Bytes for Length field). Finally, the size of the *Context&ConfigurationRequest* message is $S_{Context\&ConfigurationRequest}=\left\{105+(36\times l)\right\}$ Bytes.

The length of the *Context&ConfigurationResponse* message is the sum of its content parameters "network operator", "ranId", "time" and "contentData". The size of the parameter "network operator" is 50Bytes, of the parameter "ranId" is 4Bytes and of the parameter "time" is 20Bytes. The size of "contentData" is calculated respectively to previously.

Therefore, the size of the parameter "contentData" is $\left[222+(150\times s)+(134\times h)+(234\times l)\right]$ Bytes.

It is noted that the size of the contained parameter "accessPointsInfo" is $\left[(234\times l)+4\right]$Bytes (where 234Bytes is the size of each sequence of the l sequences, and 4Bytes are added for Tag and Length fields) and the size of the contained parameter "spectrumHolesInfo" is $\left[(134\times h)+4\right]$ Bytes (where 134Bytes is the size of each sequence of the h sequences, and 4Bytes are added for Tag and Length fields). Furthermore, for the Tag and Length fields of the "contentData" of SEQUENCE type, have been added 4Bytes.

Finally, the size of the *Context&ConfigurationResponse* message is $S_{Context\&ConfigurationResponse}=\left\{296+(150\times s)+(134\times h)+(234\times l)\right\}$ Bytes.

Conclusively, the total size of the Procedure **RAN Context & Configuration Information Request** is:

$$S_{RANContext\&ConfigurationInformationRequest}=\left\{401+(150\times s)+(134\times h)+(270\times l)\right\}\text{ Bytes.}$$

For the reference RAN of the previous paragraph, for which is requested configuration information for the 20 *AP*s from the operating 40*AP*s (so *l*=20),

- the size of *Context&ConfigurationRequest* message is $S_{Context\&ConfigurationRequest} = 825$ Bytes,
- the size of *Context&ConfigurationResponse* message is $S_{Context\&ConfigurationResponse} = 5560$ Bytes, and
- the total size of the Procedure **RAN Context & Configuration Information Request** is $S_{RANContext\&ConfigurationInformationRequest} = 6385$ Bytes.

4.6.3 Anticipated length of the messages of Procedure Reconfiguration Command

The length of the *ReconfigurationRequest* message is the sum of its content parameters "network operator", "ranId" and "reconfiguredElements". The size of the parameter "network operator" is 50Bytes, of the parameter "ranId" is 4Bytes and of the "reconfiguredElements" is 102Bytes (calculated respectively to the previous cases). So, the size of *ReconfigurationRequest* message is $S_{ReconfigurationRequest} = 156$ Bytes.

The length of the *ReconfigurationRequestAck* message, as in case of *Context&ConfigurationNotificationAck* message, is 57Bytes if the *ReconfigurationRequest* message has received correctly from the RAN, and 126Bytes if the received message contains error. In order to be assessed the necessary bandwidth for the procedure, the larger potential value of the load for the *ReconfigurationRequestAck* message is used for the corresponding estimation, namely $S_{ReconfigurationRequestAck} = 126$ Bytes.

The total size of the Procedure **Reconfiguration Command** is: $S_{\mathrm{Re}configurationCommand} = 282$ Bytes.

4.6.4 Anticipated length of the messages of Procedure Reconfiguration Execution

The length of the *ReconfigurationExecutionNotification* message is the sum of its content parameters "network operator", "ranId" and "reconfiguredElements". The size of the parameter "network operator" is 50Bytes, of the parameter "ranId" is 4Bytes and of the "reconfiguredElements" is 62Bytes (calculated respectively to the previous cases). So, the size of *ReconfigurationExecutionNotification* message is $S_{\mathrm{Re}configurationExecutionNotification} = 116$ Bytes. As mentioned, for reasons of generality and completeness, the size of the *ReconfigurationExecutionNotification* message was calculated for reconfiguration of both RAT and frequency. In case that the reconfigured element is only the RAT or the operating frequency, the size of the message is smaller.

The length of the *ReconfigurationExecutionNotificationAck* message is 57Bytes if the *ReconfigurationExecutionNotification* message has received correctly from NRM, and 126Bytes if the received message contains error. In order to estimate the necessary bandwidth for the procedure under any circumstances, the larger prospective value is used for the estimation of the size of *ReconfigurationExecutionNotificationAck* message, namely $S_{\mathrm{Re}configurationExecutionNotificationAck} = 126$ Bytes.

So, the total size of the Procedure **Reconfiguration Execution** is: $S_{\mathrm{Re}configurationExecution} = 242$ Bytes.

4.6.5 Anticipated length of the messages of Procedure Reconfiguration Failure Report

The length of the *ReconfigurationFailureReportRequest* message is the sum of its content parameters “network operator”, “ranId” and “requestedData”. The size of the parameter “network operator” is 50Bytes, of the parameter “ranId” is 4Bytes and of the “requestedData” is 5Bytes (3Bytes for the value corresponding to parameter “errorDescription” of the SEQUENCE OF ENUMERATED type, and 2Bytes for Tag and Length fields). So, the size of *ReconfigurationFailureReportRequest* message is $S_{ReconfigurationFailureReportRequest} = 59$ Bytes.

The length of the *ReconfigurationFailureReportResponse* message is the sum of its content parameters “network operator”, “ranId” and “reportedData”. The size of the parameter “network operator” is 50Bytes, of the parameter “ranId” is 4Bytes and of the “reportedData” is 72Bytes. So the size of *ReconfigurationFailureReportResponse* message is $S_{ReconfigurationFailureReportResponse} = 126$ Bytes.

The total size of the Procedure **Reconfiguration Failure Report** is: $S_{ReconfigurationFailureReport} = 185$ Bytes.

4.6.6 Anticipated length of the messages of Procedure MT Status Notification

The length of the *StatusNotification* message is the sum of its content parameters “network operator”, “time” and “statusData”. The size of the parameter “network operator” is 50Bytes, of the parameter “time” is 20Bytes and of the “statusData” is $\left[116+(78\times a)+(100\times os)+(100\times ds)\right]$ Bytes (calculated respectively to the previous cases). It is noted that from the contained parameters of the “statusData”, the parameter “active interface” has size $\left[(78\times a)+4\right]$ Bytes [78Bytes is the size of each of the a sequences, and 4 Bytes are added for the Tag and Length fields], the parameters "operatingServices" and "operatingServicesQoSMetrics" have size $(50\times os)$ Bytes each, and the parameters "demandedServices" and "demandedServicesQoSMetrics" have size $(50\times ds)$ Bytes each (as it was defined in paragraph 4.5, *os* is the number of the operating services and *ds* is the number of the demanded services). So, the size of *StatusNotification* message is $S_{StatusNotification}=\{186+(78\times a)+(100\times os)+(100\times ds)\}$ Bytes.

The length of the *StatusNotificationAck* message is 53Bytes if the *StatusNotificationAck* message has received correctly from NRM, and 122Bytes if the received message contains error. In order to estimate the necessary bandwidth for the procedure, the larger prospective value is used, as the previous cases, for the estimation of the size of *StatusNotificationAck* message, namely $S_{StatusNotificationAck}=122$ Bytes.

The total size of the Procedure **MT Status Notification** is: $S_{MTStatusNotification}=\{308+(78\times a)+(100\times os)+(100\times ds)\}$ Bytes.

For example, for a MT that has 2 active interfaces, 2 operating services and demands a new service (so, it applies that *a*=2, *os*=2 and *ds*=1),

- the size of *StatusNotification* message is $S_{StatusNotification}=642$ Bytes,
- the size of *StatusNotificationAck* message is $S_{StatusNotificationAck}=122$ Bytes, and
- the total size of the Procedure **MT Status Notification** is $S_{MTStatusNotification}=764$ Bytes.

4.6.7 Anticipated length of the messages of Procedure MT Status Request

As previously, for the ENUMERATED type of this procedure, 1Byte for the number of octets of the related INTEGER value is sufficient. So, each of the parameters of the SEQUENCE OF ENUMERATED has size 3Bytes.

The length of the *StatusRequest* message is the sum of its content parameters “mobileTerminalId”, “time” and “requestedData”. The size of the parameter “mobileTerminalId” is 50Bytes and of the parameter “time” is 20Bytes. The size of the “requestedData” is 35Bytes, 3Bytes for each of the 11 contained parameters plus 2Bytes for the Tag and Length fields. So, the size of the *StatusRequest* message is $S_{StatusRequest} = 105\,\text{Bytes}$.

The length of the *StatusResponse* message is the sum of its content parameters “mobileTerminalId”, “time” and “statusData”. The size of the parameter “mobileTerminalId” is 50Bytes and of the parameter “time” is 20Bytes. The size of “statusData” is calculated respectively with the parameter “statusData” in the *StatusNotification* message of the Procedure MT Status Notification. So, the length of the *StatusResponse* message is $S_{StatusResponse} = \{186 + (78\times a) + (100\times os) + (100\times ds)\}\,\text{Bytes}$.

Therefore, the total size of the Procedure ***MT Status Request*** is $S_{MTStatusRequest} = \{291 + (78\times a) + (100\times os) + (100\times ds)\}\,\text{Bytes}$.

It is noted that this is the maximum size of this procedure, as it contains all the possible requested information from MT, as already mentioned in paragraph 4.4.2.

For the MT of the previous paragraph (for which *a*=2, *os*=2 and *ds*=1),

- the size of *StatusRequest* message is $S_{StatusRequest} = 105\,\text{Bytes}$,
- the size of *StatusResponse* message is $S_{StatusResponse} = 642\,\text{Bytes}$, and
- the total size of the Procedure ***MT Status Request*** is $S_{MTStatusRequest} = 747\,\text{Bytes}$.

4.6.8 Anticipated length of the messages with Context Repository Information

The length of the message containing *basic Context Repository Information* for one mesh, is the sum of its content parameters “mesh” and “contextData”. The size of the parameter “mesh” is 70Bytes and the “contextData” is $\left[\left(224\times r\right)+4\right]$ Bytes, calculated respectively to the previous cases (224Bytes for each of the *r* sequences, and 4Bytes for the Tag and Length fields). So, the lengh of the message including *basic Context Repository Information* for one mesh is $S_{b-CR,mesh}=\left\{74+\left(224\times r\right)\right\}$ Bytes (for example, for a mesh that contains the relevant information of 2 RANs, $S_{b-CR,mesh}=522$ Bytes). Correspondingly, the length of the message including *basic Context Repository Information* for *m* meshes is $S_{b-CR,m-meshes}=\left\{4+\sum_{i=1}^{m}\left\{74+\left(224\times r_m\right)\right\}\right\}$ (4Bytes surplus for the Tag and Length fields).

The length of the message containing *extended Context Repository Information* for one mesh, is the sum of its content parameters “mesh” and “contextData”. The size of the parameter “mesh” is 70Bytes and the “contextData” is $\left\{4+\left\{\left[58+\left(150\times s\right)\right]\times r\right\}\right\}$ Bytes, calculated respectively to the previous cases (it is noted that $\left[\left(150\times s\right)+4\right]$ Bytes is the size of each of the *s* sequences of the parameter “providingService”). So, the lengh of the message including *extended Context Repository Information* for one mesh is $S_{e-CR,mesh}=\left\{74+\left\{\left[58+\left(150\times s\right)\right]\times r\right\}\right\}$ Bytes. Conclusively, the length of the message including *extended Context Repository Information* for *m* meshes is calculated respectively.

4.6.9 Anticipated length of messages with Policy Repository Information

The anticipated length of the general policy of basic Policy Repository is calculated as probably the most commonly used. Each other policy has a small variation from this calculated size.

The length of the message containing a general policy of *basic Policy Repository*, is the sum of its content parameters "pid", "goO", "conditionData" and "actionData". The size of the parameter "pid" is 4Bytes, of the "goO" is 3Bytes, of the "actionData" is 100Bytes and of the "conditionData" is 117Bytes, calculated respectively to the previous cases (115Bytes for the contained parameters and 2Bytes for the Tag and Length fields). So, the lengh of the message including a general policy of *basic Policy Repository* for a mesh is $S_{b-PR,general} = 224$ Bytes. A message that would include policies for more than one mesh, it will obvioulsy have size approximately multiple of the calculated above.

4.7 Conclusions

The determination of the presented procedures (and their contained messages) constitutes the base for the implemenation of the corresponding interfaces. The estimation of their anticipated size, constitutes means for the determinantion of the corresponding bandwidth for the transmission of the necessary messages for all cases (even when their size has the almost possible maximum value), which will assist the operators of the managed RANs to ensure the availability of the essential bandwidth under any circumstances. Besides, it may act as criterion for the selection of the proper legacy exchange protocols between the different candidate protocols from the operator(s) of the management architecture or as determinant parameter in the design process of new specified protocols.

Furthermore, the results of the calculations demonstrate that the accrued signalling load of the corresponding procedures is relatively small for the managed RANs and the MTs. This fact is proved in the sequel through proper experimentation and simulation. Specifically, in case of the procedures that concern the managed RANs, and where the anticipated size of the procedures is bigger than the size of the load of the procedures related to MTs, is taken into consideration that the interface between the RANs and the NRM will, most probably, be effected in core network, so the amplitude of the respective signalling load will not perturb, even in case of large RANs with significant number of operating *AP*s and services, as it will constitute a small portion of the available bandwidth. Finally, these results constitute besides an evidence for the viability of the management architecture.

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΑ

Chapter 5

Assessment of the Management Architecture

5.1 *Introduction*

The assessment of the management architecture concerns the evaluation of the performance of the architecture and the estimation of the management burden which is induced by the incorporation of the described management functionality into the network. The assessment was effectuated based on experimentation and simulation and the assessment criteria, regarding the performance of the management architecture and the management burden, were specific metrics of network operation. Specifically, the assessment is based on measurements of management signaling loads and corresponding prerequisite bandwidth, time delays associated with the operation of the proposed architecture, as well as the reaction time of the management system for the resolution of definite problematic network situation. The measurements were performed for two important scenarios, the operation of the management architecture in normal network conditions and in heavy network conditions. Especially, the second case is of extremely importance, as the successful operation of the network and the satisfaction of user's demands in heavy network conditions, via appropriate interventional actions, was one of the substantial points of reasoning in design process of the management architecture and simultaneously is one of its leading goals.

5.2 Experimentation Platform Description

The effectuation of the assessment of the management architecture was based on the agents paradigm. Agent is a software component that is autonomous, proactive and social [98]. The term autonomous signifies that agents have a degree of control on their own actions and, under some circumstances, they are able to take decisions, the term proactive refers to agent's capability to react in response to external events, to exhibit a goal-directed behaviour and to take initiative in appropriate conditions, and the term social signifies that agents are able to interact with other agents, in order to accomplish their task and achieve the complete goal of the system [98].

Specifically, the performance of the management architecture was assessed through a multi-agent environment. In a multi-agent environment/system, every component of the system utilizes a concrete intelligent agent, which acts as a mediator between the component's functionality and the other components of the system. This influential reason led to the selection of the multi-agent environment for the assessment of the management architecture, as the capability of accomplishment of a loose coupling of the entities/components that constitute the management architecture, has to characterize the assessment framework.

The assessment of the management architecture was brought into effect based on the JADE platform. JADE (Java Agent DEvelopment Framework) is a software (open source software) framework fully implemented in Java language, which simplifies the implementation of multi-agent systems through a middle-ware that complies with the FIPA specifications [99]. FIPA is an IEEE Computer Society standards organization which promotes agent-based technology [100]. FIPA specifications consist of standards that are intended to promote the interoperation of heterogeneous agents and the services that they can represent. These standards concern agent communication, agent transport, agent management, abstract architecture and applications. The JADE platform can be distributed across machines (even of different operating systems) and the configuration can be controlled via a remote graphical user interface (GUI)[99]. Also, JADE architecture can be configured to adapt to the characteristics and requirements of the deployment environment in terms of connectivity, memory and processing power [98]. Furthermore, as the JADE platform is based on standard technologies like JAVA and XML, the interoperability requirement (for future realization of different scenarios for assessment of different operational parameters) is satisfied. Finally, the JADE platform is an open source framework, which enables the incorporation of modifications that may be accrued from the needs of heterogeneous wireless communications environment.

In JADE platform, as it applies to multi-agent environment, each of the comprising components of the system/architecture is a distinct software entity, namely, an agent. Each agent is developed individually, and is free to join and leave the platform independently. This feature enables the effortless integration of new or old functionality into the platform, with introduction of the corresponding agent. The components (agents) can interact via messages, according to the FIPA Agent Communication Language (ACL) message structure specification. FIPA ACL is based on the speech act theory and on the assumptions and requirements of the agents paradigm. The structure of the messages includes fields, such as variables indicating the context of message and timeout that can be waited before an answer is received, which aim at supporting complex interactions [98].

Therefore, in the experimentation platform [101] there are agents which act as high level interfaces between the entities (managed entities and management system) and the environment (which consist of the other entities except from the reference one), and ensure their communication through asynchronous exchange of messages (a communication model established for distributed and loosely – coupled communications [98]). It is noted that there is one agent in each of the entities MT, RAN and MA, an agent in NRM, which undertakes the role of communication of all the NRM's functions with external entities except Repository, and an agent in Repository. The discrimination regarding the different agent for the function of Repository, even though Repository is a function of NRM entity, is effected in order to simplify the realization of scenarios, as well as to feature the determinant role of this agent, which in this implementation carries into effect the role of the radio enabler.

A significant feature of the experimental platform is the integrated traffic generator, which enables the flexible and simplified realization of the scenarios, via centralized generation and control of the prerequisite traffic for the conduct of each test case. Specifically, the traffic generator is an agent that generates MT requests for various types of services on behalf of the related MT agents and forwards these requests to the corresponding MT agents, which in turn forward them to the proper entities according to the executed scenario. Furthermore, the traffic generator feeds the RAN agents with background traffic, the characteristics of which are determined by the RAN's configuration and the demands of the scenario under execution.

Traffic generator generates both simulated and emulated traffic. The term simulated traffic signifies statistical magnitude derived in the generator, concerning information that is used in order to be composed the suitable network context (for example, total bandwidth consumption for a service) according to each specific scenario. The term emulated traffic refers to traffic data that are generated from software that can be executed in real hardware terminals (for example, PDAs), but due to limited relevant resources during the implementation of the assessment environment, the corresponding software was executed on laptops. All the messages and the related traffic (simulated and emulated) are sent through the network and so, measurements can be effected and analyzed.

The topology that was used for management architecture assessment is depicted in Figure 5-1. It is noted that the RAN in the experimental framework consists of only one access point (which is actually utilizing a WLAN 802.11g interface), which forms the wireless segment of the experimental platform.

NRM, MA, RAN, Repository agents, as well as traffic generator run in different machines/computers. On the computer that runs the RAN related software agent, also reside a number of agents which act as mobile terminals. Namely, numerous instances of MT software have been executed on one laptop. All the computers are connected on the same local network.

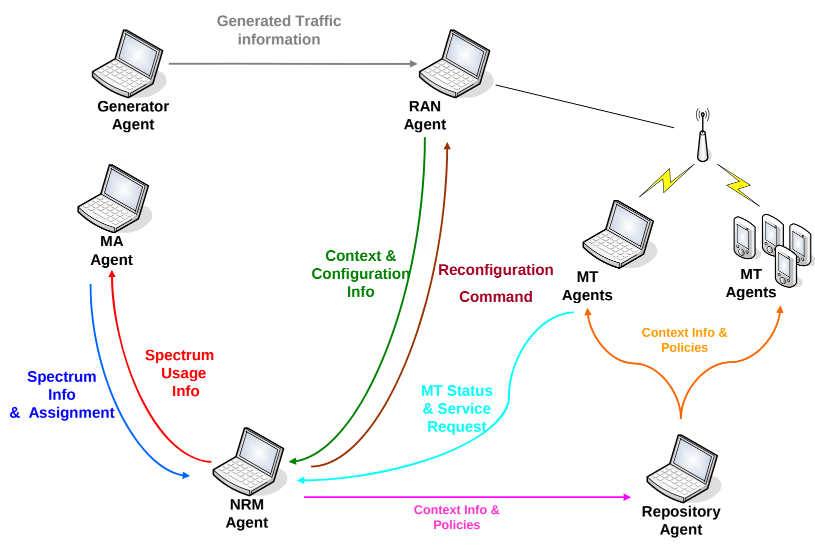

Figure 5-1: Topology of experimental platform for management architecture assessment

After modification and recompilation of the source code of JADE [101] [102], it is feasible to be recorded into a file, the timestamp (according to the operating system time), the total received or sent bytes, as well as the signalling data bytes of every message that is sent or received by an agent, on behalf of the corresponding entity. These records were performed on a per agent basis. Offline combination and/or correlation of this information were effected in order to be carried out the proper calculations for the assessment [101]. For example, the time frame in which an agent sends a request and then receives the response or an acknowledgement, can be calculated by subtracting the relevant timestamps.

5.3 Implemented Scenarios

For the assessment of the management architecture two characteristic scenarios were conducted [101]. Specifically, the performance of the architecture was studied in the context of RAN operation in normal conditions and in heavy traffic conditions. For the implementation of the scenarios in the JADE based platform, a set of messages respectively with the messages that presented in the previous chapter but in a slight simplified form, which contain the information of the chapter 3, were used. These messages were encapsulated in the ACL messages according to the FIPA specifications. It is noted that the message transport protocol used by JADE is based on Java Remote Method Invocation (RMI) [103], which provides a simple and direct model for distributed computation with Java objects. The ACL messages are serialized and transmitted over TCP connection. As result of the aforementioned procedure, there is an overhead in the total number of bytes that are conveyed for management reasons, which is also captured in the final results.

In the framework of the assessment, the values of the messages' parameters is dummy information, with no real meaning. Moreover, the size in bytes for each of the parameters is determined from their mapping to the most appropriate software variables and/or structures (e.g. java integers, doubles, arrays etc), according to the specification of the messages that presented in the previous chapter.

5.3.1 Scenario 1: Operation of the Management architecture in normal network conditions

The first scenario corresponds to the operation of the management architecture in the context of normal network conditions [101]. As presented before, the MTs of the scenario were emulated by running numerous MT agents on the same computer. The traffic generator was triggering the MT agents to start or stop a specific service, acting as the scenario conductor. This actuates MTs to send a *StatusNotification* message that consists of proper information. For example, when a MT demands a service, it sends a *StatusNotification* message, which from the whole possible information that presented in Chapter 3, comprises its current Configuration, its Geographic Coordinates, its Mobility Profile, its Priority of communication, the requested service with the corresponding QoS level and its currently active interfaces with the corresponding measured SINR.

The RAN agent was interacting with the MT agents of its area and the NRM. The NRM periodically was retrieving the RAN's context and configuration information by sending a *Context&ConfigurationRequest* message to RAN, which was sending back the corresponding information with *Context&ConfigurationResponse* message. The *Context&ConfigurationResponse* message contained the status of RAN's operating *AP*s, namely their operating frequency, their coverage area and their current and predicted load (as noted before in the experimental platform exists only one *AP*). RAN was reporting to NRM the emulated traffic load from the MTs agents and the simulated traffic load from the traffic generator. The simulated traffic data depend on the generated events that correspond to a set of specific determined services (for example an event corresponding to a voice call initiation reserves 12.2 kbps at the RAN) [101]. The message sequence between the NRM, the RANs and the MTs is depicted in Figure 5-2 [101] and a short description of the exchanged messages in the first scenario is presented in Table 5-1.

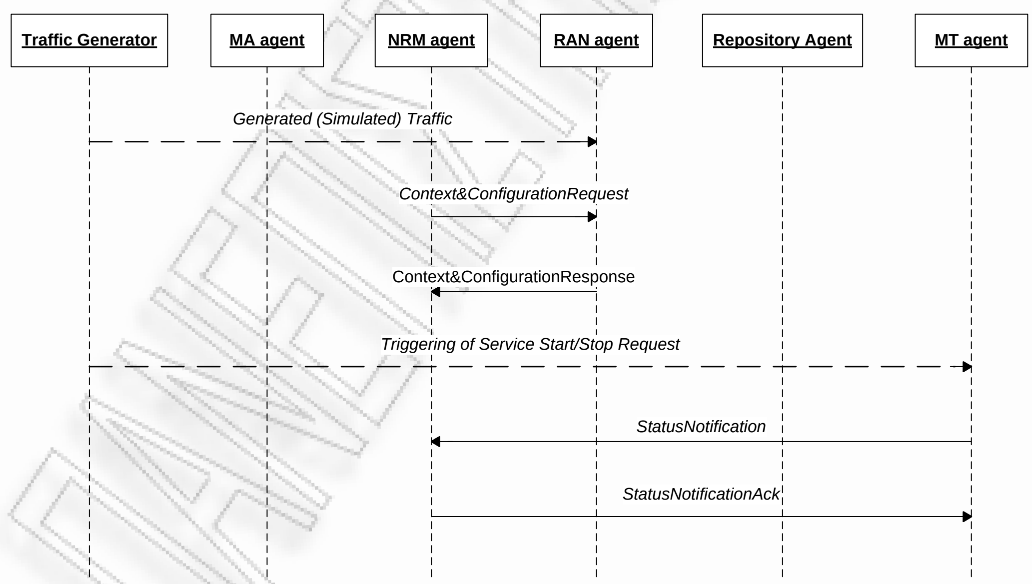

Figure 5-2: Message sequence chart for the scenario of the operation of the management architecture in normal network conditions

Interface	*Message Name*	*Description*
NRM-> RAN	***Context&ConfigurationRequest***	Request for RAN context & status information
RAN-> NRM	***Context&ConfigurationResponse***	RAN context & status information
MT -> NRM	***StatusNotification***	Terminal status & context information
NRM-> RAN	***StatusNotificationAck***	Acknowledgement for received ***StatusNotification*** message

Table 5-1: Description of messages exchanged in the scenario of the operation of the management architecture in normal network conditions

The fluctuation of the RAN's load over time, in terms of bandwidth consumption, is represented in Figure 5-3 [101]. The load is presented with two different lines that cumulatively comprise the total bandwidth consumption. The dashed line represents the user data and the solid line the management data. The lines represent the results that accrue from the test case in which new active users have constantly added to the RAN, increasing the prerequisite bandwidth. The spikes in the line of management data are due to the deliberate choice of synchronizing the transmission of *StatusNotification* message from MTs, in order to investigate the effect of the worst case scenario in which all the MTs inform at the same time for their status [101].

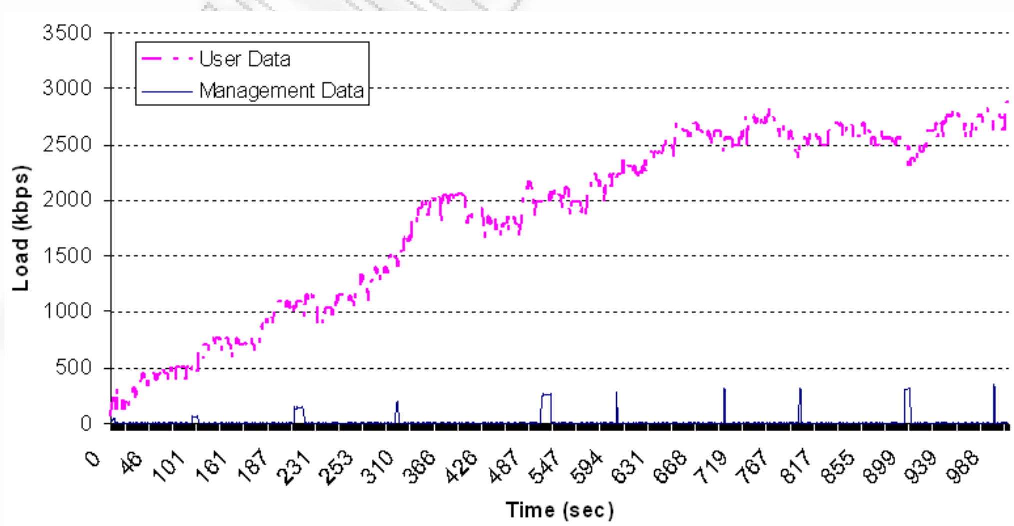

Figure 5-3: Traffic load for service data and management data

It emerges that even when the MTs report their status to the NRM coinstantaneously, the relative bandwidth is small comparatively with the necessary bandwidth for the transmission of user data. Conclusively, the necessary surplus bandwidth that is required for the exchange of the proper messages between the entities in the framework of the operation of the architecture, corresponds to a small proportion of the total RAN's load. Therefore, the level of the management burden in case of the operation of the management architecture in the context of normal network conditions is acceptable and it will not cause difficulties in ordinary network operation.

5.3.2 Scenario 2: Operation of the Management architecture in heavy traffic conditions

As already mentioned, the successful operation of the network in heavy network conditions, via appropriate interventional actions, is one of the main goals of the management architecture. In this framework, the second scenario focuses on assessing of the management burden in case of heavy network conditions. For that reason, various test cases were set up and executed, each of one concentrating on a different performance assessment aspect [101].

The scenario of the operation of the management architecture in heavy network conditions is represented in Figure 5-4. In this scenario, with the assistance of traffic generator, the managed RANs are loaded with traffic and a chosen RAN is loaded with augmented traffic, which after a time frame exceeds a specific threshold. This excess provokes the transmission of *Context&ConfigurationNotification* message from the RAN to NRM, which thereafter activates the proper processes in NRM.

Specifically, the Information Collection & Processing Function sends to the other managed RANs of the same geographical area, than the chosen one, the *Context&ConfigurationRequest* message and receives the corresponding *Context&ConfigurationResponse* with the relevant network status information. From the processed information that is obtained from Information Collection & Processing Function, Spectrum Evaluation Function, by its evaluation procedure, detects that the current spectrum allocation, which is used from RAN Reconfiguration Decision Function in order to determine the final RAN's configuration, is possible inadequate and there is necessity for re-allocation of the available frequencies. For this reason, Spectrum Evaluation Function sends the evaluation results to MA agent via *SpectrumUsageEvaluation* message. After the appropriate procedures, the MA agent sends to NRM the new allocation of the available frequencies to RATs with *SpectrumAssignment* message. Thereafter, RAN Reconfiguration Decision Function determines the reconfiguration the chosen RAN, and probably also the reconfiguration of a number of the managed RANs, in terms of operating frequencies, RAT or both. The reconfiguration commands are sent to each corresponding RAN with *ReconfigurationRequest* message.

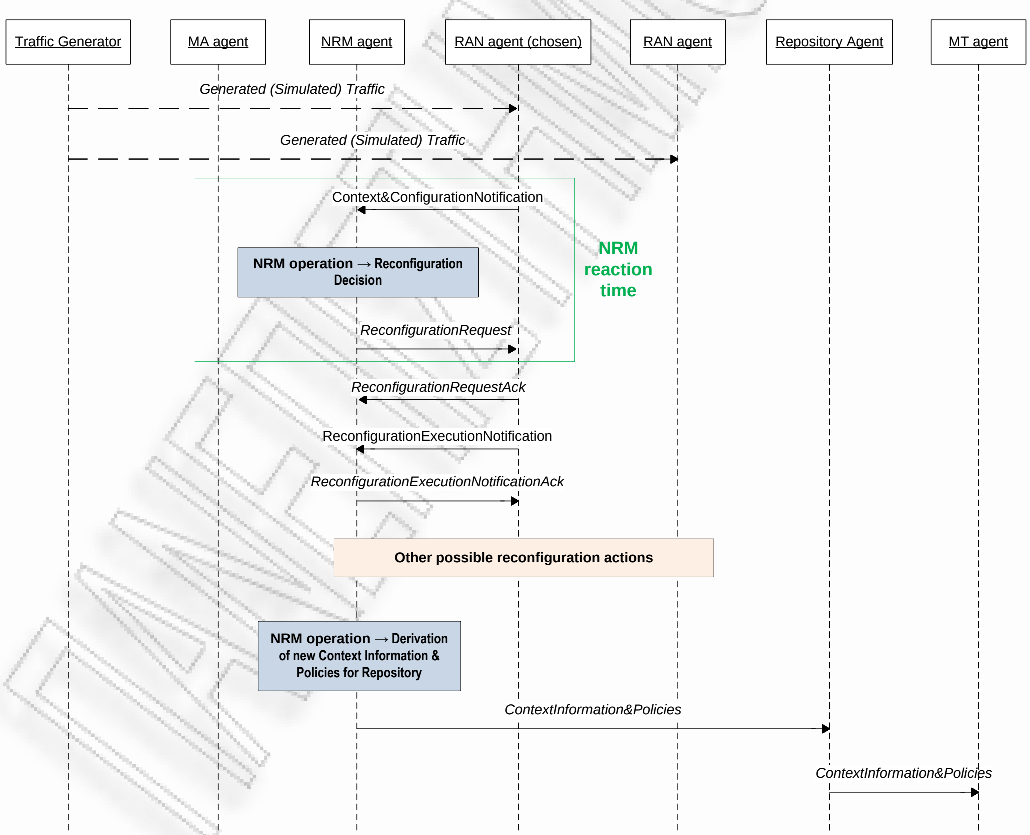

Figure 5-4: Message sequence chart for the scenario of the operation of the management architecture in heavy network conditions

The steps of the Reconfiguration Decision Process of NRM operation and the corresponding messages between the NRM agent and the other implemented agents, in order NRM to eventuate in Reconfiguration Decision in this scenario, are illustrated in Figure 5-5. A concise description of the messages, which they comprise the information that was analytically presented in Chapter 3, is displayed in Table 5-2.

When the reconfiguration procedure is accomplished, the RAN sends to the NRM a *ReconfigurationExecutionNotification* message and receives the corresponding acknowledgement (*ReconfigurationExecutionNotificationAck* message). After the completion of all the reconfigurations procedures, Information Collection & Processing Function forwards the new accrued context information to Repository and Policy Derivation Function derives new policies for current networks conditions that is also forwarded to Repository, which undertakes the mission of sending them to the MTs.

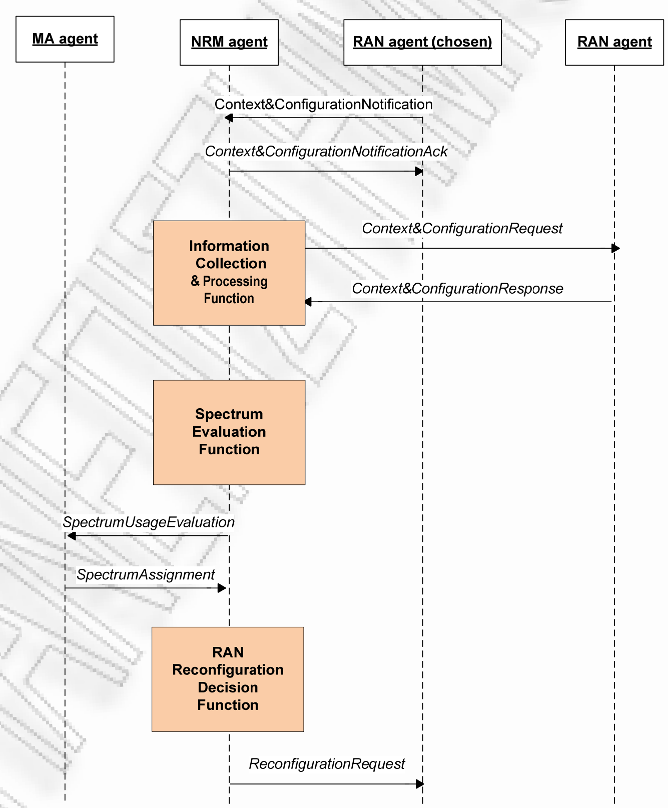

Figure 5-5: Message sequence chart for Reconfiguration Decision Process of NRM operation

Interface	*Message Name*	*Description*
RAN→NRM	***Context&ConfigurationNotification***	RAN context & configuration information
NRM→RAN	***Context&ConfigurationNotification Ack***	Acknowledgement for received ***Context&Configuration Notification*** message
NRM→RAN	***Context&ConfigurationRequest***	Request for RAN context & status information
RAN→NRM	***Context&ConfigurationResponse***	RAN context & status information
NRM→MA	***SpectrumUsageEvaluation***	Information on spectrum usage evaluation metrics
MA→NRM	***SpectrumAsssignment***	Spectrum assignment directives
NRM→RAN	***ReconfigurationRequest***	Request for RAN reconfiguration

Table 5-2: Description of messages exchanged in Reconfiguration Decision Process of NRM operation in the scenario of the operation of the management architecture in heavy network conditions

A short description of the exchanged messages in the second scenario is presented in Table 5-3.

Interface	*Message Name*	*Description*
RAN→NRM	***Context&ConfigurationNotification***	RAN context & configuration information
NRM→RAN	***ReconfigurationRequest***	Request for RAN reconfiguration
RAN→NRM	***ReconfigurationExecutionNotification***	Notification for the successful execution of reconfiguration
NRM→RAN	***ReconfigurationExecutionNotification Ack***	Acknowledgement for received ***ReconfigurationExecution Notification*** message
NRM→ Repository and Repository→ MT	***ContextInformation&Policies***	Information for the status of the networks in the vicinity of MTs and radio resource selection policies

Table 5-3: Description of messages exchanged in the scenario of the operation of the management architecture in heavy network conditions

One of the most significant metrics that constitute indicator of the viability of the architecture, is the surplus bandwidth that is demanded for the exchange of the necessary messages for the management operation in heavy network conditions. A large amount of prerequisite bandwidth for the relevant signalling load entails appreciable grade of difficulty in the incorporation of the management functionality in network operation. In this framework, the total number of bytes, which occur from the incorporated management functionality, and the corresponding bandwidth that was consumed for their transmission are depicted in Figures 5-6 and 5-7 respectively [101]. The presented results were collected by processing the relevant record files [101]. The columns in Figure 5-6 represent the total number of bytes that are needed for the communication between the involved entities. The upper part of these columns depicts the bytes that are actually containing management information. The affined overall signalling load arises also from the overheads imposed by the underlying layers' communication protocols (namely, in this case, Ethernet, IP and TCP), and the involvement of the agent platform.

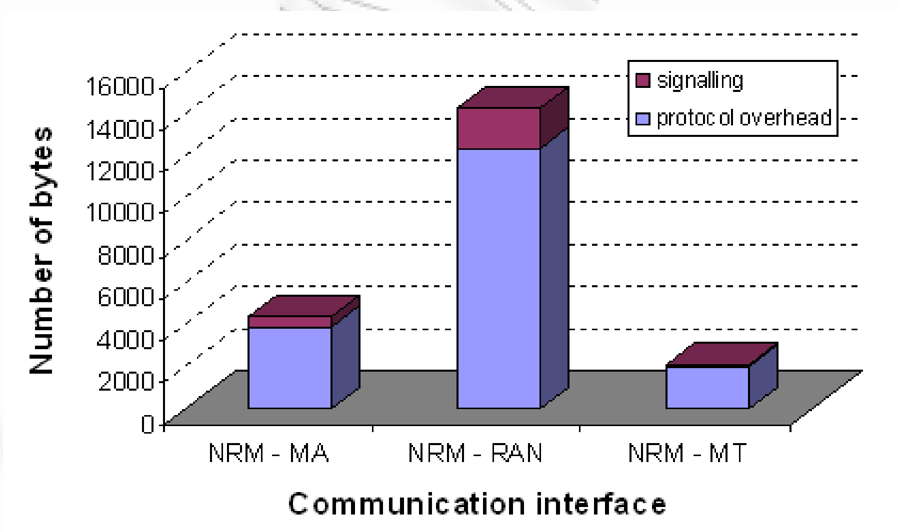

Figure 5-6: Transmitted bytes for incorporated management functionality in the scenario of heavy traffic conditions

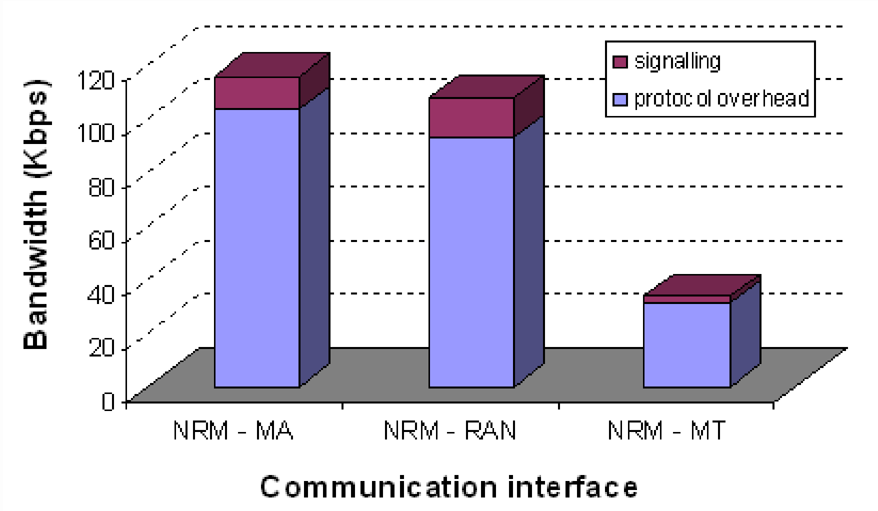

Figure 5-7: Prerequisite Bandwidth for incorporated management functionality in the scenario of heavy traffic conditions

The FIPA-ACL language, which is used by the agents in the experimental platform, is close to a human communication protocol and certainly less efficient than the "bitwise" implementation of a protocol based directly on TCP/IP. Nevertheless, JADE platform offers the desired simplicity and flexibility in the software development, the test-bed configuration and the scenario setup, and the capability of tracing useful information, such as the bandwidth that is utilized for management reasons in this case [101].

From the results presented in Figures 5-6 and 5-7, it is obviously that the management burden is low even as an absolute value. This fact constitutes important evidence for the viability of the management architecture.

Another significant point that it has to be examined, is the Reaction Time of NRM in accrued network problematic situations. Scilicet, the time that is needed from NRM in order to resolve a problematic network state. The Reaction Time depends on many factors, such as the number of the involved entities (namely, the number of the managed RANs and the connected MTs), the operative capabilities (namely, hardware and software characteristics) of the entities that implement the NRM's functions, the complexity of the congruent computations for each case, etc. It is noted that most of the influence factors of the NRM Reaction Time depend on the way of implementation of the management architecture. The most significant factor from the abovementioned, is the number of the managed RANs and the connected MTs. For this reason, proper measurements/calculations were performed in order to appraise its influence [101].

Several RAN agents were executed and, with the assistance of the traffic generator, loaded with the desirable traffic load. It is noted that in this case, the RAN agents did not control any real AP and their status was constantly updated by the traffic generator with the whole necessary information (presented analytically in Chapter 3). Based on the scenario, the majority of the users were connected to the same RAN (chosen RAN), having as result after a short time its load to exceed a definite threshold, which is the yardstick for the state of the RAN. The excess of this bound constitutes the triggering point for the transmission of the *Context&ConfigurationNotification* message from the RAN to NRM and thereafter the initiation of the proper actions from the management architecture. The Reaction Time in this scenario is from the time that the agent of the RAN, which faced the problem, sent the *Context&ConfigurationNotification* message to the NRM agent, until the same agent received the message with the proposed solution of its problem (which is its reconfiguration) from the NRM, via the respective message (*ReconfigurationRequest* message).

In order to be evaluated the influence of the number of managed RANs to Reaction Time, measurements were performed for six different test cases [101]. In these cases the number of involved MTs was almost stable (between 40 and 50 terminals), while the number of RANs (each of which comprised one *AP)* in the managed area was varying from 1 to 6. The majority of the MTs (more than 35 MTs) were always served by the chosen RAN. The measurements are depicted in Figure 5-8 [101], which illustrates the dependence of Reaction Time on the number of RANs, where in this case coincide with the number of *AP*s.

Five different test cases were carried out in order to assess the influence of the number of connected MTs to Reaction Time [101]. In these test cases, three different RANs comprised the network scene, while the number of MTs in the area was ranging from 35 to 95. The measurements are depicted in Figure 5-9, which illustrates the dependence of Reaction Time on the number of MTs [101].

The comparison between Figure 5-8 and Figure 5-9 shows that the grade of influence of the number of the managed RANs to Reaction Time is larger than of the number of the connected MTs. This results from the fact that as the number of the managed RANs is increasing, the necessary communications with managed RANs (via the proper messages/procedures) are increasing and also the significant parameters for the management process are increasing, as well as the number of the network elements that are involved in the final decisions for the overall optimization of the operation of the managed RANs. The augmentation of the number of MTs entails the increase of the essential information for the processing function of the management architecture, which affects in relatively small scale the reaction time. Conclusively, the test cases indicated that the management architecture is able to tackle problematic conditions and to optimize the operation of the involved entities in managed areas, which embrace several RANs and a high number of MTs as well.

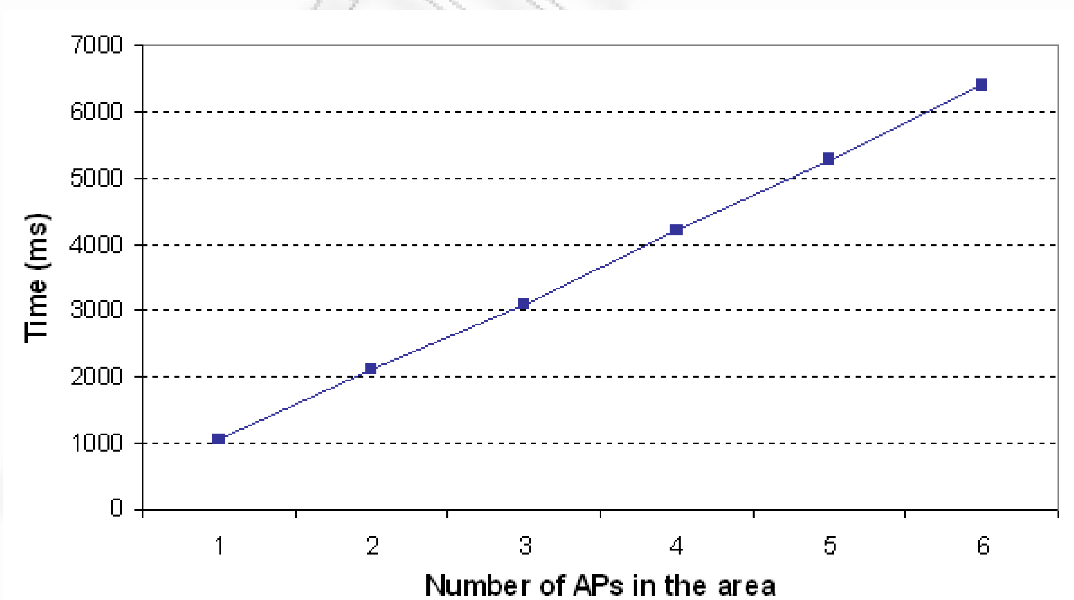

Figure 5-8: Dependence of Reaction Time on the number of *AP*s

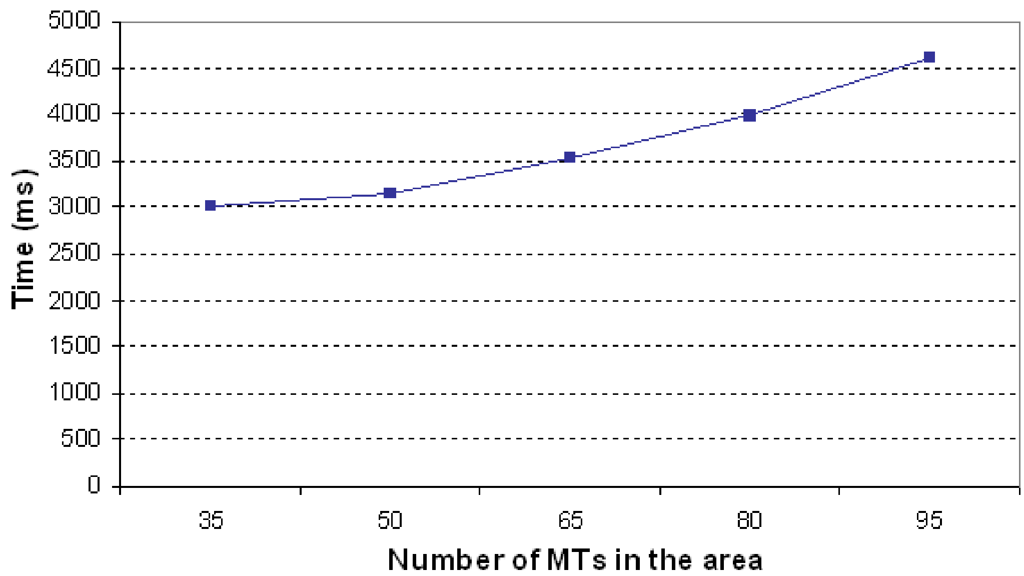

Figure 5-9: Dependence of Reaction Time on the number of MTs

The last issue that was examined, is the time that is needed for the enlightenment of MTs with context information for the managed RANs in the vicinity of MTs, as well as with the proper policies (namely, the information of Repository). For this reason, several tests were executed with different number of connected MTs in each test, varying from 20 to 45 MTs [101]. After NRM's derivation of managed RANs status and new policies, and the forwarding of this information to Repository agent, the necessary time in which the Repository agent manages to inform all the connected MT agents about the new network status and policies, was measured. In order to achieve the desirable accuracy in the measurements, one MT agent was executed on the same machine with the Repository agent, and it was designated to be the last MT agent which would be informed from the Repository. With this implementation, the timestamp of the first *ContextInformation&Policies* message sent by the Repository, as well as the timestamp recorded by the last MT agent when the message was received, is based on the same clock [101]. The rest of the MTs were all simulated and executed on the same, but different from the Repository's, machine. Figure 5-10 represents the dependence of the time of Repository's information transmission on the number of MTs [101].

As it is depicted in Figure 5-10, the requisite time for the transmission of Repository's information is less than a second in most of the cases. This fact confirms that the MTs will obtain the necessary information early enough in order to take the proper decisions for their needs, in the context of the time frame which is determined by the corresponding information.

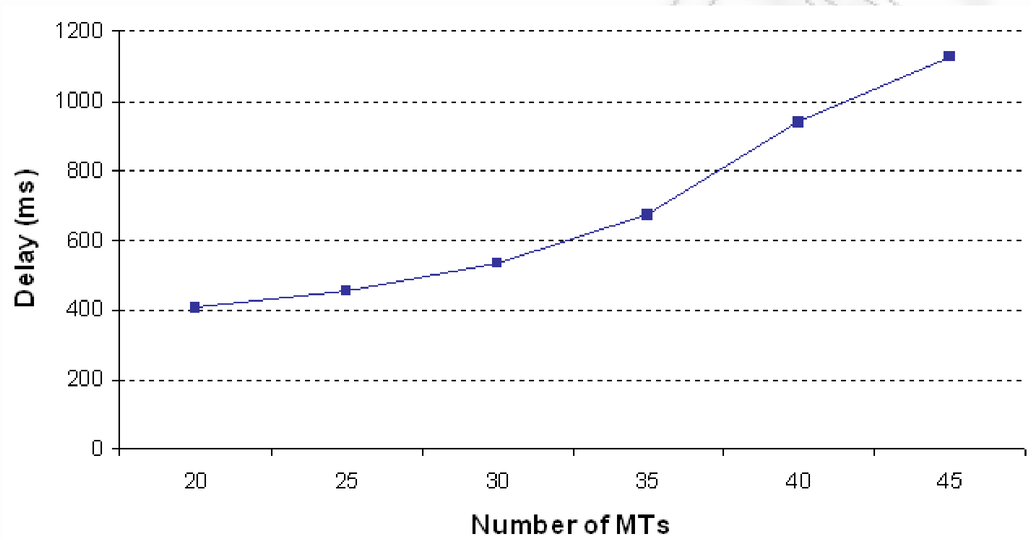

Figure 5-10: Dependence of the time of Repository's information transmission on the number of MTs

Chapter 6

Proposals for implementation of the interfaces of the Management Architecture

6.1 Introduction

The communication between NRM and the managed entities, namely RAN and MTs (for the effectuation of the procedures that presented in chapter 4), as well as the between NRM and MA, demands the existence of suitable interfaces. The realization of these interfaces neccesitates the determination of proper mechanisms and information exchange protocols. The protocols may be legacy or new specified, and may operate in different layers of the OSI model. In this framework, the chapter presents the basic requirements for effectuation of the interfaces, as well as candidate solutions.

In the sequel, it is taken under consideration the fact that, as it has already been presented, NMR may be materialised in a fully centralised way or in hybrid way, where some operations may be effected in different network entities of core network. The effectuation of the fuctions of NRM in elements of core network results from the necessity for central procession of the essential information for the operation of the architecture and the corresponding essential processing power.

6.2 Interfaces between MTs and NRM

6.2.1 Information transmission from MTs to NRM

The transmission of the necessary information for the operation of the management architecture from MTs to NRM, will be effected via the current RAN with which each MT is connected to, using the respective protocols of the operating RAT of the specific RAN. The information may be transmitted with corresponding way as in any web application in application layer.

6.2.2 Information transmission from NRM to MTs - Radio Enabler

Cognitive Pilot Channel (CPC), as already mentioned, constitutes a congruent means for propagation of the necessary miscellaneous information that is included in Repository. In order to be confronted the difficulties which accrue from the diversity of the essential information that has to be transmitted in the context of composite radio environment and the complexity of 4th generation wireless communications, two different alternatives for realization of CPC have been proposed inside E2R and ETSI work: in-band and out-band CPC. The term in-band corresponds to the usage of existing logical channels e.g. Broadcast Control Channels (BCCH) as defined in GERAN. Conversely, the term out-band corresponds to the usage of newly defined, physical channels outside the frequencies assigned to existing RATs, for the conveyance of the necessary information. Specifically, "in the Out-band solution, the CPC either uses a new radio interface, or alternatively uses an adaptation of legacy technology with appropriate characteristics" [65].

The form of CPC that would be used for propagation of Repository's information, depends on the business scenario in the frame of which the proposed management architecture operates [56]. In case that the management system operates under control of a network operator that operates RANs of different RATs, all kinds of communication between NRM and RANs/MTs are perfomed via in-band downlink and uplink legal channels. If the management architecture operates in the framework of a consortium, frequencies from the common spectrum poll, can operate as an "out-band" downlink CPC for propagation of content of b-CR and b-PR to MTs. The MTs of the members of the consortium are aware of these operating frequencies and tune into them when they power on. The propagation of the content of e-CR and e-PR is accomplished by in-band CPC after connection of MTs with an initial RAN, in order the related information to be used for optimization of their operation. Finally, if the management architecture operates in regional or national level, the most efficient solution is a real out-band broadcast CPC [70] for propagation of content of b-CR and b-PR, with the obvious difficulties for its realization in regulatory level, and in-band CPC for content of e-CR and e-PR. For this scenario, an effectual materialization of in-band CPC is an on-demand CPC, as presented in [104], with uplink and downlink components. In this instance, MTs request the respective information from e-CR and e-PR only when is needed, avoiding radio resources waste.

6.3 Interface between RANs and NRM

In the framework of the operation of the management architecture, the exchange of the messages of the elementary procedures in the interface between RANs and NRM, requires the potentiality of transmission of the corresponding signalling information, independently from the underlying technology in Link Layer and the different version of IP protocol in Internet Layer. In this context, the Stream Control Transmission Protocol (SCTP) [105][106], which is an end-to-end transport protocol for IP networks, is the most suitable candidate protocol for the interface between NRM and RANs, as it meets the relevant requirements.

Significant features that conduce to emergence of SCTP as the dominant Transport Layer protocol for the interface between RAN and NRM, are:

- SCTP is message oriented and supports framing of individual message boundaries.
- SCTP is rate adaptive, according to the prevailing network conditions.
- SCTP supports multiple IP addresses in endpoints (multi-homing feature).
- SCTP enables a flexible delivery scheme through multiple streams, capable of independent delivery (multi-streaming feature). So, if there is message loss in one stream, this affects delivery within that stream only, and does not affect the corresponding operation in the other streams.
- SCTP has been designed with features for improved security and reliability, and besides, it can utilize the IPsec for strong security and integrity protection of transmitted information.

Furthermore, it is noted that under special conditions, in which native SCTP is not supported by the operating system of one of the communicating endpoints, there is possibility of tunneling the SCTP stream over UDP.

From the numerous existing protocols in Application layer, Diameter is the most suitable candidate protocol for the aforementioned interface between NRM and RANs. Diameter consists of a base protocol and a set of “descendant” protocols, which are called Diameter applications and are based on the Diameter base protocol. The Diameter base protocol ensures reliable transport via errors notification. Furthermore, the usage of Diameter CMS (Cryptographic Message Syntax) application can enhance the security of communication between the communicating entities, as it provides end-to-end authentication and information’s integrity.

The structure of the Diameter base protocol enables its extensibility. Specifically, data transmission is performed by Attribute–Value Pairs (AVPs), and each Diameter Application can add new AVPs according to its demands. In this framework, a new

Diameter Application may be defined for each procedure that is effectuated in the interface between NRM and RANs.

In the framework of the operation of the management architecture under the control of one network operator, the NRM may exchange some signalling information even directly with the *AP*s (concering their configuration information). In this case, it is required suitable modification of the corresponding procedures and their contained messages (so, for example there will be a message that may be called *ConfigurationNotification* message, which may be send be each *AP* and include only the parameters “time” and “accessPointsInfo” from the parameters of the corresponding message *Context&ConfigurationNotification)*. The proposed conjunction of protocols enables this kind of communication.

Moreover, SCTP has been selected to be used as transport layer of S1-MME signalling bearer for the interface between the eNBs and the E-UTRAN core network [107]. This fact entails:

- the potential exploitation of the procedures that will be specified in the framework of S1-MME.
- the smooth transition of 3GPP2 systems to full reconfigurable cognitive 4th generation wireless systems, and
- the coinstantaneous efficient operation and association of systems of both generations.

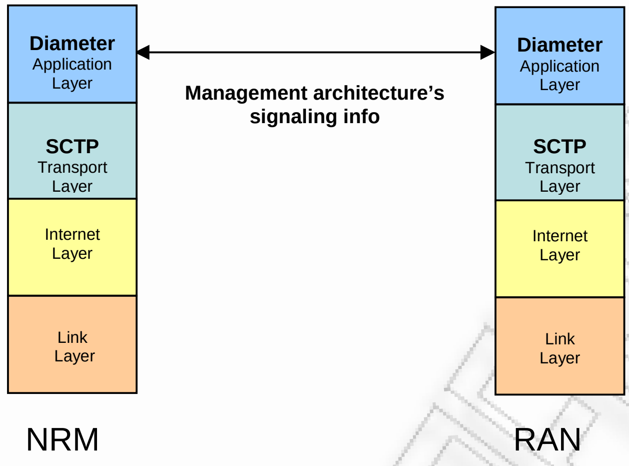

Figure 6-1: Implementation of interface between NRM and RAN

6.4 Interface between MA and NRM

The way of realization of the MA will be decided based on the scenario in the context of which operates the management architecture. Speicifically, if the management architecture operates under control of an independent organization in regional or national level, the transmitted information to the external entity MA has the form of concrete messages with definite content, which have to be transmitted independently from the underlying technology in Link Layer and the different version of IP protocol in Internet Layer.

In this case, the proposed scheme in the previous paragraph, namely the usage of Stream Control Transmission Protocol (SCTP) in Transmission Layer and Diameter Protocol in Application Layer with new corresponding specified application for this communication, is the most suitable candidate solution for the effectuation of the relevant interface.

If the management architecture operates operates in the frame of a consortium, then the MA may be effectuated as an independent external entity, where the aforementioned proposed scheme for the exchange of the relevant information is also the most suitable solution. Besides, it could be decided the implementation of the MA in the operation and management segment of one of the managed networks. In this case, the usage of GPRS Tunnelling Protocol v2 (GTPv2) [108] is suitable for the effectuation of the interface between MA and NRM. Specifically, GTP version 2 control plane (GTPv2-C) meets the requested requirements and it is already used to support the exchange signalling messages between entities of 3GPP Evolved Packet System. The specific new version of GTP-C may operate above UDP protocol in transmission level, as it is depicted in Figure 6-2. The modification of GTPv2-C header and the specification of the information elements will be determined after the exact definition of the related information in the corresponding procedures from the cooperated operators.

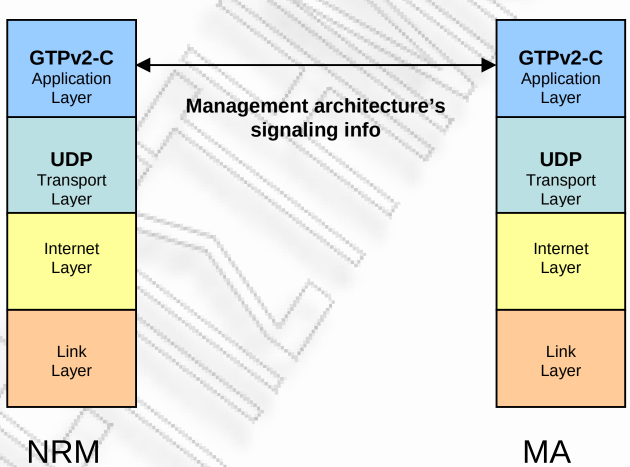

Figure 6-2: Implementation of interface between NRM and MA in case of realization of MA in operation and management segment of the network of a cooperated operator

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΑ

Chapter 7
Summary – Ongoing Challenges

7.1 Introduction

The heterogeneous high-speed 4th generation wireless communications environments call for advanced management functionality. In this thesis, a management architecture is presented as a means to guide both reconfigurable Radio Access Networks and cognitive mobile terminals in such a challenging environment. The management architecture, by utilizing the cognitive capabilities of MTs and RANs and the advantages of Software Defined Radio Technology, Reconfigurability and Flexible Spectrum Management, increases the efficiency of the overall managed system. The architecture effectuates combined optimized spectrum and radio resource utilization, by optimally exploiting the diversity of the heterogeneous radio ecosystem. Specifically, the role of the designed management architecture is twofold. First, to determine the proper operating RAT and frequencies for each managed RAN (optimized spectrum utilization), and second, to direct MTs to the selection of the appropriate RAN to operate with (optimized radio resource utilization).

The management architecture, regarding the issue of radio resource selection, focuses on the policy-based, distributed decision-making between network and terminals.

Namely, the centralised management system directs terminals via policies, under which, MTs take the final decision based on their own specific strategies, commonly reflected to specific criteria. Policies are radio resource selection directives for the guidance of users, which are derived taking into consideration variant types of information, from many possible sources, such as the managed networks, terminals, network operators, regulators.

Two slightly differentiated approaches for the functional architecture was architecture were presented analytically, as well as the correlation of their functional elements. This correlation demonstrates the possibility of the necessary cooperation and interoperability of the two architectures. For the architecture that was adopted as base for the continuance of the research, the information flow between the functions that comprise the central management entity of the architecture, and the information flow between the central management system and the external entities were presented. In the sequel, based on the presented information flow, the messages that are exchanged between the central management entity and the managed entities were determined in terms of elementary procedures (the included basic parameters of the messages and their structure), and their anticipated size was estimated. The determination of the procedures and the estimation of their anticipated size, constitute the base for the implemenation of the corresponding interfaces. The realization of the interfaces neccesitates the determination of proper mechanisms and information exchange protocols for the effectuation of the aforementioned procedures. In this framework, the basic requirements for the effectuation of the interfaces, as well as candidate solutions were presented. Moreover, assessment of the management architecture, regarding the evaluation of the performance of the architecture and the estimation of the management burden, which is induced by the incorporation of the described management functionality into the network, was effectuated. The assessemt results prove the efficiency of the management architecture, as well as its viability.

The operation of the management architecture will benefit all the related groups: network operators, network and equipment manufacturers, service providers, regulators and users. Specifically, via the exploitation of the full diversity of the cooperated heterogeneous systems and the disposable frequencies, as well as the maximum re-usage of network elements and avoidance of the network overdimensioning for accommodation of the probable unstable traffic load, the management architecture will assist network operators to reduce their capital expenditures (CAPEX) and their operational expenditures (OPEX), and to provide optimal services to users, which will correspond to provision of applications with demanded Quality of Service and personalized and ubiquitous manner, with corresponding decreased price. Simultaneously, users will have the chance to experience in a seamless manner the desirable services in acceptable prices. Moreover, the architecture will facilitate the cooperation between the application and service providers and network operators, as it will reduce the required time frame for the deployment of enhanced features of the new applications and services. Furthermore, it will enable easier migration to new standards, which will facilitate the manufactures of network and terminal equipment. Finally, the management architecture can be a simple and powerful tool for regulators, in order to achieve spectrum efficiency optimization.

7.2 Ongoing challenges- Future research activities

Although, the content of the thesis enables the implementation of the management architecture in definite context, which will be determined from the strategies of the network operators, the particularity of their networks, as well as the conditions of the agreements among the cooperating network operators, there are research challenges regarding specific issues for the realization and operation of the management architecture and its integration to Future Internet. These topics will concentrate my research interest in the near future.

Specifically, future research may include the invention and implementation of algorithms that will be used to carry out the tasks of each specific functional entity. Special consideration will be taken for the investigation of methods and algorithms for the derivation of resource selection policies for MTs (from Policy Derivation Function), as well as for the assessment of policies' efficiency (from Policy Efficiency Function).

Furthermore, interesting research topic is the determination of the exact specifications for the implementation of the interfaces of the architecture, from the proposed mechanisms (CPC) and protocols.

Billing complexity, which will accrue from the seamless mobility of MTs among RANs that belong to different operators in case of the operation of the management architecture in the framework of a consortium, or under an independent authority in regional or national range, is also an open issue that will interest network operators.

Finally, Future Internet will be an integrated global network [88], which will consist of smaller interconnected networks, operating at diverse technologies, terminals with different operations and needs, and a variety of services. Each of the services will be characterized by a minimum Quality of Experience (QoE) level, which have to be guaranteed end-to-end, under any circumstances, from all the networks which are crossed by the relevant traffic. The augmented processing capabilities of information systems and the developing methods will enable the objective determination of QoE. Each QoE level will correspond to different definite Quality of Service (QoS) indicators per access technology. Consequently, in the connections of different network segments, the conditions have to ensure invariability of the specific QoE.

In this demanding environment, the management of networks generally and radio access networks specifically, as wireless access segments will constitute significant and the most vigorous part of Future Internet, will be key enabler for the implementation of Future Internet. The efficient management of Radio Access Networks (RANs) of different Radio Access Technologies (RATs), which will guarantee the satisfaction of MT's demands and RAN's interoperability with the other segments of Future Internet network, in order to be ensured the invariability of the aforementioned QoE, necessitates the adoption of innovative and reliable architectures, as the presented management architecture. In this context, it seems essential the existence of a Central Management Authority [109], which role will be the efficient coordination of the Future Internet networks.

Central Management Authority will process information collected from MAs, NRMs and the management entities of wired networks, in the context of the rules of relevant official (international and local) organizations, and it will decide on subjects such as the correlation of QoE levels to specific QoS indicators per RAT and service and the allocation of spectrum to RATs. Furthermore, it will control the implementation of QoE invariability in segment's connections, if the transmitted context and policy information ensures the independency of MT's behaviour and if it is consistent with the principles of free competition, etc. The topic of Central Management Authority operation is important for the realization of Future Internet and can concentrate significant research effort in different fields.

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΑ

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΑ

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΑ

APPENDIX – LIST OF PUBLICATIONS (MARCH 2011)

Short CV

Aristi Galani was born in Athens, Greece. She received the diploma in Electrical and Computer Engineering from the University of Patras in July 1999. Since September 1999 she works as a network engineer in the Network Management Centre at the University of Piraeus, where she has been actively involved in several projects concerning the design, implementation, development and management of telecommunication networks, services and applications. She is a member of the Technical Chamber of Greece. She has been involved in Information Communications Technologies (ICT) "End-to-End Efficiency" (E3) project, which was partially funded by the European Commision under 7th Framework Pragram (FP7). Her research interests include the design, management and optimization of communication networks and reconfigurable radio systems.

Journal Publications

1. A.Galani, K.Tsagkaris, P.Demestichas, "Information Flow for Optimized Management of Spectrum and Radio Resources in Cognitive B3G Wireless Networks", Journal Of Network and Systems Management, Volume 18, Number 2/June, 2010, DOI 10.1007/S10922-009-9150-4125-149

2. A.Galani, K.Tsagkaris, N.Koutsouris, P.Demestichas, "Design and assessment of functional architecture for optimized spectrum and radio resource management in heterogeneous wireless networks", International Journal Of Network Management, 2010, DOI 10.1002/nem.736

3. 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, vol.4, no.1, pp.42-48, March 2009

4. A.Kaloxylos, K.Nolte, K.Tsagkaris, T.Rosowski, M.Stamatelatos, A.Galani, E.Bogenfeld, P.Magdalinos, J.Tiemman, P.Arnold, J.Gebert, D.Von Hugo, N.Alonistioti, P.Demestichas, W.Koenig, "The E3 architecture: Enabling future cellular networks with cognitive and self-x capabilities", International Journal Of Network Management, 2010, DOI: 10.1002/nem.762

Conference Publications

1. A.Galani, K.Tsagkaris, P.Demestichas, "A functional architecture for optimized radio resource and spectrum usage in heterogeneous wireless networks", ICT-mobile summit 2008, Stockholm, June 2008

2. A.Kaloxylos, T.Rosowski, K.Tsagkaris, J.Gebert, E.Bogenfeld, P.Magdalinos, A.Galani, K.Nolte, "The E3 architecture for future cognitive mobile networks", IEEE International Symposium on Personal Indoor and Mobile Radio Communications, Tokyo, 2009

3. K.Tsagkaris, N.Koutsouris, A.Galani, P.Demestichas, "Performance assessment of a spectrum and radio resource management architecture for heterogeneous wireless networks", ICT-mobile summit 2010, Florence, June 2010

4. K.Tsagkaris, M.Akezidou, A.Galani, P.Demestichas, "Signaling load evaluations for policy-driven cognitive management architectures", BROADNETS 2010, 7th International ICST Conference on Broadband Communications, Networks, and Systems, Athens, October 2010, (invited paper)

Meeting -Workshop

1. A.Galani, K.Tsagkaris, P.Demestichas, "Functional architecture for optimized management and interoperability of radio access networks in Future Internet", Poster presentation, Future Internet Assembly (FIA) 2009, Stockholm, Sweden, 23rd-24th November 2009

2. G.Dimitrakopoulos, P.Demestichas, A.Saatsakis, A.Galani, "Exploitation of Location Awareness in Functionality for Cognitive Wireless Infrastructures", Presentation, Workshop on Localization and Context Awareness, September 28, 2009, Brussels, Belgium

Whitepaper

Z. Feng, Q. Zhang, P. Cordier, B. Mouhouche, C. Le Page, E. Buracchini, P. Goria, A. Trogolo, W. Hau Chin, A. Merentitis, J. Pérez-Romero, R. Agustí, O. Sallent, K. Tsagkaris, A. Galani, P. Demestichas, "Support for heterogeneous standards using Cognitive Pilot Channel (CPC)", White Paper του End-to-End Efficiency (E3) project, July 2009

Standardization Participation/Contibution

IEEE Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks, IEEE Std 1900.4™-2009, February 2009

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