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Σχολή Τεχνολογιών
Πληροφορικής και Επικοινωνιών
Τμήμα Ψηφιακών Συστημάτων

UNIVERSITY OF PIRAEUS
School of Information and
Communication Technologies
Department of Digital Systems

ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ

Γνωσιακά Συστήματα Διαχείρισης Για Δυναμικά Δίκτυα Πρόσβασης

Πέραν της 4ης Γενιάς

Ανδρέας Ν. Γεωργακόπουλος

Πειραιάς, 2015

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PH.D. DISSERTATION

Cognitive Management Systems for Dynamic Access Networks beyond 4th Generation

Andreas N. Georgakopoulos

Piraeus, 2015

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ABSTRACT

The vision of a wireless world beyond 4^{th} generation and towards the 5^{th} generation, which will be empowered with cognitive technologies comes closer to reality as traffic traversing through wireless networks gradually increases and novel techniques on cognitive, intelligent management and autonomicity are needed in order to handle effectively the ever-growing traffic demand, diversity and heterogeneity. The opportunistic exploitation of the radio-environment through operator-governed opportunistic networks (ONs) is one of the investigated areas towards the realization of that vision. Operator-governed ONs are dynamically created, temporary, coordinated, device-to-device (D2D) extensions of the infrastructure. Operator governance is being realized through the use of cognitive systems which acquire contextual information of the environment through control channels and make decisions on the creation of ONs.

ONs are intended to be operator-governed, in order to assist the infrastructure according to the rules obtained by the operator. Opportunistic use of resources through the establishment of ONs could be used in order to provide extra capacity in congested wireless access network segments e.g., by exploiting the possibility of using neighboring terminals or by utilizing small cells, in order to redirect traffic from congested service areas into non-congested ones.

Specifically, this dissertation has investigated the following issues:

- Definition of scenarios of ONs and D2D networks for coverage and capacity expansion of the infrastructure through the opportunistic use of neighboring

terminals that are available in a service area. These aspects are covered in Chapter 2.

- Development of an algorithm for the selection of nodes in order to be part of an ON so as to provide coverage extension of the infrastructure. The algorithm relies on the definition of a fitness function in order to be able to select the 'good' neighboring nodes by categorizing them according to certain criteria. These aspects are covered in Chapter 3.
- Development of an algorithm for the capacity extension of the infrastructure through the redirection of traffic from congested base stations to neighboring, available base stations. The algorithm is based on Ford–Fulkerson algorithm for computing the maximum flow in a network. These aspects are covered in Chapter 4.
- Since the algorithms that have been mentioned previously rely also on the exchange of contextual information between neighboring nodes, it is essential to define certain mechanisms which will ensure the successful exchange of contextual information without adding a lot of overhead to the networks. As a result, Chapter 5 discusses and evaluates the notion of control channels.
- Finally, the impact of usage of ONs to energy consumption of the network is investigated by evaluating the benefits of such techniques to the network. These aspects are discussed in Chapter 6.

Considering the above structure it can be claimed that the dissertation proceeds to the performance assessment of ONs in situations where coverage and capacity extension of the infrastructure network is deemed necessary. This is actually realized by acquiring contextual information of the neighboring nodes and then selecting the most suitable ones according to certain optimization criteria. Evaluation of various scenarios and use cases is based on extensive simulations in order to increase the validity of the finally extracted conclusions and

recommendations. Finally, energy efficiency of such solutions is being assessed in order to check what happens in situations prior to and after the creation of ONs.

Keywords: opportunistic networks; device-to-device communications; cognitive management systems, functional architecture; control channels; coverage extension; capacity extension; energy efficiency

ΠΕΡΙΛΗΨΗ

Το όραμα ενός ασύρματου κόσμου πέραν της 4ης γενιάς, το οποίο θα περιλαμβάνει γνωσιακές δυνατότητες και τεχνολογίες έρχεται ολοένα πιο κοντά στην πραγματικότητα, καθώς η κίνηση δεδομένων μέσω ασύρματων δικτύων αυξάνεται σταδιακά και νέες τεχνικές για έξυπνη διαχείριση και αυτονομία των δικτύων κρίνονται απαραίτητες για τον ομαλό και αποτελεσματικό χειρισμό της ολοένα αυξανόμενης ζήτησης σε ετερογενή δίκτυα νέας γενιάς. Η παροδική, ευκαιριακή εκμετάλλευση πόρων του ράδιο-περιβάλλοντος μέσω ευκαιριακών δικτύων ελεγχόμενα από τους παρόχους (operator-governed opportunistic networks) κρίνεται ως ένας από τους υπό εξέταση τομείς για την υλοποίηση του ανωτέρω οράματος. Τα ευκαιριακά δίκτυα δημιουργούνται δυναμικά και προσωρινά αποτελώντας επεκτάσεις των βασικών υποδομών των δικτύων. Ο έλεγχος της λειτουργίας τους (δημιουργία, χρήση, τερματισμός) υλοποιείται μέσω της χρήσης γνωσιακών συστημάτων διαχείρισης, τα οποία έχουν τη δυνατότητα να αποκτούν πληροφορίες του περιβάλλοντος μέσω καναλιών ελέγχου και να λαμβάνουν αποφάσεις για τη δημιουργία και τον τερματισμό των ευκαιριακών δικτύων.

Η παροδική χρήση πόρων μέσω της δημιουργίας των ευκαιριακών δικτύων, δύναται να χρησιμοποιηθεί για να παρέχει επιπλέον χωρητικότητα και κάλυψη σε προβληματικά τμήματα του δικτύου ασύρματης πρόσβασης, π.χ., με την αξιοποίηση της δυνατότητας χρησιμοποίησης γειτονικών τερματικών ή με τη χρήση μικρών κυψελών, έτσι ώστε να ανακατευθυνθεί η ροή δεδομένων από προβληματικές περιοχές σε μη προβληματικές.

Συγκεκριμένα, η παρούσα διατριβή καλύπτει τα κάτωθι σημεία:

- Ορισμός σεναρίων χρήσης ευκαιριακών δικτύων για την επέκταση κάλυψης και χωρητικότητας των δικτύων μέσω διαθέσιμων γειτονικών τερματικών. Περαιτέρω ανάλυση των εν λόγω σεναρίων περιλαμβάνεται στο Κεφάλαιο 2.

- Δημιουργία αλγορίθμου για την επιλογή κατάλληλων κόμβων οι οποίοι δύνανται να χρησιμοποιηθούν στη δημιουργία των ευκαιριακών δικτύων με στόχο την επέκταση κάλυψης του δικτύου του παρόχου. Ο αλγόριθμος προτείνει τον ορισμό συνάρτησης καταλληλότητας (fitness function) μέσω της οποίας καθίσταται εφικτή η επιλογή των καλύτερων δυνατών γειτονικών τερματικών λαμβάνοντας υπόψη συγκεκριμένα χαρακτηριστικά. Περαιτέρω λεπτομέρειες περιλαμβάνονται στο Κεφάλαιο 3.

- Δημιουργία αλγορίθμου για την επέκταση χωρητικότητας του δικτύου του παρόχου μέσω της επανακατεύθυνσης της ροής της κίνησης από προβληματικούς σταθμούς βάσης σε άλλους διαθέσιμους, γειτονικούς σταθμούς. Ο αλγόριθμος βασίζεται στον αλγόριθμο Ford–Fulkerson maximum flow. Περαιτέρω λεπτομέρειες περιλαμβάνονται στο Κεφάλαιο 4.

- Για τη λειτουργία των αλγορίθμων απαιτείται και η ανταλλαγή συγκεκριμένων πληροφοριών της κατάστασης των γειτονικών κόμβων χωρίς να επιβαρύνεται κατά πολύ το δίκτυο με επιπρόσθετη, υψηλή ροή δεδομένων. Ως εκ τούτου, το Κεφάλαιο 5 πραγματεύεται θέματα σχετικά με τη δημιουργία και αποτίμηση επίδοσης διαύλων ελέγχου επικοινωνίας.

- Τέλος, η επίπτωση της χρήσης ευκαιριακών δικτύων στην ενεργειακή κατανάλωση του παρόχου, τα πλεονεκτήματα και τα μειονεκτήματα αποτυπώνονται στο Κεφάλαιο 6.

Λαμβάνοντας υπόψη τα ανωτέρω, στην παρούσα διατριβή παρουσιάζεται η αξιολόγηση της αποδοτικότητας των ευκαιριακών δικτύων σε περιπτώσεις όπου κρίνεται αναγκαία η επέκταση της κάλυψης ή της χωρητικότητας του δικτύου υποδομής. Για να πραγματοποιηθεί κάτι τέτοιο είναι σημαντική η απόκτηση πληροφοριών των γειτονικών, διαθέσιμων κόμβων και στη συνέχεια η επιλογή των καταλληλότερων σύμφωνα με ορισμένα κριτήρια βελτιστοποίησης. Η αξιολόγηση των διαφόρων σεναρίων και περιπτώσεων χρήσης βασίζεται σε εκτενείς προσομοιώσεις, προκειμένου να υπάρχουν συμπεράσματα και συστάσεις. Τέλος, η ενεργειακή αποδοτικότητα των εν λόγω ευκαιριακών δικτύων αξιολογείται προκειμένου να υπάρχει άποψη του τι συμβαίνει σε καταστάσεις πριν και μετά τη δημιουργία των ευκαιριακών δικτύων.

Λέξεις-Κλειδιά: ευκαιριακά δίκτυα, επικοινωνία μεταξύ συσκευών, γνωσιακά συστήματα διαχείρισης, αρχιτεκτονική, κανάλια ελέγχου, επέκταση κάλυψης, επέκταση χωρητικότητας, ενεργειακή αποδοτικότητα

FOREWORD

The completion of this dissertation has been a greatly rewarding experience. Also, interesting discussions with my advisors and colleagues have been very valuable. For this, I would like to express my special gratitude for his dedication and efforts to my supervisor Prof. Panagiotis Demestichas, whose academic experience and support at all stages of this dissertation has been catalytic and invaluable. Moreover, I would like to cordially thank the co-supervisors and my professors during my undergraduate and postgraduate studies that have played an important role for the accomplishment of academic achievements during these years.

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Last but not least, I would like to express my sincere gratitude to the endless support of my family and Mr. Anastasis and Mrs. Eleni Parios. In memory of my father Nikolaos.

Sincerely,
Andreas N. Georgakopoulos
Athens, 2014

ΠΡΟΛΟΓΟΣ

Η ολοκλήρωση της παρούσας διατριβής υπήρξε μία σημαντική εμπειρία η οποία περιελάμβανε πολύτιμες και ενδιαφέρουσες συζητήσεις με τη συμβουλευτική επιτροπή και τους συναδέλφους. Πρώτα απ᾽όλα θα ήθελα να εκφράσω την ευγνωμοσύνη και εκτίμηση μου στον επιβλέποντα Καθηγητή Παναγιώτη Δεμέστιχα για την αμέριστη και πολυεπίπεδη συμπαράσταση του σε όλα τα στάδια εκπόνησης της παρούσας διατριβής. Η συνεισφορά του ήταν και είναι πολύτιμη και καταλυτική. Επιπροσθέτως, θα ήθελα να ευχαριστήσω τους καθηγητές της συμβουλευτικής επιτροπής και τους καθηγητές και διδακτικό προσωπικό των προπτυχιακών και μεταπτυχιακών σπουδών οι οποίοι συνέβαλαν καθοριστικά στην εκπλήρωση των ακαδημαϊκών επιτευγμάτων όλων αυτών των ετών.

Επίσης, θα ήθελα να εκφράσω ιδιαίτερες ευχαριστίες στους συναδέλφους και συνεργάτες μου με τους οποίους μοιραστήκαμε πολύτιμες εμπειρίες κατά τη διάρκεια απαιτητικών στιγμών. Ιδιαίτερες ευχαριστίες στην Επ. Καθηγήτρια Βέρα Σταυρουλάκη, Δρ. Κωνσταντίνο Τσαγκάρη, Δρ. Παναγιώτη Βλαχέα, κο. Δημήτριο Καρβουνά, κο. Αριστοτέλη Μάργαρη και Δρ. Μάριο Λογοθέτη για την υποστήριξη τους και τις πολύτιμες και χρήσιμες συζητήσεις μας κατά τη διάρκεια της εκπόνησης της διατριβής.

Τέλος, θα ήθελα να εκφράσω τις ειλικρινείς μου ευχαριστίες και την ευγνωμοσύνη μου για τη συμπαράστασή τους στην οικογένειά μου και στους κκ. Αναστάση και Ελένη Παρίου. Εις μνήμην του πάτερα μου Νικολάου.

Με εκτίμηση,
Ανδρέας Ν. Γεωργακόπουλος
Αθήνα, 2014

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1 Introduction

Chapter Outline

The introductory section provides the main motivation and challenges for conducting research related to "Cognitive Management Systems for Dynamic Access Networks beyond 4th Generation". In addition, an overview of the wireless world beyond 4th generation and towards 5th generation is provided. The work contributes with approaches that can be characterized as evolutionary due to the fact that evolve legacy and emerging reference features of wireless networks.

1.1 Research Area

1.1.1 Motivation and Scope

Motivation. Beyond 4th generation and towards 5th generation of wireless/ mobile broadband, numerous devices and networks will be interconnected and traffic demand will constantly rise. The wireless world is increasingly calling for the effective management of heterogeneous infrastructures in order to meet the Future Internet (FI) requirements [1]-[4] in an energy-efficient and cost-efficient manner. Heterogeneity will also be a feature which is expected to characterize the emerging wireless world as mixed usage of cells of diverse sizes and access points with different characteristics and technologies in an operating environment will be deployed. Wireless network operators are trying to satisfy the growing traffic demand [5] by deploying cells of various sizes (mostly small cells), instead of utilizing only typical macro base stations. All these cells constitute the elements of heterogeneous infrastructures which should be effectively managed by introducing cognition.

Accordingly, wireless communications have to properly address key challenges and requirements driven by multiple perspectives of society, environment, economy, users and operators so as to successfully achieve the vision of an inclusive, cohesive and sustainable society. To that respect, future networks should be capable of handling complex context of operations characterized by traffic increase by a factor of at least 10x [6], various mobility levels and interference. In addition, multiple requirements need to be met including QoE satisfaction, operation in an energy efficient manner (90% improvement by 2020 [7]), resource efficiency and cost efficiency.

By taking into account a comprehensive approach with respect to the determination of requirements and heterogeneity of the infrastructures, there is a holistic presentation of the key challenges stimulating next generation wireless. In order to address the key challenges, there is need for enhanced, next generation mobile broadband through cognition and by taking into account device-to-device (D2D) communications as well, in order to temporarily solve coverage and capacity issues in local, problematic areas.

Scope. As a result the scope of this dissertation is to realize and assess the vision of a wireless world which will be empowered with cognitive technologies as traffic traversing through wireless networks gradually increases and novel techniques on self-management and autonomicity are needed in order to handle effectively the ever-growing traffic demand, diversity and heterogeneity. The opportunistic exploitation of the radio-environment through operator-governed opportunistic network (ONs) is one of the investigated areas towards the realization of that vision. Operator-governed ONs are dynamically created, temporary, coordinated, D2D extensions of the infrastructure. Operator governance is being realized through the use of cognitive systems which acquire necessary contextual information of the environment through control channels and make decisions on the creation of ONs in order to solve localized, temporary coverage and capacity issues of the network.

1.1.2 An Overview of the Wireless World Beyond 4th Generation and Towards 5th Generation

Figure 1-1 depicts an overview of the wireless world of wireless/ mobile broadband. Specific technical directions have been identified, so as to achieve cost efficient resource provisioning, proper application provisioning and the augmentation of cognition.

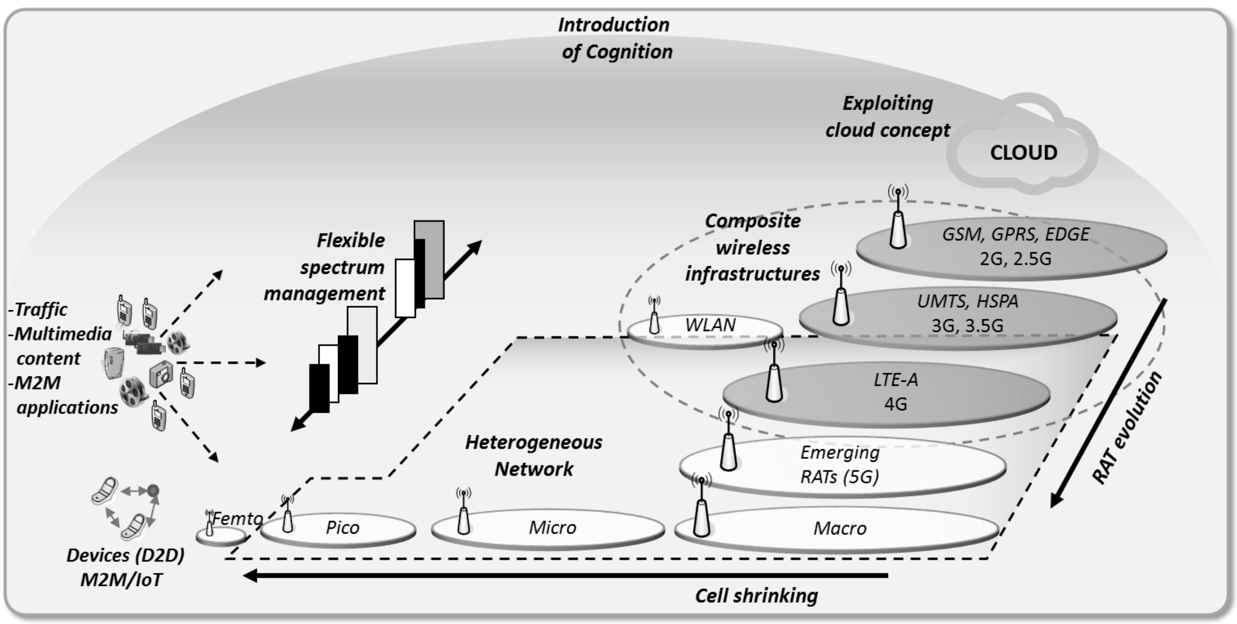

Figure 1-1: An overview of the wireless world

1.1.2.a Evolution of Radio Access Technologies

A direction for improving the service provision and the cost-efficiency has been the evolution, from the 2nd generation (2G), to the 3rd generation (3G) and the 4th generation (4G) or LTE-Advanced (Long Term Evolution-Advanced), of mobile/cellular communications. 3G and 4G technologies have been the focus of the 3GPP (3rd Generation Partnership Project) standardization [9]. In parallel, there has been introduction of various other wireless local-/metropolitan-/personal-area broadband systems, standardized in the context of IEEE (Institute of Electrical and Electronic Engineers [10]). This evolution has primarily been the outcome of the development of advanced RATs (Radio Access Technologies), which led us from the FDMA/TDMA (Frequency/Time Division Multiple Access) and WCDMA (Wideband Code Division Multiple Access) to the OFDMA (Orthogonal Frequency Division Multiple Access) schemes. Regarding the cost-efficiency, this direction is primarily targeted to the improvement of the resource use (use of spectrum and other radio resources).

1.1.2.b Ultra densification of networks – Decreasing cell size

Another evolving direction is the constant decrease in the sizes of the cells that are being deployed which leads to the densification of networks and the realization of ultra-dense networks (UDN). This direction aims at improving the capacity and cost of the resources that are deployed, as well as the resource (e.g., spectrum) use. Therefore, there are cells that have sizes that range from macro cells to the most modern small cells [11], which are able to provide significant capacity improvements (with a lower cost compared to macrocells).

1.1.2.c Device-to-Device (D2D) and Machine-to-Machine (M2M) Communications

Another important direction, which is expected to characterize beyond 4G and 5G networks, is the creation of dynamic networking constructs consisting of interconnected end-user equipment (D2D concept) or several machines/ sensors/ actuators (in the context of Internet of Things -IoT). All these dynamic network constructs will co-exist with evolved access infrastructure. Additionally, traffic generated from various M2M applications will have to be properly assigned to access points without causing congestion issues. Therefore, cognitive management mechanisms will be necessary in order to efficiently control and manage all these networked devices.

1.1.2.d Composite wireless infrastructures

A direction, which emerged about a decade ago, aimed at the joint operation and exploitation of a heterogeneous, in terms of the RATs it comprises, wireless access infrastructure. This direction led us to the concept of composite wireless infrastructures. Significant portion of this work has been on the interworking of cellular systems with wireless local area networks.

1.1.2.e Heterogeneous network deployments

Heterogeneous network deployments [12], are primarily aimed at increasing the cost-efficiency. Unlike the composite wireless paradigm, which comprises diverse RATs, a heterogeneous network is based on one cellular standard, e.g., 4G/LTE-Advanced (even though, under certain conditions, especially operator governance, there can also be IEEE standards).

According to 3GPP [12], a heterogeneous network may consist of different types of infrastructure elements (Base Stations-BSs), such as macro, micro, pico and femto BS. The mixed usage of all these types in an operating network is necessary. Low power BSs like pico will be used to enhance coverage and capacity by covering areas that are much smaller than a macro BS coverage area. Thus, it is expected that all these elements need to be properly managed while the configuration requirements for the cellular network supported by low power nodes are still very similar as for macro cells.

Heterogeneous networks offer multiple options (e.g., numerous and diverse access points in terms of their capabilities, different spectrum portions that may be used, various transmission power levels, etc.) for satisfying applications requirements (situations in general). This direction positively impacts the cost of the deployed resources and their use/utilization.

1.1.2.f Dynamic spectrum management

Another direction which is also targeted to improved resource utilization, is dynamic spectrum management [13]. According to this, network operators have the freedom to flexibly allocate spectrum to the RATs they operate, and to operate a RAT at various spectrum bands. To this respect, it is worth mentioning some key elements to provide this flexibility, such as the spectrum refarming, which allows having technology neutral spectrum bands and to set-up communication on a specific RAT in different frequency bands. Also, another key element is the opportunistic spectrum access, in which secondary users are allowed to independently identify unused spectrum bands, at a given time and place, and utilize them while not generating harmful interference to primary license holders (e.g. through the exploitation of the so-called TV White Spaces, which refer to portions of spectrum that are unused either because there is currently no license holder for them, or because they are deliberately left unused as guard bands between the different TV channels).

In addition, concepts like Authorized-Shared Access (ASA) and Licensed Shared Access (LSA) enable dynamic sharing of spectrum bands in space and time. Also the Collective Use of Spectrum (CUS) allows spectrum to be used by more than one user simultaneously without requiring a license. This would be particularly useful in short-range devices e.g., Radio Frequency Identification Devices (RFID) that can support automation in the supply chain process and machine-to-machine (M2M) applications [14].

1.1.2.g Exploiting the Cloud-RAN and mobile clouds concepts

More recently there is one more direction which is being pursued for further enhancing the cost-efficiency. The direction capitalizes on cloud concepts. The rationale is that there can be total cost of ownership (especially, capital and operating expenditures) savings if wireless networks are based on cloud principles. This is possible through the shared use of storage or computing resources. Therefore, common repositories for networking functionality shall be utilized in order to avoid multiple deployment of the same component.

1.1.2.h Cognitive management ecosystem

Cognitive management can address complexity of heterogeneous networks, since it encompasses, apart from self-management (inherent also in the self-organizing network concept [9]), machine learning and knowledge-derivation. This combination enables increased performance and reliability in decision-making. In other words, the entities of the cognitive management ecosystem will conduct context/ profile-aware, knowledge/ policy-driven self-management of radio resources of heterogeneous networks. The approach will lead to the reactive/proactive handling of encountered/anticipated situations.

The aspects above will require and lead to the following innovations in the components of the relevant entities of the cognitive management ecosystem.

- Development (and exploitation) of knowledge on how to best handle given situations through given heterogeneous networks.
- Evolution and consolidation of decision-making algorithms, in order to enable situation handling with the identified quality criteria (proper application provisioning, cost-efficient resource provisioning).
- Derivation of policies related to situation handling through heterogeneous networks and development of knowledge regarding their efficiency.
- Evolution and consolidation of functionality for developing knowledge on the context of operation of a heterogeneous network (i.e., the faced traffic demand,

mobility and radio conditions, the internal status of the elements) and on the profiles of the entities in a heterogeneous environment.

A cognitive management ecosystem shall be capable of augmenting the intelligence of wireless networks (leading them in the direction of cognitive wireless networks) and contributing to the improvement of their cost-efficiency. The rationale for this direction is that the diverse characteristics/ requirements of applications and the options for satisfying them have also increased the complexity in the wireless world. Therefore, cognition is needed for coping with the complexity. In general, cognition is required for finding the best (e.g., cost efficient, leading to proper rendering of applications, etc.) resource configurations that satisfy application requirements. Cognitive systems are appropriate due to their self-management and learning features. The following facts should be noted:

- Self-management enables the real-time discovery of solutions that can satisfy diverse requirements, and spatio-temporal variations of users/ applications/ services, through the flexible allocation of resources to where/when they are needed. Consequently, the volume of resources that needs to be deployed is reduced and the resource utilization is improved (less resources handle the situations). All these lead to reductions in capital expenditures.
- Self-management also enables the automation of processes and tasks, which currently comprise phases that rely on manual intervention; this has a positive effect on the operational expenditures.

1.2 Dissertation's Contribution

The dissertation deals with "Cognitive Management Systems for Dynamic Access Networks beyond 4th Generation". In this respect, its main contribution can be categorized at the following topics:

- Definition of Dynamic Access Networks and Opportunistic Networking (ON)

- Expanding the Coverage of Wireless Access Infrastructures through the Exploitation of Dynamic Access, Opportunistic Networks
- Expanding the Capacity of Wireless Access Infrastructures through the Exploitation of Dynamic Access, Opportunistic Networks
- Control Channels for the Cooperation of Cognitive Management Systems
- Energy efficient Device-to-Device Communications

The dissertation's main scope contribution is visually explained in the figure that follows:

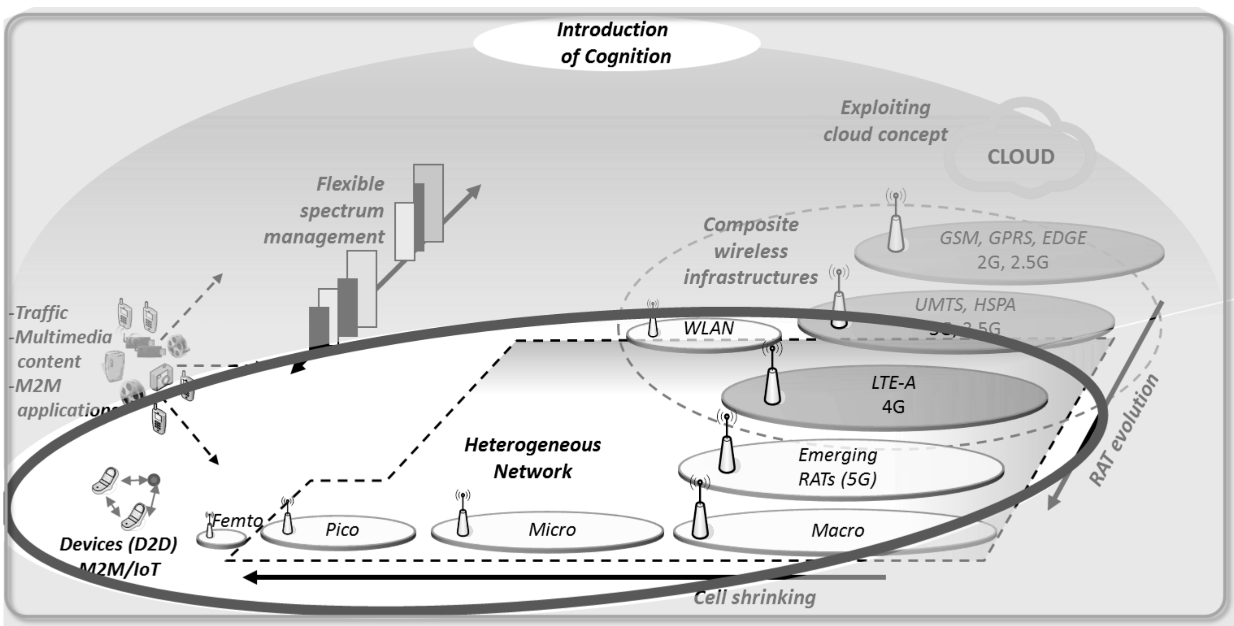

Figure 1-2: Dissertation's main scope and contribution

1.2.1 Definition of Dynamic Access Networks and Opportunistic Networking (ON)

Opportunistic networks (ONs) can be characterized as Dynamic Access Networks (DANs) which introduce an era of wireless communications, beyond the 4th generation, where nodes and terminals engage occasional mobility and routing patterns are dynamically configured. It is assumed that ONs are operator-governed, temporary, coordinated extensions of the infrastructure.

1.2.2 Expanding the Coverage of Wireless Access Infrastructures

In evolved, dynamic access networks, mechanisms for extending the coverage of the wireless access infrastructure and service provisioning to locations that cannot be served otherwise or for engineering traffic whenever the infrastructure network is already congested will be required. Opportunistic networks are a promising solution towards this direction and more details on how to achieve this are provided in Chapter 3.

1.2.3 Expanding the Capacity of Wireless Access Infrastructures

Dynamic access, opportunistic networks can be used for the capacity extension of wireless access in order to address opportunistically the issue of the overloading of an infrastructure element. This can be achieved by redirecting traffic from congested elements to neighboring non-congested ones by taking advantage of operator-governed opportunistic networking. Further details are provided in Chapter 4.

1.2.4 Control Channels for the Cooperation of Cognitive Management Systems

Opportunistic networks and cognitive management systems for cellular extensions are one of the emerging communication paradigms in wireless mobile communications. Operator-governed ONs use the basic concepts of opportunistic networking and extend them by proposing coordination mechanisms which cooperate with the infrastructure. Control channels have been identified as a key feature required for supporting the cognitive management systems in their operation, through the provision of useful information. Specific structures of the information conveyed through cognitive management systems can be found in Chapter 5.

1.2.5 Energy efficient Device-to-Device Communications

It is observed that different levels of energy consumption are observed for intermediate terminals (in the middle of the ON 'chain') and edge terminals (at the end of the ON 'chain'). It should be noted that through intermediate terminals, traffic of edge terminals is also served, thus energy consumption of intermediate terminals is expected to be higher. Further details are available in Chapter 6.

1.3 Dissertation Structure

The dissertation is structured in chapters, each of which provides a detailed description on the research activities performed with regards to the topics described in Section 1.2.

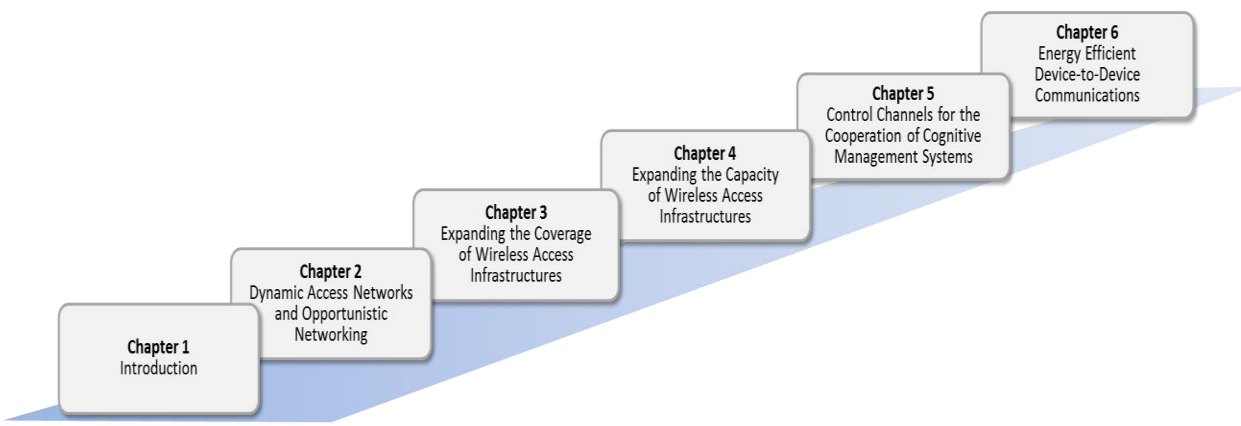

Figure 1-3: Dissertation's Structure

The structure of the dissertation is depicted in Figure 1-3 in order to provide a clear and comprehensive view of the logical sequence of the chapters. Finally a brief description of the chapters is provided therein.

Chapter 1 provides the main introduction and motivation of our work and sets the requirements of the necessary research for operator-governed device-to-device, opportunistic networking. Main aspects of this chapter have been also published in the following manuscripts:

- A. Georgakopoulos, K. Tsagkaris, D. Karvounas, P. Vlacheas, P. Demestichas, "Cognitive networks and systems for a wireless Future Internet: status and emerging challenges", IEEE Vehicular Technology Magazine, vol.7, no.3, pp.48-56, 2012
- P. Demestichas, A. Georgakopoulos, D. Karvounas, K. Tsagkaris, V. Stavroulaki, J. Lu, C. Xiong, J. Yao, "5G on the Horizon: Key Challenges for the Radio Access Network", IEEE Vehicular Technology Magazine, vol.8, no.3, pp.47-53, 2013

Chapter 2 focuses on the elaboration of ON definition and features by taking into account the special nature of ONs and proposing integrated ON business scenarios for the further promotion of ONs to real life. Research on the proposed solution, as it is described in this chapter, resulted in the following publications:

- A. Georgakopoulos, D. Karvounas, V. Stavroulaki, M. Tosic, D. Boskovic, J. Gebert, W. Koenig, P. Demestichas, "Cognitive cloud-oriented wireless networks for the Future Internet", in Proc. IEEE Wireless Communications and Networking Conference (WCNC) 2012, Paris, France, April 1-4, 2012
- A. Georgakopoulos, V. Stavroulaki, J. Gebert, O. Moreno, O. Sallent, M. Matinmikko, M. Filo, D. Boskovic, M. Tosic, M. Mueck, C. Mouton, P. Demestichas, "Opportunistic Networks for efficient application provisioning in the Future Internet: Business Scenarios and Technical Challenges", in Proc. 20th Future Networks and Mobile Summit 2011, Warsaw, Poland, June 15-17, 2011

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Chapter 3 presents the role of cognitive management systems and then focuses on the issues of opportunistic network creation and specifically, the technical challenges of network creation and node selection followed by an assessment evaluation. Main aspects of the chapter have been published at the following manuscripts:

- J. Gebert, A. Georgakopoulos, D. Karvounas, V. Stavroulaki, P. Demestichas, "Management of Opportunistic Networks through Cognitive Functionalities", in Proc. 9th International Conference on Wireless On-demand Network Systems and Services (WONS) 2012, Courmayeur, Italy, January 9-11, 2012
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- A. Georgakopoulos, K. Tsagkaris, V. Stavroulaki, P. Demestichas, "Specification and assessment of a fitness function for the creation of opportunistic networks",

in Proc. 20th Future Networks and Mobile Summit 2011, Warsaw, Poland, June 15-17, 2011

- A. Georgakopoulos, K. Tsagkaris, V. Stavroulaki, P. Demestichas, "Opportunistic Network Creation for Efficient Application Provisioning in the Wireless Future Internet", in Proc. 26th Wireless World Research Forum, Doha, Qatar, April 11-13, 2011

Chapter 4 describes the problem of capacity extension in the wireless access, providing a mathematical formulation and also proposes a corresponding solution approach. Evaluation results are also presented in order to obtain some proof of concept for the proposed solution. Main outcome of this work has been published at the following manuscripts:

- A. Georgakopoulos, D. Karvounas, V. Stavroulaki, K. Tsagkaris, M. Tosic, D. Boskovic, P. Demestichas, "Scheme for Expanding the Capacity of Wireless Access Infrastructures through the Exploitation of Opportunistic Networks", Mobile Networks and Applications (MONET), vol.17, no.4, pp.463-478, 2012, Springer
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Chapter 5 focuses on the issue of cooperation of cognitive management systems which are discussed in previous chapters. Control channels and specific mechanisms need to be defined in order to increase the accuracy of obtained knowledge on the context of the operational environment. Proposed solutions and evaluation related to this chapter have published in the following manuscripts:

- A. Georgakopoulos, D. Karvounas, V. Stavroulaki, K. Tsagkaris, P. Demestichas, "Intersystem Coexistence and Cooperation Through Control Channels", Cognitive Communication and Cooperative HetNet Coexistence, Signals and Communication Technology, Springer, pp.119-131, 2014

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- D. Karvounas, A. Georgakopoulos, V. Stavroulaki, K. Tsagkaris, P. Demestichas, "Evaluation of Signaling Load in Control Channels for the Cognitive Management of Opportunistic Networks", available online at Wiley Transactions on Emerging Telecommunications Technologies, 2014

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- A. Georgakopoulos, K. Tsagkaris, V. Stavroulaki, P. Demestichas, "Requirements on the information flow for intersystem coexistence and cooperation in the emerging cognitive wireless world", in Proc. 5th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom), Cannes, France, June 9-11, 2010

Chapter 6 elaborates on certain use cases in order to evaluate the energy efficiency posed by the usage of D2D communications. Aspects of this chapter have been also published in the following manuscripts:

- D. Karvounas, A. Georgakopoulos, D. Panagiotou, V. Stavroulaki, K. Tsagkaris, P. Demestichas, "Achieving energy efficiency through the opportunistic exploitation of resources of infrastructures comprising cells of various sizes", Journal of Green Engineering, vol.2, no.3, pp.233-253, 2012, River Publishers
- D. Karvounas, A. Georgakopoulos, D. Panagiotou, V. Stavroulaki, K. Tsagkaris, P. Demestichas, "Opportunistic Exploitation of Resources for Improving the Energy Efficiency of Wireless Networks", in Proc. IEEE International Conference on Communications (ICC) 2012, Ottawa, Canada, June 10-15, 2012

Finally, **Chapter 7** presents key concluding remarks and elaborates on the ongoing research challenges which are linked with the dissertation's topic. Moreover, during the research conducted for this Ph.D. dissertation the author has also contributed to additional publications which were indirectly linked to the main topic of the dissertation. These publications include:

- A. Georgakopoulos, D. Karvounas, V. Stavroulaki, K. Tsagkaris, P. Demestichas, "Challenges Towards a Cloud-RAN Realization", Cognitive Radio and Networking for Heterogeneous Wireless Networks, Springer, to appear, 2015

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- D. Karvounas, A. Georgakopoulos, V. Stavroulaki, N. Koutsouris, K. Tsagkaris, P. Demestichas, "Resource Allocation to Femtocells for Coordinated Capacity Expansion of Wireless Access Infrastructures" EURASIP Journal on Wireless Communications and Networking: Special Issue on Femtocells in 4G Systems, 2012:310
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2 Dynamic Access Networks and Opportunistic Networking

Chapter Outline

In the emerging wireless world, it will be required to provide coordinated extensions of the infrastructure as a potential solution to matters such as coverage and capacity extension, infrastructure supported opportunistic ad-hoc networking and traffic aggregation in the access and backhaul network. Dynamic Access Networks are a solution to that direction. Opportunistic networks can be a category of Dynamic Access Networks which are temporary, localized, operator-governed network segments that are created under certain circumstances. To that respect, opportunistic networks are dynamically created, managed and terminated. Mechanisms for the efficient, dynamic creation, management and termination of opportunistic networks are needed. These can be implemented through cognitive management functionality. Furthermore, various stakeholders such as network operators, end-users and content/ service providers can be benefited from the new network paradigm which will lead to increased revenue for the operator, better QoS for the end-users and new opportunities for the content/ service providers.

The rest of the chapter is structured as follows: Section 1 provides an introduction to the Chapter. Section 2 describes main scenarios that have been defined for the realization of operator-governed opportunistic networks. Section 3 analyzes the main management phases of such networks, including suitability determination, creation, maintenance, termination. Finally, Section 4 presents the main benefits of such an approach.

Keywords: opportunistic networks; coverage extension; capacity extension; management phases

2.1 Introduction

Opportunistic networks (ONs) can be characterized as Dynamic Access Networks (DANs) which introduce an era of wireless communications, beyond the 4th generation, where nodes and terminals engage occasional mobility and routing patterns are dynamically configured. It is assumed that ONs are operator-governed, temporary, coordinated extensions of the infrastructure. They are dynamically created, through operator spectrum/ policies/ information/ knowledge, in places and at the time they are needed to deliver multimedia flows to mobile users, in a most efficient manner. They can comprise network elements of the infrastructure, and terminals/ devices potentially organized in an infrastructure-less manner. To that respect, mechanisms for the efficient, dynamic creation, management and termination of ONs are needed. These can be implemented through cognitive management functionality.

The concept of coexistence of ONs with network infrastructure is not new as it has been already empirically analyzed in [1]. For example, the possibility of extending ad-hoc networks with the support of infrastructure, in the so-called hybrid networks, has also been considered in [2] as a way of improving the connectivity in large-scale ad-hoc networks. Also in [3] the benefits of using a hybrid network architecture over pure ad hoc wireless networks with no infrastructure are theoretically analyzed in terms of throughput capacity increase. In these cases, the studies are based on a theoretical framework but neither architectural aspects nor considerations on the peculiarities of infrastructure-less networks formation for service provision are addressed.

In this context, this chapter focuses on the elaboration of ON definition and features by taking into account the special nature of ONs and proposing integrated ON business scenarios for the further promotion of ONs to real life.

2.2 Business Scenarios

For the further development and implementation of the ON concept, specific business scenarios have been considered as part of our approach. Specifically, main scenarios include the opportunistic coverage extension, the opportunistic capacity extension, the infrastructure supported opportunistic ad-hoc networking, the opportunistic traffic aggregation in the radio access network and the opportunistic resource aggregation in the backhaul network. Figure 2-1 illustrates problematic situations prior to the creation of ONs, while Figure 2-2 depicts the solutions to the aforementioned problematic situations through the usage of ONs.

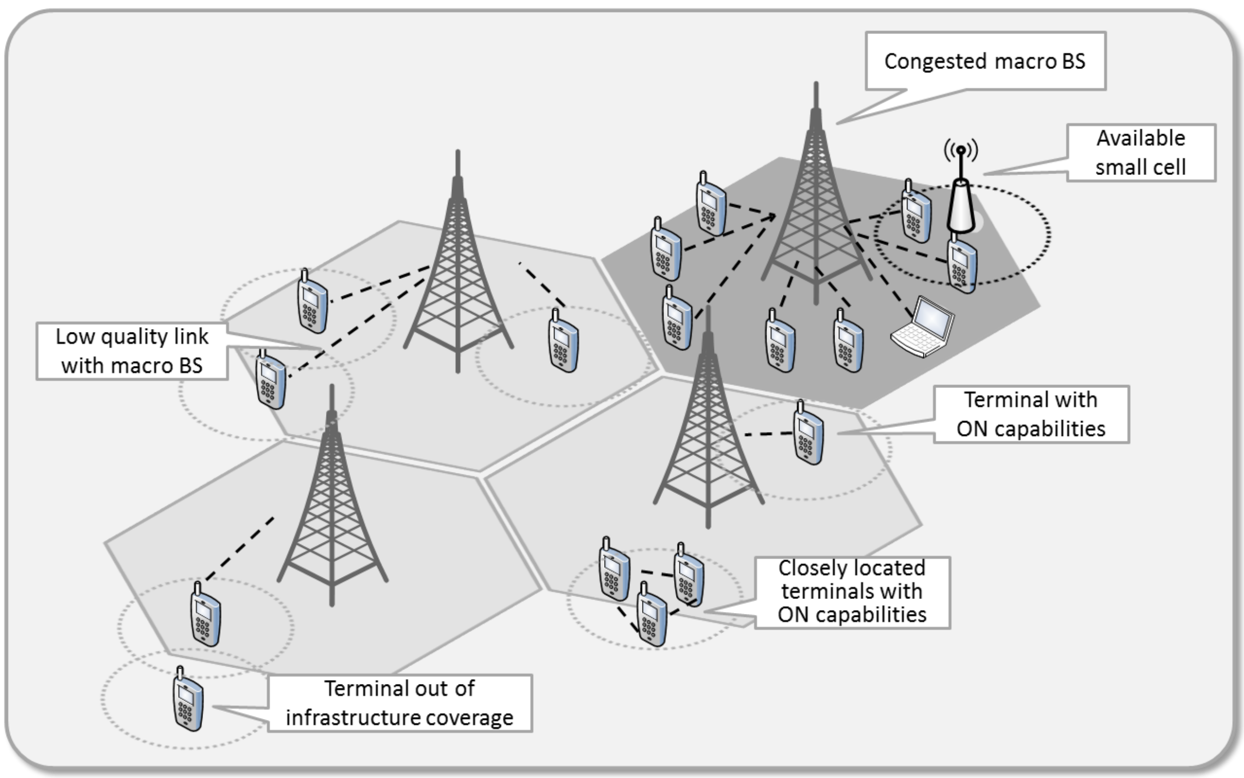

Figure 2-1: Problematic situations prior to the creation of ONs

In this dissertation, we mainly focus in the coverage and capacity extension scenarios (i.e., the first and second scenario described in the subsections that follow), in order to evaluate the performance of ONs. The envisaged technical solution and the challenges of each scenario are addressed in the following subsections.

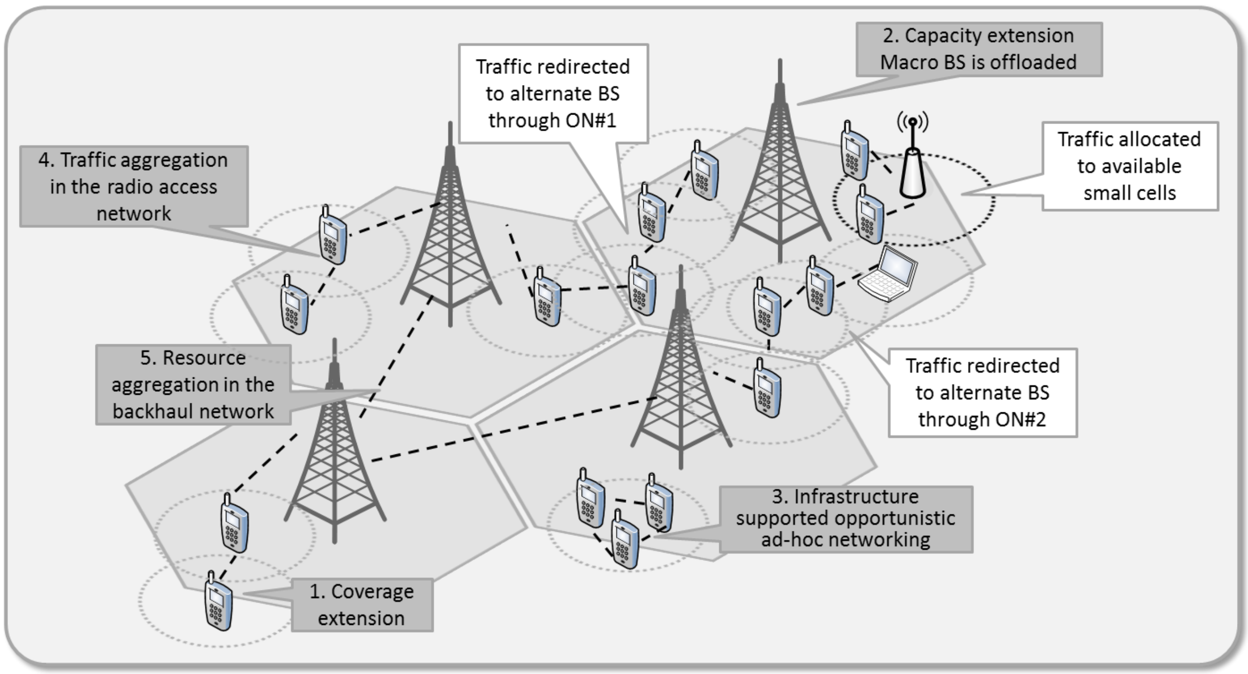

Figure 2-2: Creation of ONs

2.2.1 Opportunistic coverage extension

The rationale of the opportunistic coverage extension scenario lies on the fact that a device which acts as a traffic source is out of the coverage of the infrastructure. As a result, a solution would comprise the creation of an ON in order to serve the out of infrastructure coverage source. The notion of opportunism primarily lies in i) the selection for participation in the ON of the appropriate subset of nodes, among candidate nodes that happen to be in the particular area and ii) the use of resources that will be designated by the operator, for the communication of the nodes of the opportunistic network.

Specifically, ON-enabled terminals which are out of coverage of the infrastructure can initiate a discovery procedure where they can sense and retrieve information of neighboring ON-enabled terminals which are available for helping and providing connectivity to a nearby infrastructure element (e.g., a BS). For the selection of most suitable nodes to participate in the ON, a fitness value is considered. Details on the fitness value and the selection criteria are also provided in Chapter 3 of this dissertation.

2.2.2 Opportunistic capacity extension

In this scenario, it is assumed that a specific area which experiences traffic congestion issues can be off-loaded with the creation of an ON, in order to redirect the traffic to non-congested Access Points (APs). This scenario enables devices to maintain the required level of QoS for a wireless communication link even though a congestion situation occurs.

Following the scenario, for the terminals in the congested and the non-congested BSs context information is acquired. Such information includes the BS to which each terminal is currently registered/ connected and the status of the terminal and its neighboring terminals. This kind of information is needed by the BS in order to obtain information on all potential paths from terminals in the congested area to alternative BSs or available small-sized cells, through other terminals of the non-congested or congested area. Each path comprises a set of nodes (BS or terminal) and the links between the nodes. The aim is to find the most appropriate path, which is a subset of all available paths in order to reroute traffic from the terminals in the congested area to available neighboring BSs or small cells. As an outcome, each terminal should be provided with a path to an alternative point of attachment (i.e., non-congested BS). More details on the specific mechanisms utilized for providing capacity extension are provided in Chapter 4 of this dissertation.

2.2.3 Infrastructure supported opportunistic ad-hoc networking

The scenario, considers a completely infrastructure-less, but still operator-governed ON. The rationale for building the ON in this case is to exploit the fact that often the end-points of an application are located in nearby positions so that traffic exchange can be limited within its scope. That would result to a potential reduction of the traffic load that has to flow through the infrastructure. The target applications of the infrastructure supported opportunistic ad-hoc networking scenario are those involving intensive multimedia exchanges between end users located close to each other etc.

2.2.4 Opportunistic traffic aggregation in the radio access network

This scenario considers the fact that there is a certain concentration of users in a certain service area region that request a set of applications. Therefore, the infrastructure is required. On the other hand, the operator provides to the users that are in the particular service area region the possibility of forming an ON with, at least, one network element of the infrastructure which can act as a gateway between the infrastructure and the ON. The formed ON will comprise a BS providing macrocell or small cell coverage and a set of served devices, a subset of which is organized in an ad-hoc network mode. As a result an ON is created, in order to enable traffic aggregation from the ON to infrastructure through the gateway instead of having direct links from all nodes to the Macro BS.

2.2.5 Opportunistic resource aggregation in the backhaul network

The idea of the fifth and final scenario is that an ON is created across multiple APs in order to primarily aggregate backhaul bandwidth and match the bandwidth of modern wireless access technologies towards the user with the adequate bandwidth on the backhaul/ core network side. The same ON can be used to pull together processing or storage resources across multiple APs in order to pre-process user generated content and relieve pressure on the bandwidth resources needed for its transmission or the storage.

2.3 ON Management Phases

The proposed ON approach is based on four discrete phases as depicted in Figure 2-3. These phases include the ON suitability determination, the ON creation, the ON maintenance and the ON termination.

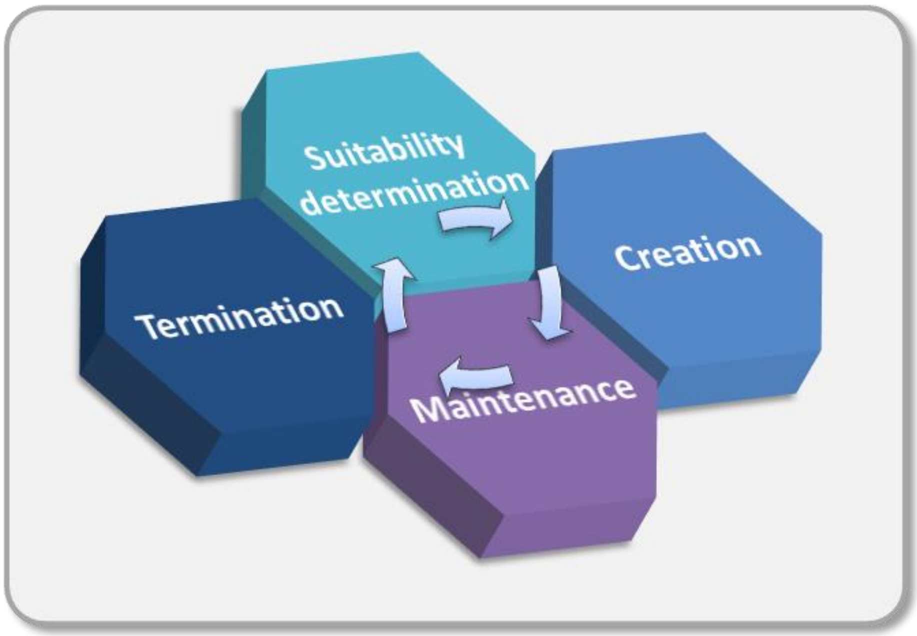

Figure 2-3: ON management phases

2.3.1 ON Suitability determination

Specifically, the ON suitability determination deals mainly with the node/ infrastructure discovery, the identification of candidate nodes and the identification of opportunities from the infrastructure side. The output of the suitability determination phase is expected to be the request for the creation of the ON.

2.3.2 ON Creation

The creation phase follows, which is responsible for evaluating the data received from the suitability determination phase and then continues with the selection of the participant nodes, the selection of links/ spectrum /RATs and the routes. As a result, the ON is created. Main challenges of the creation phase are focused on the development of mechanisms that will lead to the inter-connection of selected nodes, the optimization of routes, and usage of the selected spectrum followed by the signaling procedure establishing the ON. In some cases though, the creation phase could also come up with a decision for not finally establishing the ON.

2.3.3 ON Maintenance

Furthermore, in the post-creation phase, monitoring and possible reconfiguration procedures if QoS levels tend to drop have to be dealt. For the monitoring and reconfiguration of the ON, the responsibility lies in the maintenance phase. Main challenges of the maintenance phase will include the development of the proper mechanisms in order to handle the consistent monitoring of nodes, spectrum, policies, QoS and decide whether it is suitable to proceed to a reconfiguration of the ON.

2.3.4 ON Termination

Finally, the termination phase can be distinguished into termination due to the cessation of application provisioning, termination due to inadequate gains from the ON or forced termination. The challenge of the first case is to successfully achieve the release of resources, while the latter two cases facilitate the handover to infrastructure as well, in order to maintain as flawless as possible, the application streams.

The technical challenges associated to the different phases outlined above will require the design of proper algorithmic solutions. The overall dynamic operation of the ON will be based on a comprehensive solution ensuring the integration and synergic operation among the different algorithms. For example, in the maintenance stage, the identification of spectrum opportunities functionality can dynamically monitor the status of diverse license and un-licensed bands in order to feed the spectrum selection decision-making process with updated information. In turn, the spectrum selection algorithm may decide e.g. a reconfiguration of the ON by executing a spectrum handover to a more suitable spectrum piece.

2.4 Main Benefits

Numerous benefits for different stakeholder categories can be derived from the ON approach, with respect to each scenario. Specifically, the coverage extension capability of an ON enables end users to gain access to the infrastructure in situations where it normally would not be possible, while the access provider may experience increased cashflow as more users are being supported, without at the same time being necessary to invest in new and rather costly infrastructure.

From the opportunistic capacity extension, access providers benefit from the fact that more users can be supported since new incoming users who otherwise would be blocked, can now be served, while end users experience improved QoS since congestion situations can be resolved. Additionally, infrastructure nodes should be able to save resources that could be used with new users, enhancing the service level of current ones, or just reducing their energy consumption. When envisioned solution is fully deployed, statistical gains in capacity/ coverage/ load management with a given dual-layer (macro & small cell) network are expected, allowing for better Return On Investment (ROI).

With respect to the infrastructure supported opportunistic ad-hoc networking, a potential reduction of the traffic load (user/ control planes) that has to go through the infrastructure is expected as an ON is created to serve closely located nodes which share common application interests. Other expected benefits from the infrastructure supported opportunistic ad-hoc networking approach are the reduction of the energy consumption of involved devices through the reduced required transmission power and the reduction of interference which can lead to a more efficient frequency reuse.

The exploitation of an ON solution with respect to the traffic aggregation in the radio access network includes lower transmission powers in the infrastructure (and therefore, reduced operational expenditures), similar volume of traffic served with less signaling traffic going through the infrastructure and higher utilization of resources (e.g., spectrum, therefore, higher capacity levels) without investing in the infrastructure. This leads to reduced capital expenditures with at least equivalent QoE/QoS levels.

Finally, main business benefits from the opportunistic resource aggregation in the backhaul network concept include that end users are experiencing better QoS in situations where backhaul would normally be congested, while access providers can make more efficient use of their network resources and generate increased revenue. When the resource aggregation in the backhaul network solution is fully deployed, it is expected that the overall capacity of the system to serve rich data applications should be increased. The concept will become increasingly attractive as the wireless system solutions become more heterogeneous and incorporate small cells underlay based on 3GPP or non-3GPP based technologies.

2.5 Conclusions

This chapter presented a common ground to study and elaborate on the introduction of ONs to the implementation for efficient application provisioning in the Future Internet era. Additionally, five different scenarios, where ONs may pose a promising solution have been introduced. Derived from the scenarios, the envisaged technical solution and challenges have been identified. The chapter concludes with the main benefits deriving from the introduction of ONs.

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3 Expanding the Coverage of Wireless Access Infrastructures through the Exploitation of Dynamic Access, Opportunistic Networks

Chapter Outline

This chapter focuses on the issues of opportunistic network creation and specifically, the technical challenges of network creation. During the creation phase of an opportunistic network, the nodes that will constitute the network need to be selected and assigned with the appropriate resources. In this respect, the opportunistic network creation problem and particularly the efficient selection of nodes to participate therein is explained. This is achieved via the formulation of the node selection problem and the consideration of a fitness function which takes into account various attributes of nodes. Evaluation is also provided in order to assess the benefits of coverage extension from the creation of opportunistic networks.

The rest of the chapter is structured as follows: Section 1 provides an introduction to the chapter. Section 2 proceeds to the definition of the role of the cognitive management systems which will be used in order to facilitate the creation, maintenance and termination of ONs. Section 3 describes and formulates the problem for the selection of nodes which can be considered in the coverage extension scenario. Finally, Section 4 proceeds to the evaluation results and recommendations by considering two sets of simulations.

Keywords: ON creation; coverage extension; cognitive management systems

3.1 Introduction

In evolved, dynamic access networks, mechanisms for extending the coverage of the wireless access infrastructure and service provisioning to locations that cannot be served otherwise or for engineering traffic whenever the infrastructure network is already congested will be required. Opportunistic networks are a promising solution towards this direction. During the creation phase, nodes that will constitute the opportunistic network needs, are selected and assigned with the proper resources. Selection is based on acquired contextual information in order to facilitate the decision making. The selection functionality relies on the introduction of cognitive management systems. Accordingly, this chapter focuses on the opportunistic network creation problem and particularly on the efficient selection of nodes to participate therein. Steps towards the formulation and solution of the opportunistic network creation problem are made, whereas results are also presented in order to obtain some proof of concept for the proposed solution.

3.2 Role of cognitive management systems

Cognitive management systems have been proposed mainly for enhancing the infrastructure-based networks with cognitive functionalities. A cognitive management system hosts and implements capabilities for: (i) context acquisition, profile management, and policy-awareness; (ii) the cooperation with other cognitive management systems, through the exchange of profiles, policies and context information; (iii) building and sharing knowledge, which, in principle, refers to the situations (contexts) typically encountered, the policies applied, the optimization decisions taken, and the resulting efficiency achieved; (iv) decision-making through functionality that takes into account the context of an operation, the profiles, the policies (potentially, of various business level stakeholders), and the acquired knowledge and experience.

The operational context describes aspects like the: (i) location and time period in question; (ii) applications requested; (iii) mobility levels; (iv) radio quality; (v) element or device status. The profile component provides information on the capabilities of devices and infrastructure-elements, the characteristics of applications, and the requirements and preferences of users. The policies provide rules for context handling, in terms of objectives to be achieved, strategies to be used for the optimization, and constraints to be respected.

Two types of systems are envisaged called ("Cognitive systems for Managing the Opportunistic Network" -CMONs) and ("Cognitive management Systems for Coordinating the Infrastructure"- CSCIs) which are also depicted in Figure 3-1. A fundamental idea behind this concept is to provide the means to facilitate close cooperation between the infrastructure and the opportunistic networks. Such collaboration is essential for ensuring viability, deployment and value creation for all the stakeholders. The cognitive management entities (CMONs and CSCIs) provide the means for determining the suitability, creating, modifying and handling forced terminations of opportunistic networks. The two entities will have synergies for accomplishing the role. Moreover, they have a similar high-level structure, comprising context, profiles, policies, decision-making and learning capabilities. However, they will play primary roles in different phases.

Further legacy functionalities which are depicted in Figure 3-1 include the Dynamic Spectrum Management (DSM), the Dynamic, Self-Organizing Network Planning and Management (DSONPM), the Joint Radio Resources Management (JRRM), and the Configuration Control Module (CCM) which are located above the underlying Radio Access Technologies (RATs). Specifically,

- While extensive research activities have dealt with the identification of spectrum opportunities [1]-[5] and management [6], the DSM provides mid- and long-term management (e.g. in the order of hours and days) of the spectrum for the different radio systems;

- The DSONPM which provides mid- and long-term decisions upon the configuration and reconfiguration of the network or parts of it. The DSONPM decides for example on the configuration of a base station and then instructs the CCM in order to execute the reconfiguration;

- The JRRM which performs the joint management of the radio resources across different radio access technologies [7]. It selects the best radio access (Access-Selection & Handover Decisions) for a given user based on the session's requested Quality of Service (QoS), radio conditions, network conditions like cell load, user preferences and network policies;

- The CCM which is responsible for executing the reconfiguration of a terminal or a base station, following the directives provided by the JRRM or the DSONPM.

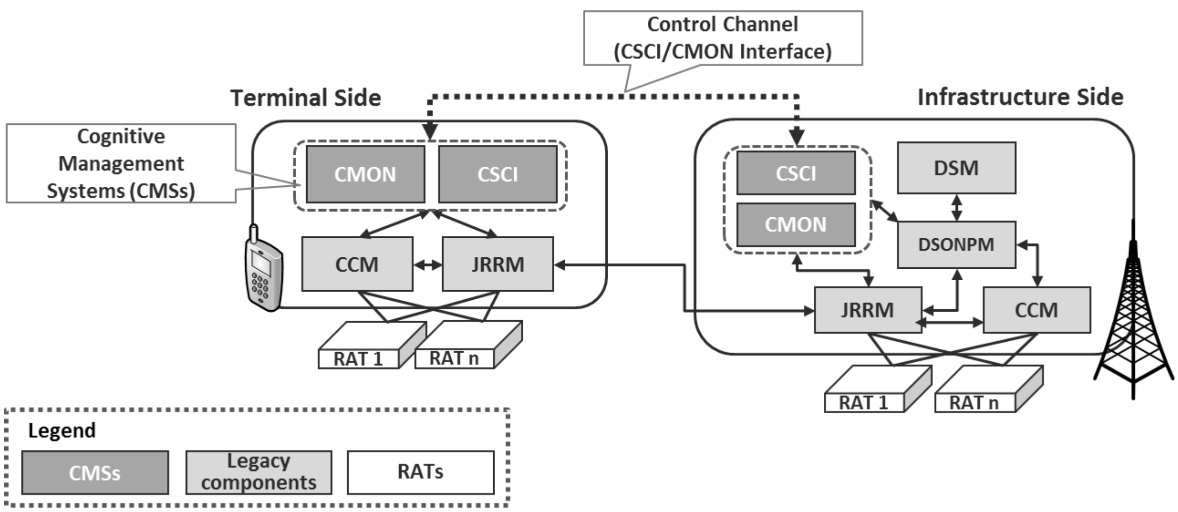


Figure 3-1: Positioning of Cognitive Management Systems in the Functional Architecture

3.2.1 Cognitive management Systems for Coordinating the Infrastructure

The CSCI will have the primary role in feasibility determination, even though it will cooperate with the CMONs. It is expected that the CSCI will be the entity to indicate (and generate) spectrum opportunities and take the final decision on whether to attempt the establishment of an opportunistic network. It will also provide the policies, resources and other information/ knowledge that will govern the opportunistic network.

3.2.2 Cognitive systems for Managing the Opportunistic Network

The CMONs, on the other hand, will have a primary role in the creation and maintenance of the opportunistic networks. The structures will be created and maintained within the framework indicated by the CSCIs. Furthermore, the CSCIs and CMONs will have a balanced role in the forced termination handling phase. Figure 3-2 illustrates the functional split among the CSCI and CMON.

Figure 3-3 illustrates the main components of CMON. Specifically, the context awareness functional entity of the CMON involves QoS assessment, in order to provide constant feedback of the ON’s experienced QoS and to initiate reconfiguration or termination procedures in case of a degredation of QoS. Also, application status monitoring is essential in order to know whether the application provisioning has ended, in order to terminate the ON. Resource monitoring is also included to the context entity in order to initiate reconfiguration or termination procedures in case of a sudden loss of resources.

The policy acquisition functional entity in both infrastructure and terminal sides, obtains and manages the policies which are being defined by the operator. Policies are used as input during the decision making mechanism for selecting the most appropriate configuration, based on the user profile (preferences) and the context. More particularly, a certain policy specifies a set of rules that the CMON must follow.

	CSCI	CMON
Coordination with the infrastructure	YES	-
Coordination with other nodes in ON	-	YES
Detection of situations where an ON may be useful	YES	-
ON suitability determination	YES	-
Execution of ON establishment/creation	-	YES
Maintenance of ON, e.g. reconfiguration	-	YES
Termination decision when ON is no longer suitable	-	YES
Execution of ON termination	-	YES

Figure 3-2: Functional split of CSCI and CMON

The profile management functional entity involves the device capabilities and user preferences. Indicative information includes (i) the set of potential configurations, (ii) the set of applications/services that can be used and the sets of QoS levels associated with the use of an application/service, and (iii) the ON-related user preferences (e.g. the utility volume/ user satisfaction) associated with the use of an application/service at a particular quality level.

Further on, the decision making functionality is present in order to handle effectively the ON creation, maintenance and ON termination according to the input from the context awareness, policy acquisition and profile management functional entities. According to the derived decision, the control entity deals with issues such as the execution of ON establishment/ creation, execution of ON reconfiguration/ maintenance or execution of ON termination. To that respect, it controls whether to proceed with an ON reconfiguration as defined in the maintenance phase or initiate the handover to infrastructure and release of resources in the case of the termination. In case a reconfiguration is deemed necessary, the CCM component will be triggered to control over terminal reconfiguration capabilities. Via the JRRM entity, CMON will control over communication protocol stacks in the terminals and infrastructure nodes by managing operations.

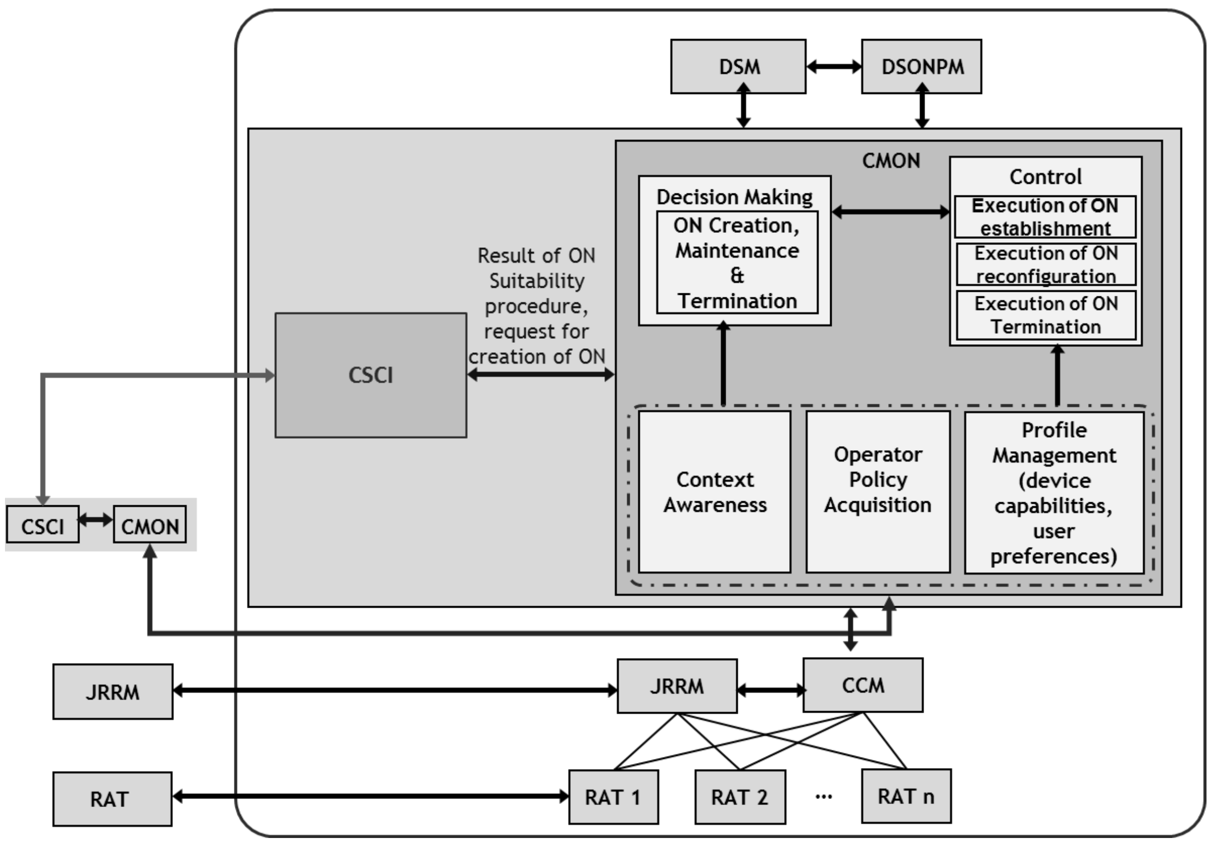


Figure 3-3: Main components of CMON

3.3 Problem on selection of nodes for coverage extension

Following the brief analysis of cognitive management systems, the section focuses on the part of the ON creation phase and more specifically to the selection of nodes which will form the ON. In order to be able to create the ON and enable service provisioning to end-users, it is needed to gain awareness of the status of candidate, relay nodes (i.e., nodes that can be used as routers, even when they do not need to use an application) and the application nodes (i.e., the nodes that use a specific application). Moreover, gateway nodes have to be defined in order to provide connectivity between the ON and the infrastructure (e.g., macro base station), upon request. Figure 3-4 illustrates a problematic situation where some terminals may left out of coverage of the infrastructure while Figure 3-5 presents the resolution of the problematic situation through the execution of coverage extension.

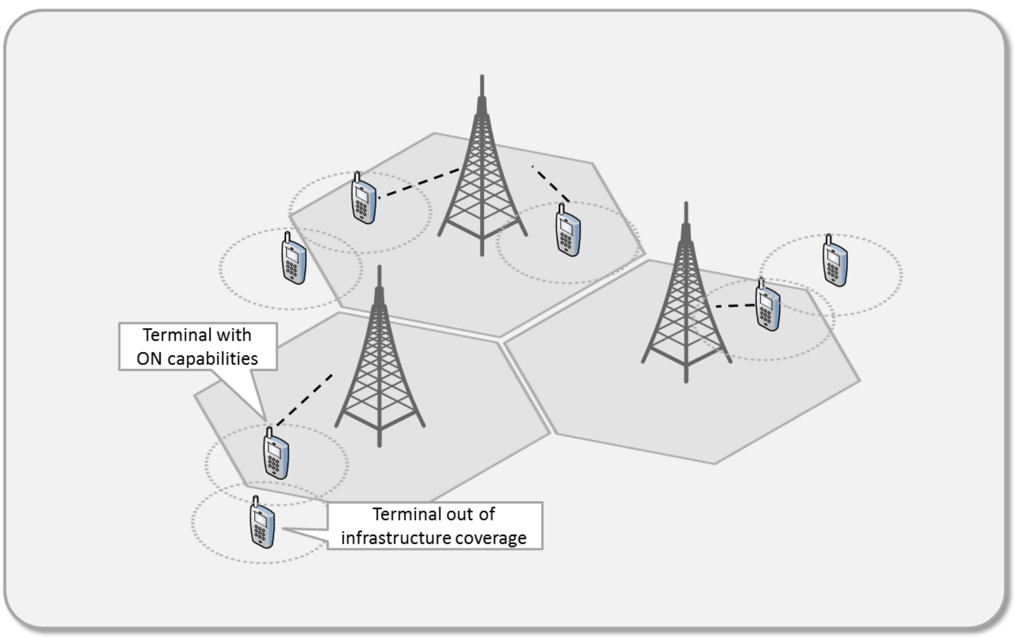


Figure 3-4: Problematic situation

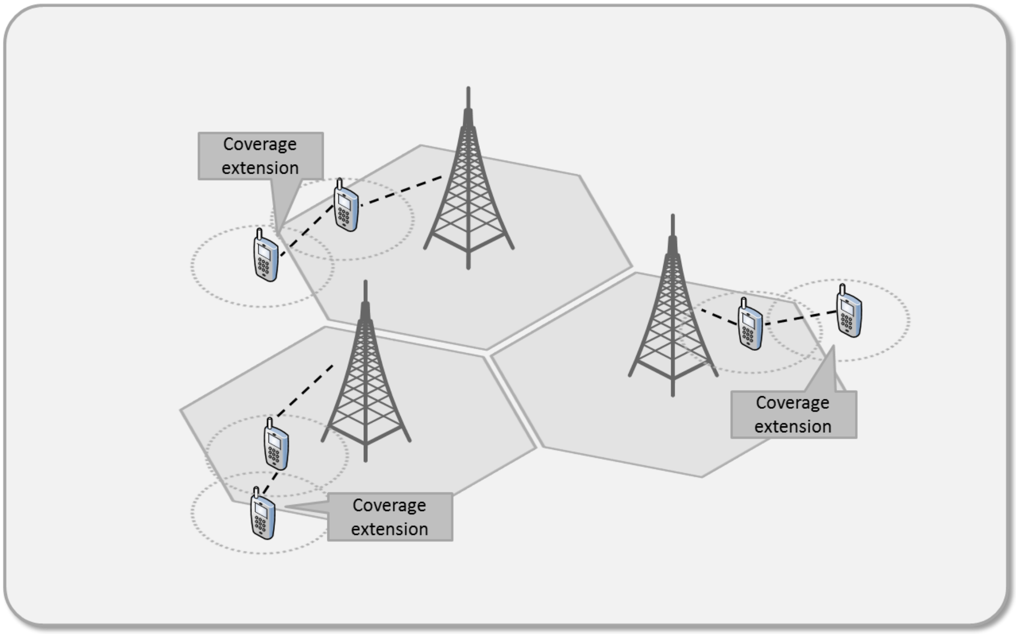


Figure 3-5: Resolving problematic situation through coverage extension

In order to gain awareness of the status of the candidate nodes in the vicinity, a monitoring mechanism is needed, that will be able of monitoring aspects that has to take into account, each node's related information in order to be able to calculate a fitness function. For the efficient creation of the ON, specific node attributes need to be taken into consideration in order to ensure flawless application streams. As a result, participant nodes are not chosen randomly but according to a set of evaluation criteria. Aligned to that goal, the fitness function aims to select fewer but better nodes (i.e. nodes with as high fitness values as possible). This means that on average fewer nodes need to be crossed for message delivery. Therefore the fitness function approach means anticipated lower delays. However, the lifetime of the network may be negatively impacted by the fitness function approach and the associated selection of fewer nodes. Nodes with lower fitness values compared to others can participate to the delivery of some messages. Therefore, they can assist the nodes with higher fitness values which in turn they are expected to get weary later, since even the nodes with lower fitness values can do some of the work. Hence, the ON is expected to live more when more nodes are used. Also the fitness function approach may have a positive impact on the loss of data packets as if the ON is created by a lot of nodes with lower fitness values, then these nodes may become unavailable when a data packet has started transmission. So, the inclusion of fewer nodes with lower fitness values means less data packet losses. The aspects which are taken into account for the calculation of the fitness function are the following:

- Energy level of the node;
- Availability level of the node –taking into account node's capabilities (including available interfaces, supported RATs, supported frequencies, support of multiple connections, relaying/ bridging capabilities, gateway capabilities-wherever applicable), status of each node in terms of resources for transmission (status of the active links), storage, processing, mobility levels –location, supported applications (according to node capabilities and application requirements);
- Delivery probability of the node, in order to designate the effectiveness of the node;

The aforementioned node characteristics provide the input to a fitness function which according to a specified threshold, decides on whether to accept or reject a candidate node for being part of the ON. The accepted nodes are eligible of forming the ON. Relation 3.1 below shows the fitness function considered in this paper for the node selection:

$$Fitness\ Function = x_i * [\ (e_i * w_e) + (a_i * w_a) + (d_i * w_d)\ ]\ . \quad (3.\mathbf{1})$$

where e_i denotes the energy level of node i, a_i denotes the availability level of node i at a specific moment and d_i denotes the delivery probability of packets of node i. Also x_i acts as multiplier according to Relation 3.2:

$$x_i = \begin{cases} 1, e_i > 0 \cap a_i > 0 \\ 0, e_i = 0 \cup a_i = 0 \end{cases} . \quad (3.2)$$

Table 3-1: Algorithm overview

Algorithm: Opportunistic node selection
Input: 1. *Check* the legitimacy of candidate node *i* according to the policies obtained by the operator 2. *Retrieve* energy, availability, delivery probability data for candidate node *i* **Main process:** 3. *Calculate* fitness value of candidate node *i*, according to fitness function 4. *Check* the calculated fitness value of candidate node *i* according to a specified threshold 5. *Set* candidate node *i* as accepted or rejected and add it to the corresponding subset **Output:** 6. *Form* ON with accepted nodes

For the definition of weights of the fitness function, the Analytic Hierarchy Process (AHP) has been used. As the AHP theory suggests [8], initially a decision maker decides the importance of each metric as AHP takes into account the decision maker's preferences. For our example it is assumed that energy is a bit more important than availability and the delivery probability is less important from both energy and availability. According to these assumptions a matrix is completed. The matrix contains the three factors (i.e. energy, availability and delivery probability) along with their levels of importance. As a result, the weight for energy is w_e=0.53, the weight for availability is w_a=0.33 and the weight for delivery probability is w_d=0.14. Furthermore, the theory explains that in order to have consistent results an λ_{max} attribute must be greater than 3 (for our assumption). In our example the λ_{max} turns to be 3.05. Finally, a Consistency Ratio is calculated. Saaty in [8] argues that a Ratio > 0.10 indicates that the judgments are at the limit of consistency though Ratio > 0.10 could be accepted sometimes. In our case, the Consistency Ratio is around 0.04, well below the 0.10 threshold, so our estimations tend to be trustworthy according to the AHP theory.

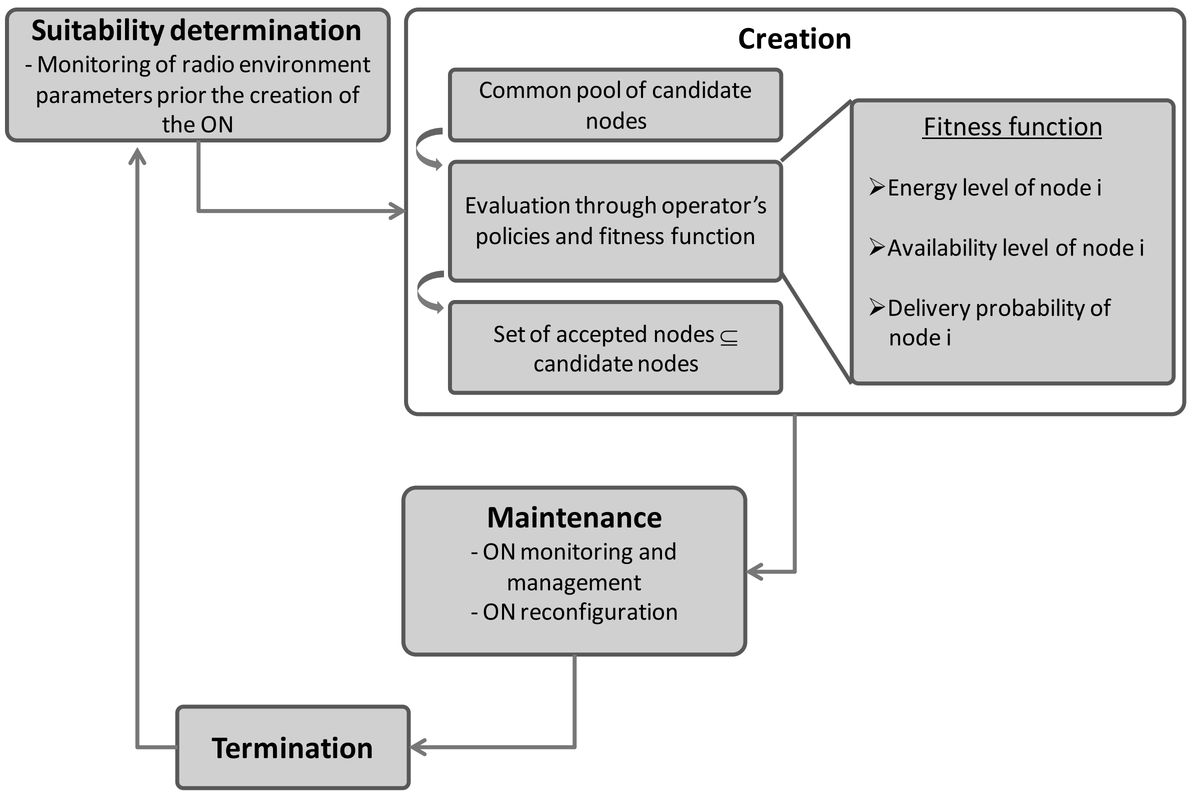


Figure 3-6: Detailed view of the ON creation phase

Additionally, the detailed view of the ON creation phase is depicted in Figure 3-6 where the responsibilities of the creation phase are visually explained. These responsibilities include the evaluation and selection of nodes and spectrum conditions which will provide the set of the accepted nodes to the ON. Also, the interconnections of the creation phase with the suitability determination and the maintenance are visible.

3.4 Evaluation results and recommendations

The performance of the created dynamic access networks is being examined. Particularly, key performance indicators (KPIs) such as throughput and delay will be measured with respect to the number of selected nodes in the network (which affects the number of hops) that are needed in order to reach the servers of the access point.

3.4.1 Simulation parameters

3.4.1.a First set of simulations

In our evaluation communication between nodes themselves uses Wi-Fi technology, while the last link with the base station relies on 3GPP-based technology or Wi-Fi (if we have a Wi-Fi AP for the connection to the Internet). Also, for the evaluation, three different applications are considered, namely simple ping application, a file transfer application and a video streaming application. Figure 3-7 illustrates indicative topologies which are being considered in the evaluation with variable number of selected terminals.

Table 3-2: Evaluation parameters

	File transfer application	**Real-time application**
KPI measured	Average Throughput (Kbps)	Average Throughput (Kbps)
Number of participating nodes (terminals in the ON)	2-10	2-10
Size of data transmitted	20 MBytes	20 MBytes

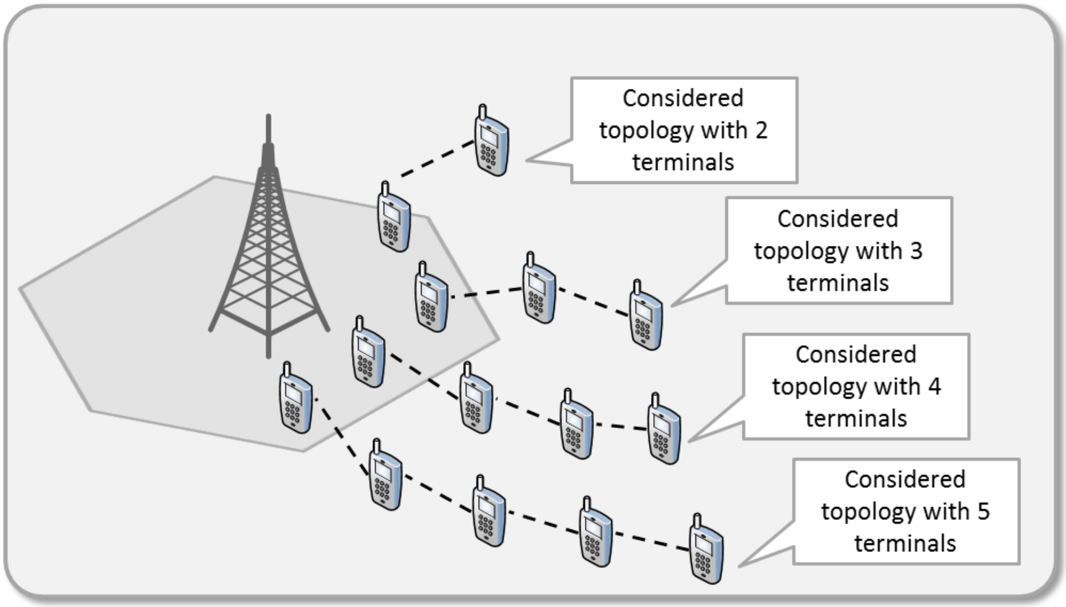


Figure 3-7: Indicative topologies with variable number of selected terminals

3.4.1.b Second set of simulations

In order to obtain some proof of concept for our network creation solution, we have developed a Java-based prototype which calculates the fitness function and informs the system on the accepted and rejected nodes. By using the derived number of accepted nodes, indicative results on the potential performance of these nodes when used in an ON have been also collected and analyzed using the Opportunistic Network Environment (ONE) [9], [10].

The examined network topology consists of 3 source nodes from where data packets are transmitted to 3 destination nodes via 18 discovered, intermediate nodes. Each node features 2 interfaces, a Bluetooth interface (IEEE 802.15.1) [11] and a high-speed interface (e.g. IEEE 802.11 family) [12]. For the high-speed interface, nodes may have a data transmission rate of up to 54Mbps and an outdoor transmission range of 250 meters. On the other hand, the Bluetooth interface has a transmission data rate of around 1Mbps but it is used only for short-range connections (e.g. 10 meters). New data packets are created every 30 seconds according to the packet generation engine of the simulator. Also, each node has a fitness value which enables the node selection process. Limitations in terms of battery life are also taken into account. Thus, the simulation runs until there is a loss of all paths towards one destination node. Simulation scenarios include multiple runs in order to evaluate the performance of the fitness function when the top 30% and the top 70% of discovered nodes are accepted to participate to the ON. For comparison reasons, result sets include the performance of the ON, when the fitness function is not applied, thus every discovered node participates to the ON (even nodes with low fitness values). To that respect it is assumed that the ON consists of 18 ON nodes (the source and destination nodes are not counted to this total), the top 70% includes the first 12 ON nodes according to their fitness value and the top 30% includes the first 6 ON nodes.

Additionally, each case is compared with two routing schemes. Specifically, a flooding-based opportunistic routing protocol is considered, where nodes replicate and transmit messages to neighbouring nodes that do not already have a copy of the message. A representative example of such a protocol is the Epidemic protocol [13]. Another implemented protocol is the Spray&Wait [14] which sets a maximum allowed number of copies per message in the ON. For our investigation that upper bound is set to 10 copies of the original. As a result, lower overheads of replicated messages are observed (compared to Epidemic).

3.4.2 Performance evaluation

3.4.2.a First set of simulations

Regarding the file transfer application, a file of 20MB was downloaded by the terminals and the achieved throughput (in terms of Kbps) was measured with respect to the number of participating nodes. Figure 3-8 depicts the performance of the file transfer application with respect to the number of participating nodes when one node in the created network is downloading the file. When a terminal is directly connected to the AP (i.e., one only hop) the achieved throughput was around 13Mbps, while when the terminal is 2 hops away, the throughput drops by around 1/3 at around 8Mbps. In the worst case that 9 hops are needed the throughput was a bit more than 400Kbps. Apparently, due to the instability of the network that comprises so many hops, the packets are dropped and hence a retransmission is needed that causes the throughput to decrease.

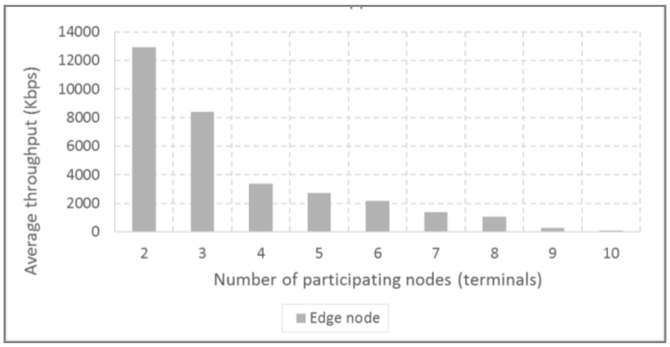


Figure 3-8: Average throughput achieved for a file transfer application

Also, another application that was studied was a real-time application. The achieved throughput was measured with respect to the number of participating nodes in the ON. Figure 3-9 illustrates the achieved throughput of a terminal using the real-time application with respect to the number of hops that are needed to reach the AP. As it can be observed, the achieved throughput of the terminal is around 700Kbps for the first 7 hops, while for 8 and 9 hops it drops below 500Kbps for both. Therefore, real-time application is not recommended when the number of hops is so high.

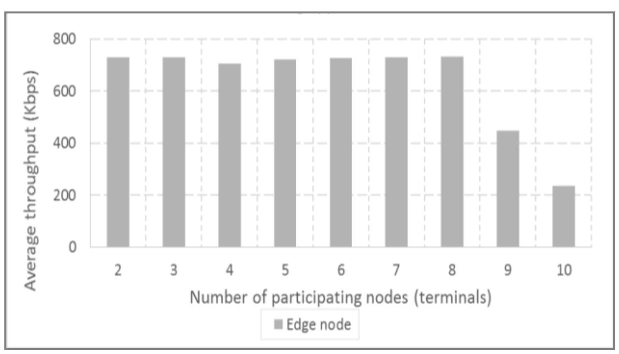
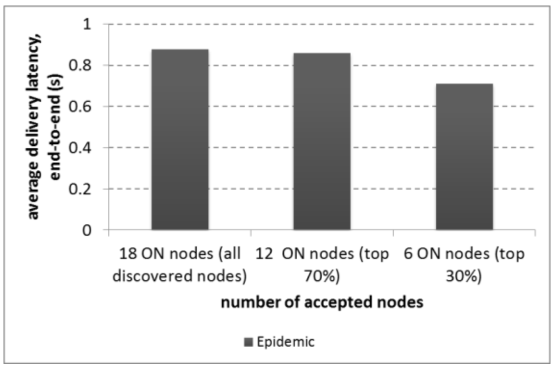


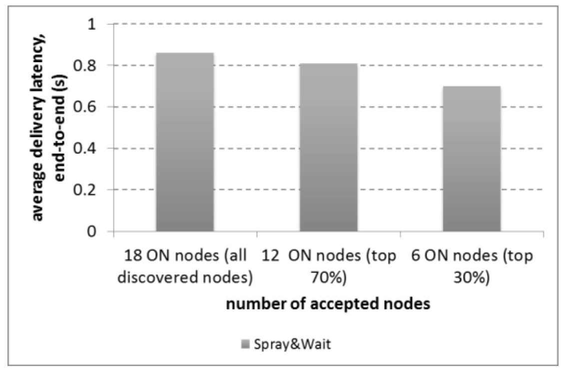
Figure 3-9: Average throughput achieved for a real-time application

3.4.2.b Second set of simulations

The simulator provided measurements regarding the average, end-to-end, latency of delivery for data packets with connection links up to 20Mbps. Figure 3-10 illustrates the observed values, where the falling tendency of the delivery latency (end-to-end) is denoted as fewer but better nodes are selected according to their fitness value.



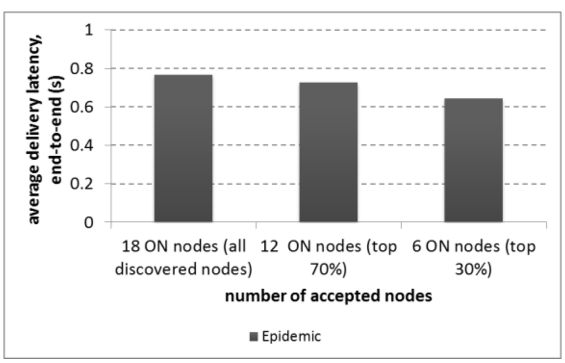
(a) Epidemic



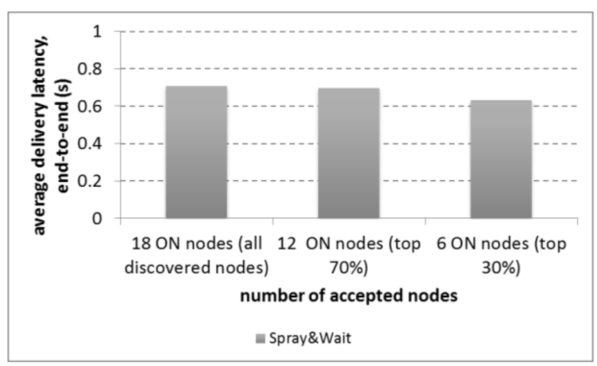
(b) Spray&Wait

Figure 3-10: Average delivery latency estimation (from source to destination nodes and connection links up to 20Mbps).

Figure 3-11 provides data of the delivery latency when the ON nodes use connection speeds of up to 54Mbps. It is expected that even lower values are obtained.



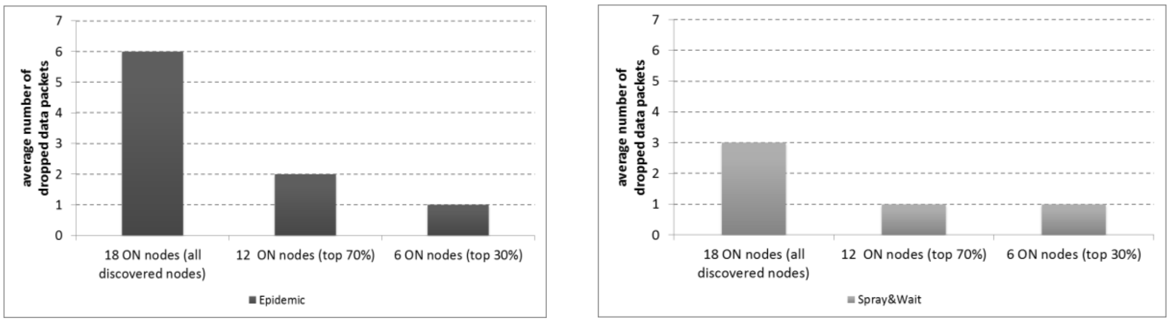
(a) Epidemic



(b) Spray&Wait

Figure 3-11: Average delivery latency estimation (from source to destination nodes and connection links up to 54Mbps).

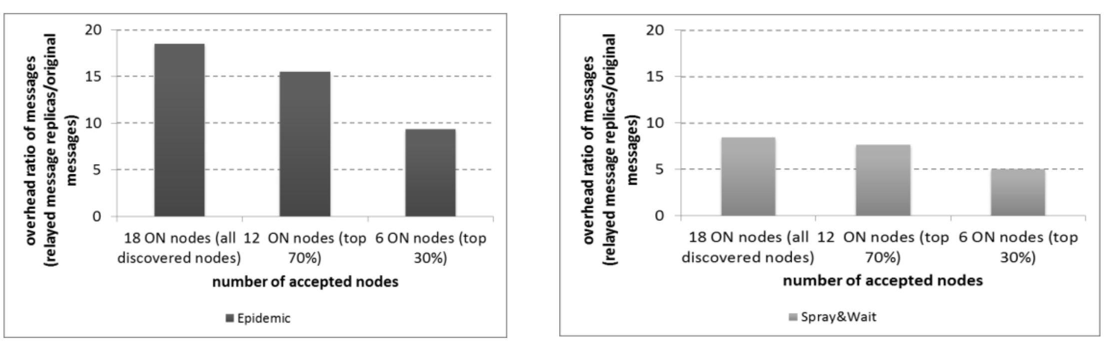
Figure 3-12 illustrates the average number of dropped packet transfers. This number corresponds to the packets which were lost when the connection is broken before the packet transfer had successfully finished. It is estimated that as fewer but better nodes are accepted by the ON, the number of dropped packet transfers tend to decrease.



(a) Epidemic (b) Spray&Wait

Figure 3-12: Average number of dropped data packets estimation

Figure 3-13 illustrates the overhead ratio of messages which corresponds to the number of relayed message replicas (copies) divided by the number of original messages that were injected to the ON is relatively lower as fewer nodes are accepted to the ON. Additionally, Spray&Wait is expected to obtain even lower overhead values (compared to Epidemic) due to the fact that there is an upper bound constraint to the creation and circulation of message replicas to the ON. Spray&Wait makes better use of resources due to the fact that it limits the flooding of messages to an upper bound.



(a) Epidemic (b) Spray&Wait

Figure 3-13: Overhead ratio of messages estimation

3.4.3 Key findings and recommendations

For the efficient creation of the ON, specific node attributes need to be taken into consideration in order to ensure flawless application streams. As a result, participant nodes are not chosen randomly but according to a set of evaluation criteria. Aligned to that goal, this section proposed a fitness function in order to address the node selection problem. The fitness function aims to select fewer but better nodes (i.e., nodes with as high fitness values as possible). It is shown that in terms of end-to-end delivery latency of data packets from source to destinations, lower values are obtained when the selection of nodes according to the fitness function takes place. Also, there is a positive impact to the number of dropped data packets. Regarding the application provisioning, it is shown that when large chains of terminals are created, the quality of the provided application tends to decrease. Decrease is greater as more terminals are connected to each other.

3.5 Chapter References

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4 Expanding the Capacity of Wireless Access Infrastructures through the Exploitation of Dynamic Access, Opportunistic Networks

Chapter Outline

Dynamic access, opportunistic networks can be used for the capacity extension of wireless access in order to address opportunistically the issue of the overloading of an infrastructure element. This chapter describes the problem of capacity extension in the wireless access, providing a mathematical formulation and also proposes a corresponding solution approach. Evaluation results are also presented in order to obtain some proof of concept for the proposed solution. According to the obtained results through the simulations, terminals that switch from a congested BS to an ON may experience an average decrease of their consumption of around 25%. Also, through the creation of ONs in order to redirect traffic from the congested BS to neighboring cells, a reduction of 15-25% in the transmission power of the congested BS is observed. Also, the quality of communication is benefited, as delay of successfully delivered messages drops approximately 15-35%, compared to the congested situation. Estimations on the extra consumption of nodes that acquire extra traffic through the ON are also provided.

The chapter is structured as follows: Section 1 provides an introduction to the chapter. Section 2 describes and formulates the problem for the selection of nodes and paths which can be considered in the capacity extension scenario, in order to redirect traffic from congested APs to non-congested ones with the usage of ONs.

Finally, Section 3 proceeds to the evaluation results and recommendations by executing a set of simulations.

Keywords: capacity extension; maximum flow

4.1 Introduction

The notion of a dynamic access, ON builds on the idea that a network is created in order to exploit opportunities or solve problematic situations of the radio environment that appear in a specific place and time. For example, in the scope of capacity extension of the wireless access, an infrastructure element which experiences congestion, thus quality of communication is decreased (e.g. low bitrate etc.), it could redirect a proportion of the users that are closely located towards alternative infrastructure elements. As a result, the users will enjoy better quality of the requested service. Similar capacity extension concepts can also be applied to the backhaul segments in order to provide mechanisms for the sharing and assignment of network resources wherever and whenever needed in an opportunistic manner. It is anticipated that users will be served with the requested bitrates by participating to an ON which will be formed under the supervision of the operator. Due to the dynamic, operation environment of an ON, cognitive mechanisms are proposed in order to manage such networks in an effective way. Cognitive management mechanisms may be located in both the network infrastructure and the terminals/devices. Moreover, a cooperation mechanism is required for efficient coordination between the infrastructure and the devices in the scope of an ON. Therefore, cognitive control channels are required for the exchange of information and the coordination between cognitive management systems. Such control channels [1], [2] may be logical channels transporting information on top of a physical channel. This chapter presents a scheme for the dynamic, operator-governed creation of ONs aiming to enable the capacity extension of wireless access infrastructures in congested areas. It describes the problem of capacity extension in the wireless access, providing a mathematical formulation and also proposes a corresponding solution approach. Indicative results are also presented in order to obtain some proof of concept for the proposed scheme.

4.2 Problem on capacity extension and formulation

It is assumed that a specific area which experiences traffic congestion issues can be decongested with the dynamic creation of an ON for opportunistic capacity extension. In particular a system operating in a licensed/unlicensed band is assumed to be overloaded and cannot guarantee the provision of the required quality (e.g. in terms of bitrate) anymore. This is reflected in Figure 4-1 which illustrates a problematic area in grey. Traffic is rerouted to neighboring non-congested Access Points (APs) as depicted in Figure 4-2, thus enabling devices to maintain the required quality of communication (e.g. bitrate) for a wireless communication link even though a congestion situation occurs. The proposed solution differs from reconfiguring the infrastructure which remains intact. Our approach shows improved energy efficiency and improved bitrate due to smaller distances of the nodes and capacity expansion through ONs that have an average length ranging from 1 to 3 nodes depending on cell range.

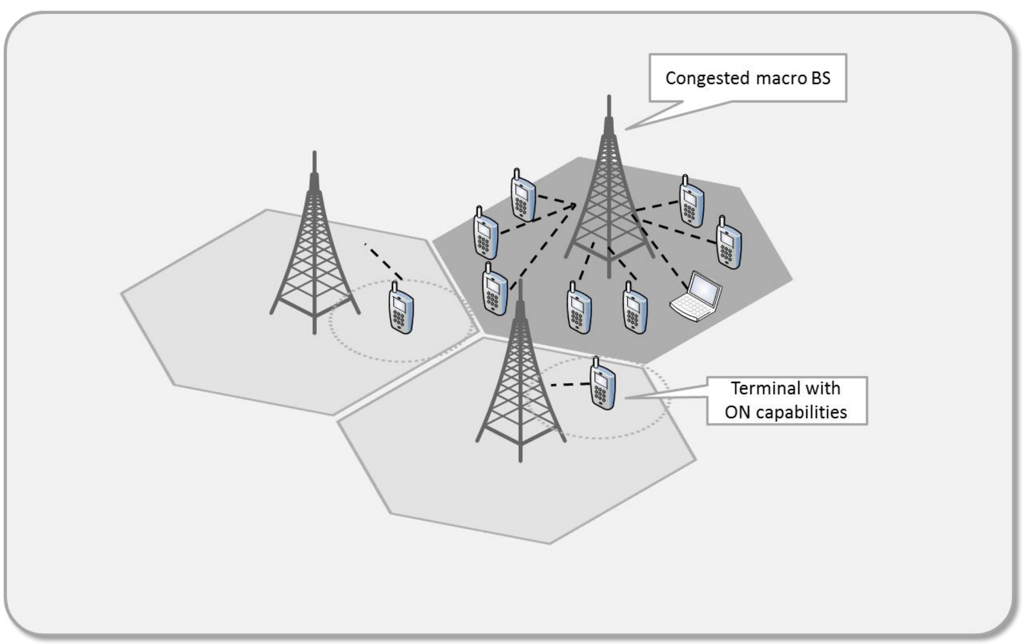


Figure 4-1: Problematic situation (congested macro BS) prior to the creation of ON

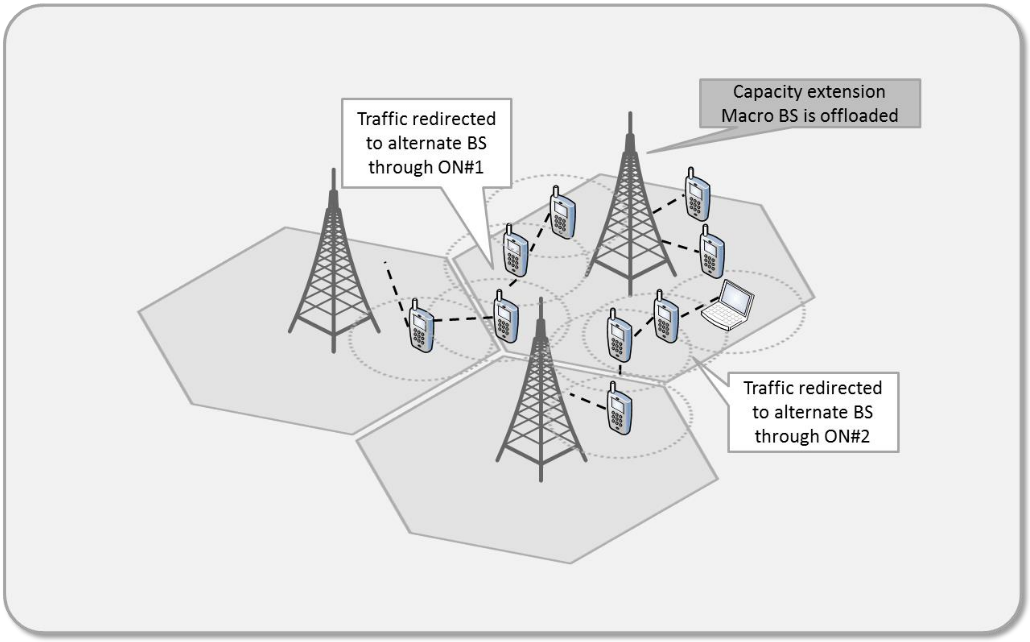


Figure 4-2: Capacity extension through the utilization of ONs

In the following, the capacity extension problem is described in more detail. A mathematical formulation is provided and an algorithm is proposed that takes into account congested and non-congested infrastructure elements and end-user terminals which are located in the previously mentioned infrastructure elements.

A high level description of the algorithm comprises the input, the main process and the output. Specifically, the sets of the congested BSs, non-congested BSs, terminals with ON capabilities in the congested area and the connections between all the available devices would be considered as the input. The main process is responsible for the discovering of paths from a terminal in the congested area to an alternative BS which will be returned in the output. The output will designate to each terminal in the congested area, the path to an alternative BS.

Input

The set of congested BSs is denoted as B_1 while the set of non-congested BSs is denoted as B_2. Let T_c be the set of terminals that are connected to the congested

BSs (represented by B_1 set). Also, let $T_{cm} \subseteq T_c$ be the set of terminals which have ON capabilities. Let T_{nc} be the set of terminals that are connected to the non-congested BSs (represented by B_2 set). Let graph $G(V,E)$ be a directed graph, consistent or not, where $V= T_{cm} \cup T_{nc} \cup B_1 \cup B_2$ and E is the set of links among the nodes of the graph G. Let P be a set of paths from terminals $t \in T_{cm}$ to BSs $b \in B_1 \cup B_2$ that were discovered from the execution of breadth-first search for graph G. Each path $p \in P$ includes a starting point $t_p \in T_{cm}$, an ending point $b_p \in B_1 \cup B_2$ and a set of links $L_p \subseteq E$. For each $p \in P$ the starting point t_p is connected with a virtual link to a "super-source" (*ss*) virtual node and the ending point b_p is connected with a virtual link to a "super-destination" (*sd*) virtual node. Each link $l(u,v) \in L_p$ has a starting point $u \in T_{cm} \cup T_{nc} \cup \{ss\}$, an ending point $v \in V \cup \{sd\}$, the RAT that is used for the transmission and the capacity $cap[l(u,v)] \in N \setminus \{0\}$ where N is the set of natural numbers. The capacity is considered as the number of simultaneous traffic flows that can be served through this link. Furthermore, each link $l(ss,t)$, $t \in T_{cm}$ (from the "super-source" to a terminal in the congested area) has a capacity $cap[l(u,v)]=1$, because through this link only one flow f is pushed. A flow $f[l(u,v)]$ represents the number of terminals that are being relayed through link $l(u,v)$. All the BSs are connected to a "super-destination" node (*sd*) which is also a virtual node. The algorithm takes as input a graph G and the sets B_1, B_2 and T_{cm}.

<u>Process</u>

At the initialization phase the link capacities are estimated. Their values derive from parameters such as the RAT of the link, the quality of the link, operator policies and users' profiles.

In addition, the flows of all links are initialized to zero. Then the set P is created by the paths that are being discovered by the breadth-first search algorithm which yields the shortest path. The algorithm runs for each $p \in P$ for which there is a link where more flow can be directed. As soon as all possible paths are saturated (i.e.

there is no path with available capacity anymore and flow could not be pushed to it) the algorithm finalizes.

Output

The output of the algorithm consists of the selected path $p_s \in P$ for which the flow f is maximized. The selected path includes a starting point (e.g. a terminal in the congested region), an ending point (e.g. a BS), and the links that create the full path from the starting to the ending point (each link is identified by a starting point and ending point each of which is an intermediate node). The approach followed here for the creation of an ON is based on the Ford-Fulkerson maximum flow algorithm [3]. An overview of the aforementioned algorithm is provided in the table that follows:

Table 4-1: Algorithm overview

Algorithm: Selection of paths

Input:

Graph G

Sets B_1, B_2

Set T_{cm}

Main process:

Estimate $cap[l(u,v)]\ \forall\ l(u,v)$

Initialize $f[l(u,v)] \leftarrow 0\ \forall\ l(u,v)$

Creation of set P through the breadth-first search

for each $p \in P \mid \exists\ l(u,v) \in L_p :\ f[l(u,v)] < cap[l(u,v)]$

$cap(p) \leftarrow \min \{ cap[l(u,v)] \}\ \forall\ l(u,v) \in L_p$

$f[\ l(u,v)\ ] \leftarrow \{ f[l(u,v)] + cap(p) \}\ \forall\ l(u,v) \in L_p$

Update the residual capacities of the rest of the links of p

end for

Output:

Return the selected path ($p_s \in P$)

The flowchart of the proposed algorithm is also depicted in Figure 4-3.

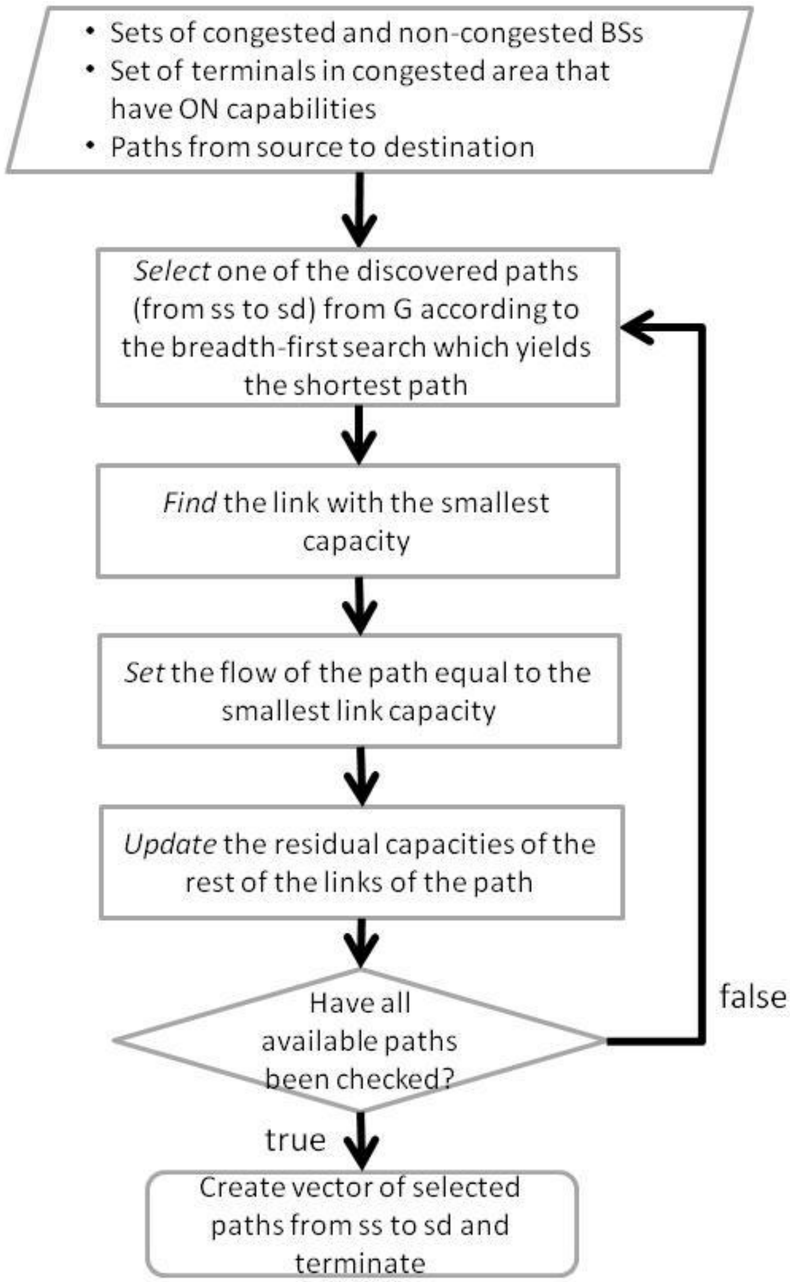


Figure 4-3: Flowchart of the proposed algorithm for the selection of paths

The involved entities in the algorithm namely, the terminals served by congested BSs, the terminals served by non-congested BSs and the BSs, are illustrated in Figure 4-4.

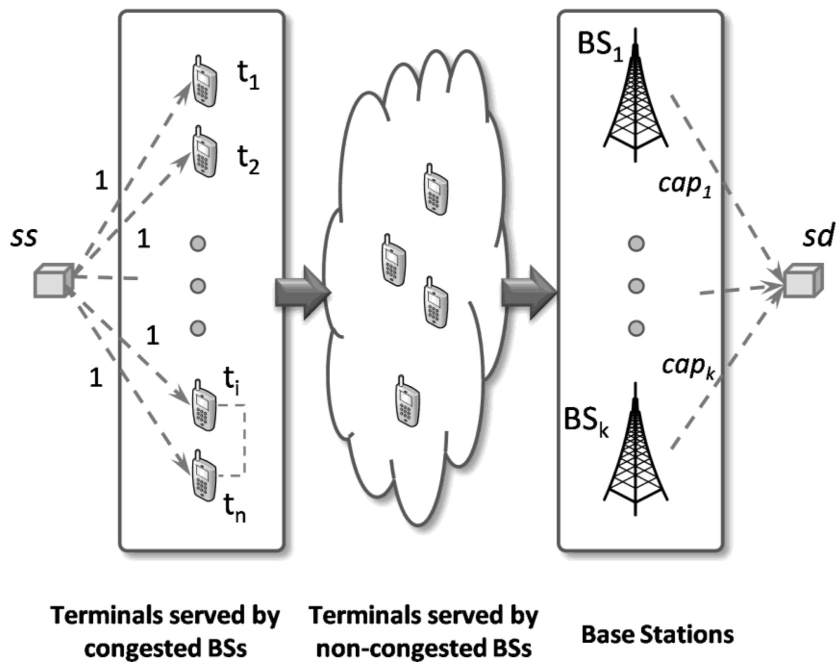


Figure 4-4: Involved entities in the algorithm

4.3 Evaluation results and recommendations

This section presents results on the performance of the developed capacity extension scheme through the creation of ONs. An agent-based, Java prototype has been developed by using the Java Agent Development Platform (JADE) [4]. JADE has been used for the management functionality and the exchange of messages. Also, an area of 4000m x 4000m is investigated through the Opportunistic Network Environment (ONE) simulator [5]. It has been modified accordingly, in order to include also communication with infrastructure and to integrate the developed Java prototype so as to find paths from terminals located in congested areas to neighboring, non-congested areas. The ONE simulator has been chosen for the experiments due to its inherent capabilities in measuring performance of traditional ONs. Seven infrastructure elements (e.g., BSs) cover the aforementioned area –one in the middle and one in each side of the central cell.

4.3.1 Simulation parameters

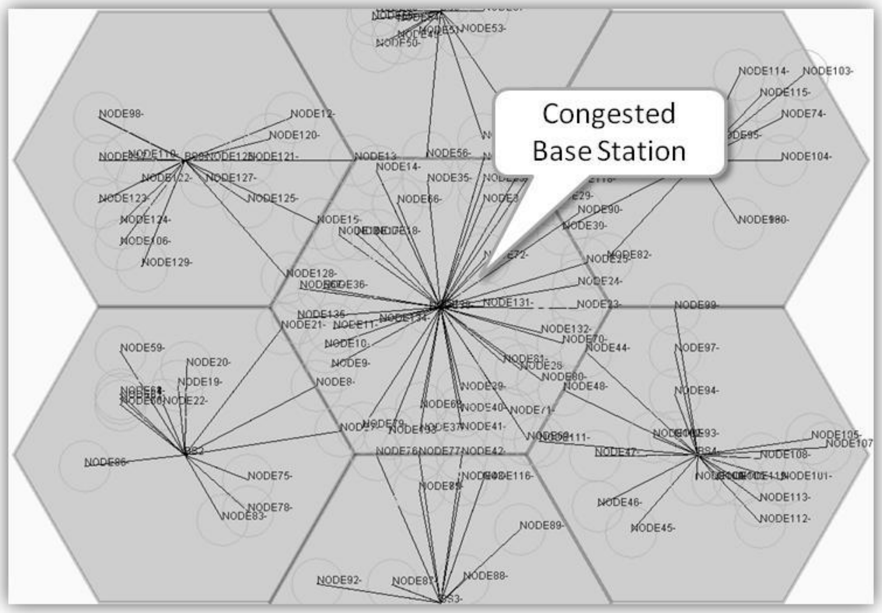
A hundred and thirty terminals are deployed in the area. All terminals are assumed to be capable of participating in an ON, if the right conditions exist (e.g. their mobility level is relatively low, such as a few m/s, or the policies of the operator allow the formation of further ONs etc.) The majority of the terminals are located in the central BS (BS1) in order to be able to emulate a congestion situation. The following spatial distribution of terminals is considered: 40 terminals in the congested, central cell and 15 in each adjacent cell. Data services are taken into account and rate of message generation is a random variable ranging from 3 to 7 seconds, uniformly distributed, with mean of 5 seconds. Message size is a random variable in the range of 64 to 1024 KB uniformly distributed. Also, the number of terminals that generate traffic in each interval is random as well. Twenty-seven testcases have been evaluated according to Table 4-2. In terms of mobility, the Random Walk mobility model has been used and measurements have been performed for specific moving velocities ranging from stationary (0 m/s) to 2m/s. Mobility level of 0-2 m/s following a Random Walk model has been considered in order to maintain traffic distribution in cells. Simulations were executed in a system equipped with an Intel Core i3 CPU at 2.5 GHz and 4GB of RAM.

Table 4-2: Definition of testcases

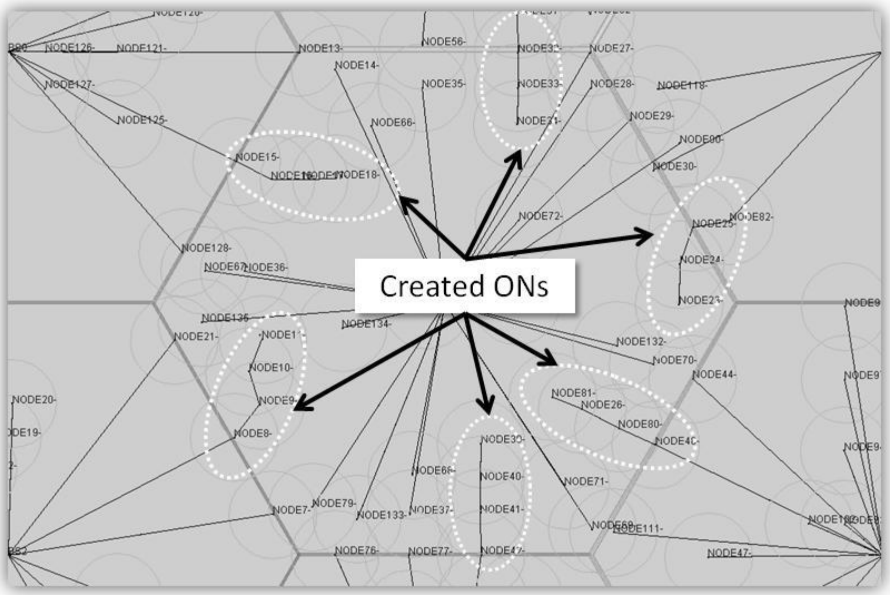
Testcase	**Number of nodes in the congested area switching to ON**	**Capacity (assumed in the links of the maximum flow problem)**	**Mobility level of each terminal (m/s)**
1	6	1	0
2	12	1	0
3	18	1	0
4	6	2	0
5	12	2	0
6	18	2	0
7	6	3	0
8	12	3	0
9	18	3	0
10	6	1	1
11	12	1	1
12	18	1	1
13	6	2	1
14	12	2	1

15	18	2	1
16	6	3	1
17	12	3	1
18	18	3	1
19	6	1	2
20	12	1	2
21	18	1	2
22	6	2	2
23	12	2	2
24	18	2	2
25	6	3	2
26	12	3	2
27	18	3	2

Figure 4-5 illustrates the topology as described earlier in the paragraph. Each simulation lasts for 1000 simulated seconds, due to the fact that according to the definition of ONs, ONs are created in a specific place for a limited timeframe in order to serve temporarily the involved users.



(a)



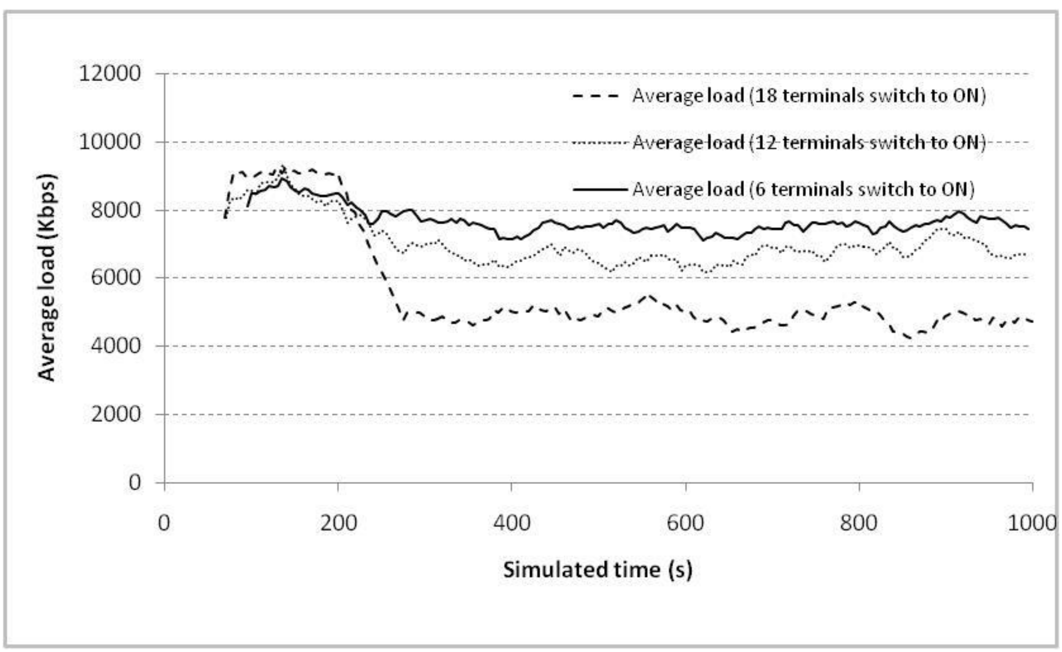
(b)

Figure 4-5: Topology snapshot from ONE simulator (a) before the creation of ONs and (b) after the creation of ONs

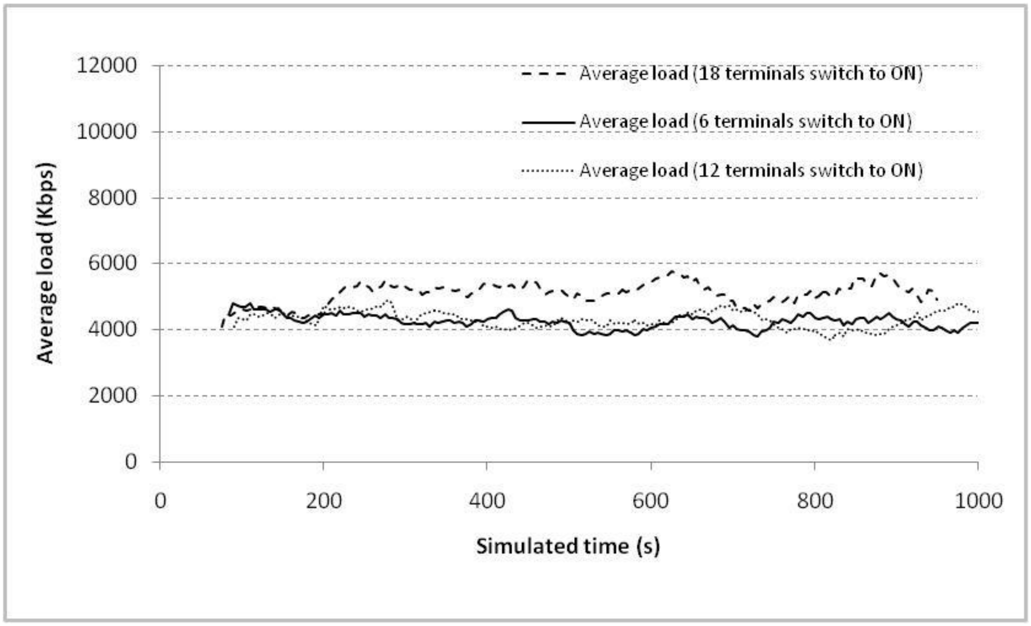
Created ONs have an average number of participating nodes ranging from 1 to 3 according to the considered testcase. According to the “tethering” concept, a single terminal can be used in order to serve as many as 5 to 8 users. The “tethering” concept makes possible the connection of nearby users to gain access to the network by connecting to a single terminal and using its connection (as long as its owner permits it of course). In our simulations though, relatively smaller ONs are considered. According to the definition of the testcases, if 18 terminals need to switch to ON with a capacity of 1, means that neighboring 6 cells will acquire 3 of these terminals which are closely located to the edge of the cell and need to connect only to one neighboring node which is located in the non-congested cell. In addition, if 18 terminals need to switch to ON with a capacity of 3, means that neighboring 6 cells will again acquire 3 of these terminals, but in this case, some of them may not be located near the cell edge, so they will need to create an ON of 3 hops in order to gain access to the non-congested BS. Consequently, this means that in the first case 18 small ONs of 1 hop (till they connect to the node which will give them access to the non-congested BS) will be created, while in the other case, 6 larger ONs of 3 hops will be created in order to connect to the node which will give them access to the non-congested BS. In the same manner, if 12 terminals need to switch to ON with a capacity of 2, this means that 6 ONs of 2 hops will be established in order to redirect traffic from the congested BS to the neighboring non-congested BSs.

4.3.2 Performance evaluation

In the following paragraphs, results are presented related to the performance of the proposed scheme in terms of the load of the infrastructure elements before and after the solution enforcement, the impact on packet loss, delay and energy consumption in BSs and terminals. Initially, BS1 is considered congested, while neighboring BSs are considered as not congested, so traffic from terminals in the congested area can flow through intermediate users into the non-congested BSs. Figure 4-6a provides the trend of the load in the congested BS before and after the solution enforcement while Figure 4-6b provides the trend of the load in a non-congested BS which acquired traffic. In both figures, the horizontal axis shows the simulated time in seconds while the vertical axis provides the average load in Kbps when 18, 12 or 6 terminals switch to ON, for all capacity and mobility levels. On the other hand, the six neighboring BSs acquire the traffic of an average of 1 to 3 terminals each time, so impact on their load is not very significant as suggested from Figure 4-6b. Figure 4-6a and b show the impact on the load when 18, 12, 6 terminals switch to ON, since in all other testcases where capacity and mobility level are changing, the impact on the load remains the same. This is because even if we create 18 small ONs or 6 larger ONs (e.g. of 3 intermediate nodes), that will not change the impact on traffic as in all cases the same amount of terminals switches to ON. On the other hand, capacity and mobility level shall have an impact (sometimes significant) in the delay and power consumption measurements. As a result, the figures that follow provide specific evaluations for each of the aforementioned 27 testcases in order to have a clearer picture on the impact of these attributes to the various performance metrics.



(a)



(b)

Figure 4-6: Trend of load for all capacity and mobility levels of terminals (a) in the congested BS (BS1) before and after the solution enforcement and (b) in a neighboring, non-congested BS which acquired traffic after the creation of ON

Furthermore, Figure 4-7 provides the average delay for delivering messages from all 40 terminals in the congested BS after the solution, for each one of the 27 investigated cases. This is also compared to the average delay in the congested BS, before the solution enforcement. As delay, is considered the difference between the creation time of a message till the successful delivery of the full message to the final destination (which is always a BS). The horizontal axis shows the testcases and the vertical axis provides the average delay in seconds. In all cases, the proposed scheme, seems to perform better compared to the congestion situation. The decrease in the delay is higher (around 35%) when 18 terminals switch to ON and decreases to around 25% and 15% when 12 and 6 switch to ON respectively.

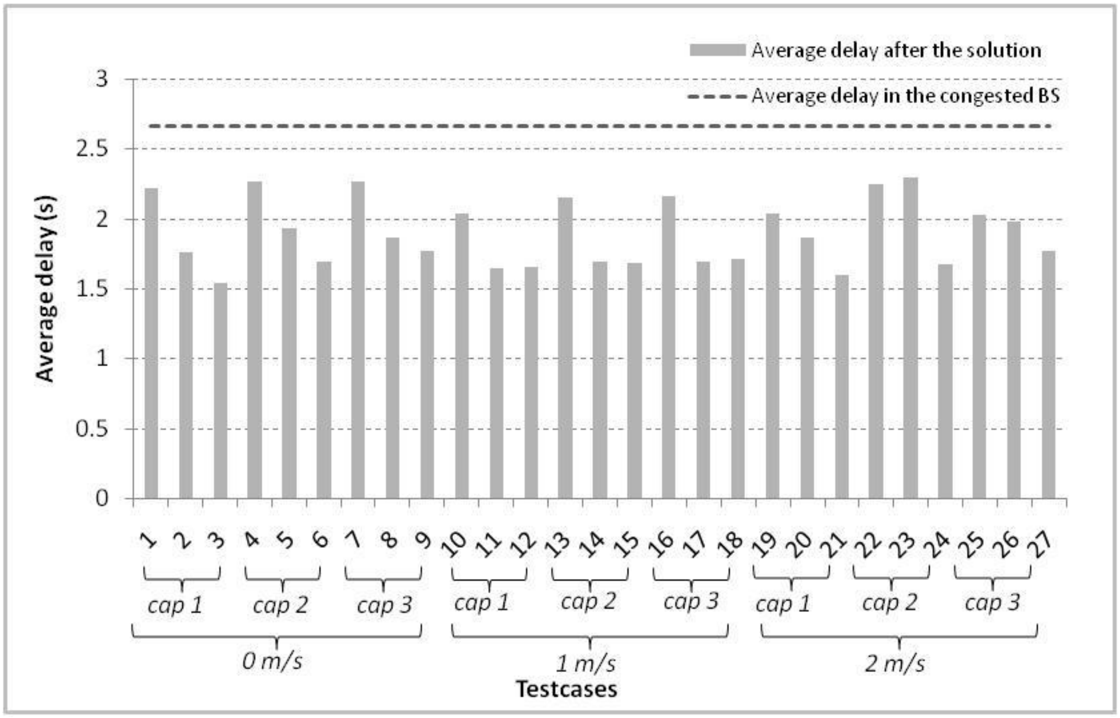


Figure 4-7: Average delay measurements for the transmission of a whole message (64KB-1024KB) in each testcase

Also, Figure 4-8 illustrates the percentage of non-delivered messages from all 40 terminals in the congested BS after the solution, for each one of the 27 investigated cases. The horizontal axis shows the number of the testcases and the vertical axis provides the percentage of non-delivered messages. The general trend shows that as mobility level increases from 0 to 2 m/s, the percentage of non-delivered messages tends to increase due to more frequent break of connections.

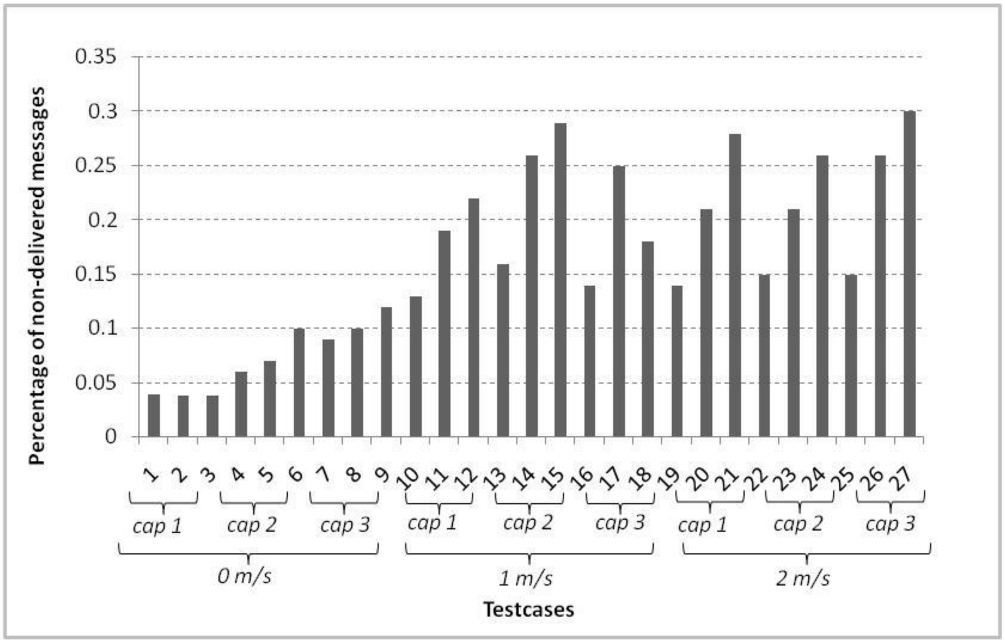


Figure 4-8: Percentage of non-delivered messages in each testcase

Moreover, energy consumption has been estimated in each testcase for the congested BS, the terminals that switch to ON and the intermediate nodes. Figure 4-9 illustrates the average gains in the transmission power of the congested BS. For the communication between BS-terminal the Winner 5Bf propagation model has been used [6]. The horizontal axis of Figure 4-9 shows the simulated time in seconds and the vertical axis provides the average transmission power of the congested BS in Watts. The figure suggests that as more terminals of the congested BS switch to ON the energy savings in the BS range from 15 to 25%.

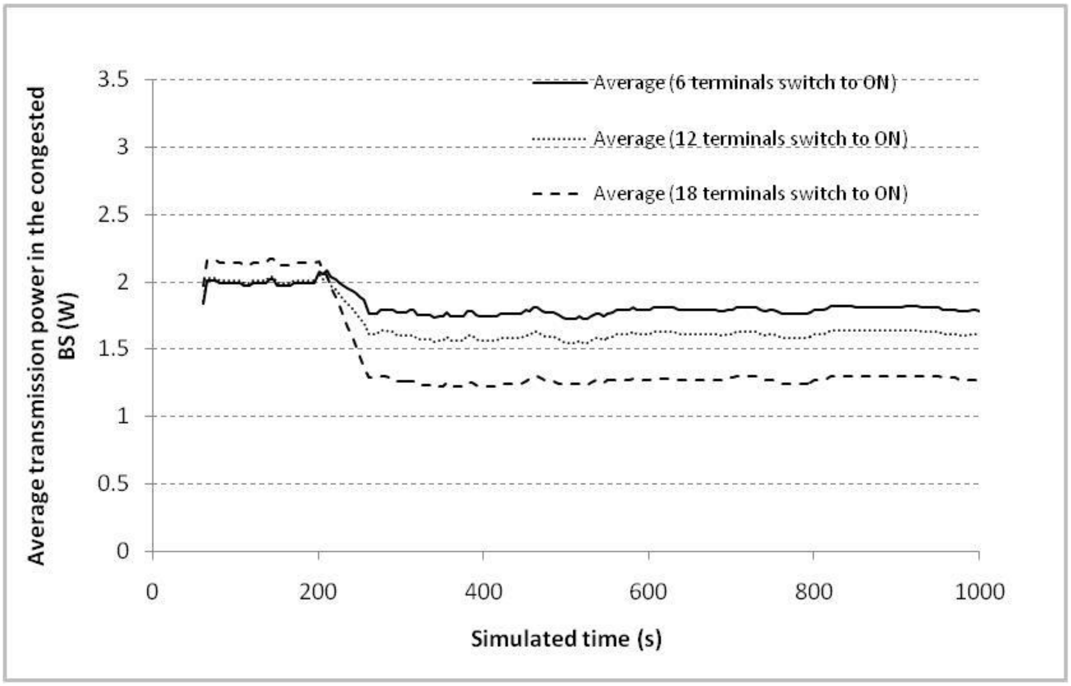


Figure 4-9: Average transmission power (for all capacity and mobility levels of terminals) of the congested BS before and after the solution enforcement

Figure 4-10 provides also a graphical representation of the average transmission power of terminals that switch to ON in each testcase. The horizontal axis of the figure enumerates the testcases while the vertical axis provides the average transmission power of terminals that switch to ON. A decrease of the metric is observed which ranges from 10 to 50% depending on the testcase. Also, the decrease is greater in the cases where 6 terminals switch to ON, since these terminals tend to be nearer the edges of the cell, hence transmission power is greater before the solution. On the other hand, when 12 and 18 terminals switch to ON, there is a greater variety of distances of terminals from the centre of the cell, so the decrease in energy savings is lower.

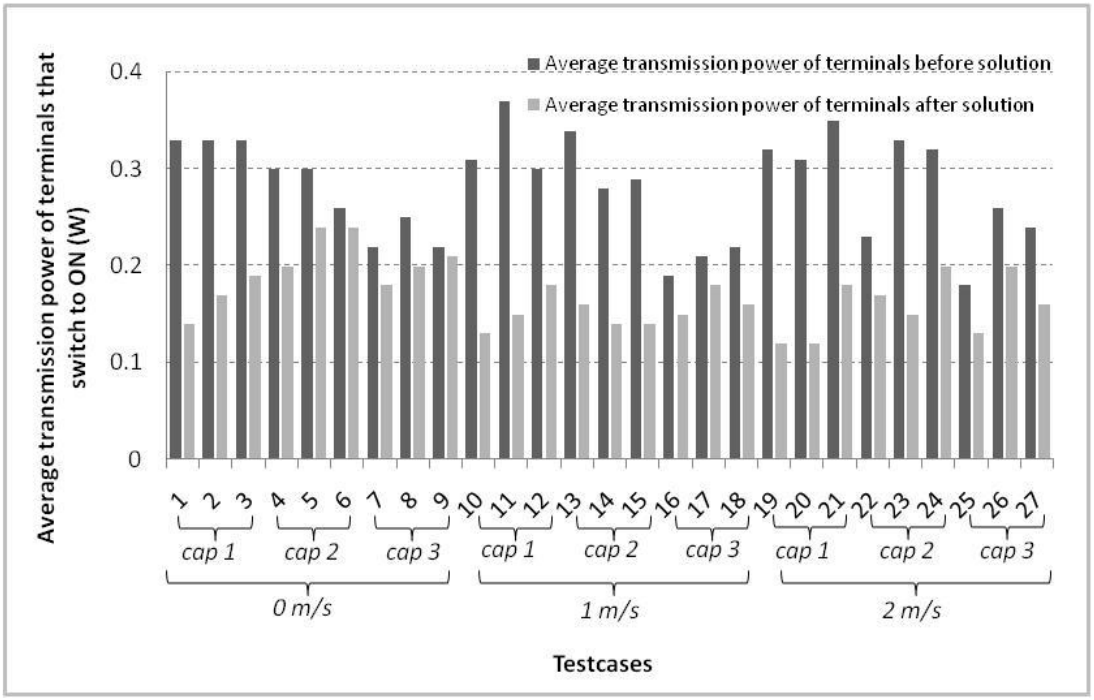


Figure 4-10: Average transmission power of terminals that switch to ON in each testcase

Figure 4-11 illustrates the average transmission power of intermediate nodes of the ON in each testcase. The horizontal axis of the figure shows the testcases while the vertical axis provides the average transmission power measured in Watts. In all testcases, an increase is observed which ranges from 8 to 50% depending on the testcase. When intermediate nodes are stationary higher increase is measured due to the fact that the always the same nodes acquire the extra traffic. As the average velocity of intermediate nodes increases, the transmission power tends to drop to lower levels compared to stationary nodes.

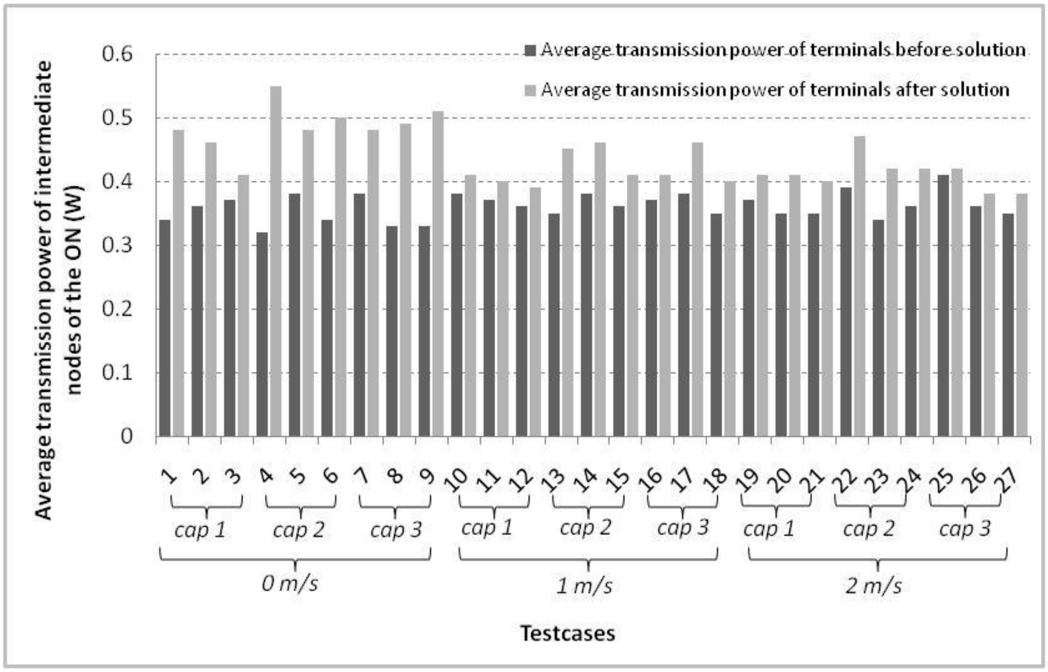


Figure 4-11: Average transmission power of intermediate nodes of the ON in each testcase.

4.3.3 Key findings and recommendations

The subsection that follows summarizes in a paragraph the key findings that derive from the results. According to the obtained results through the simulations that are provided earlier in this section, it is observed that terminals which act as intermediate nodes may experience an increase in their transmission power of around 8 to 50%, compared to the situation before the solution, depending on the testcase, e.g., whether they are stationary or moving, or depending on the allowed capacity. At the same time, the terminals that switch from the congested BS to an ON may experience a decrease of their consumption from 10 to 50% depending again on the testcase which is evaluated. Through the creation of ONs in order to redirect traffic from the congested BS to neighboring cells, a reduction of 15-25% in the transmission power of the congested BS is observed. Also, the quality of communication is benefited, as delay of successfully delivered messages drops approximately 15-35%, compared to the congested situation, depending on the testcase. Furthermore, an average decrease of 15-40% has been achieved in the load of the congested BSs, depending on the number of terminals which switched to ON. Finally, extra traffic related to signalling for the establishment of ONs is limited due to the limited size of the ON which means that a small number of terminals need to exchange constantly control messages among them.

4.4 Chapter References

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5 Control Channels for the Cooperation of Cognitive Management Systems

Chapter Outline

Opportunistic networks (ONs) and cognitive management systems (CMSs) for cellular extensions are one of the emerging communication paradigms in wireless mobile communications. Operator-governed ONs use the basic concepts of opportunistic networking and extend them by proposing coordination mechanisms which cooperate with the infrastructure. Control Channels (CCs) have been identified as a key feature required for supporting CMSs in their operation, through the provision of the information and knowledge [1]-[4]. It should be noted that, by processing the information acquired through CCs, there can be more elaborate knowledge that can be generated through machine learning, and, therefore, there can be efficient intersystem coexistence and cooperation and a reactive or proactive response to situations. Moreover, it can be seen that the CC concept comprises information on all the layers of the protocol stack, e.g., ranging from spectrum sensing and spectrum awareness to various application and user requirements.

The rest of the chapter is structured as follows: Section 1 provides necessary introductory information. Section 2 analyzes the information (parameters) conveyed for each of the main structures including profiles; context; decisions; knowledge; policies. Section 3 proceeds to the numerical evaluation and the recommendations coming from this chapter.

Keywords: control channels; data structures

5.1 Introduction

For the cooperation of CSCIs and CMONs, specific mechanisms need to be defined in order to increase the accuracy of obtained knowledge on the context of the operational environment. Also, a cooperation mechanism is required for efficient coordination between the infrastructure and the devices in the scope of an ON. Therefore, CCs are required for the exchange of information and the coordination between CMSs. Such control channels can be based on the exploitation and evolution of two concepts: the cognitive pilot channel (CPC) and the cognitive control radio (CCR) (as defined by ETSI). The CPC can be seen as an enabler for providing information from the network to the terminals and vice-versa (e.g., available RATs, spectrum, bands etc.) [5].Specific data structures have been developed so as to formulate the structure of the information that needs to be exchanged through CCs for supporting the various scenarios described before by mainly containing information on the context of operation, on the profiles of the involved nodes, on the policies to be obeyed, on the decisions made, as well as on knowledge derived for all the above [6].

5.2 Exchanged information

This section describes the structure of the information of which a subset of it may be exchanged in the scope of cognitive wireless communication systems for the various scenarios described in the previous section. Figure 5-1 provides a high-level description of the various types of information considered.

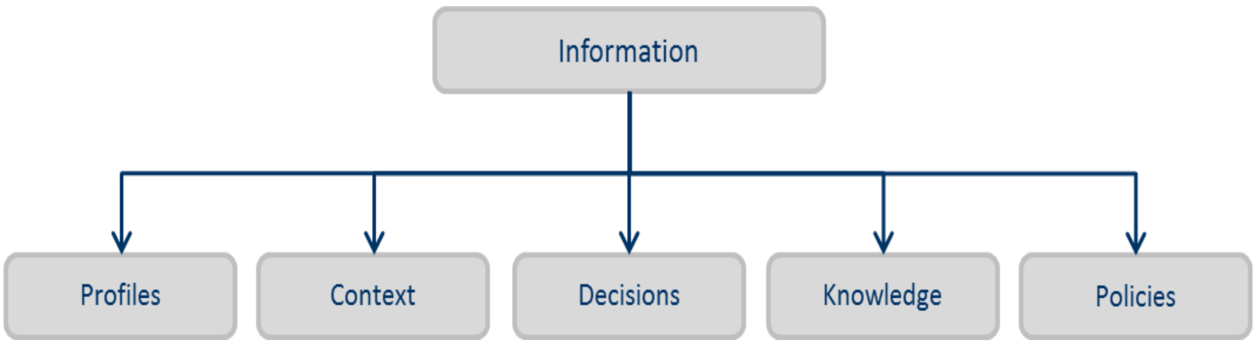

Figure 5-1: High-level description of exchanged information

5.2.1 Profiles information

The Profiles (Figure 5-2) are primarily divided into terminal, base station, user and operator profiles. Terminal and Base Station (BS) profiles include parameters related to "General capabilities", e.g. Node ID, Node Type etc.; "Communication capabilities", e.g. Network interface capabilities, supported spectrum sensing techniques etc.; "Computing capabilities", e.g. CPU, memory size etc.; "Storage capabilities", e.g. caching size etc.; "Energy capabilities", e.g. battery capacity etc.; and "ON capabilities", e.g. does the terminal/BS support ONs, incentives, how many times has the terminal participated in an ON etc. The figure and the tables that follow provide an analysis of the aforementioned parameters. The type of each parameter corresponds to the data types as proposed in the IEEE 802.21 specification.

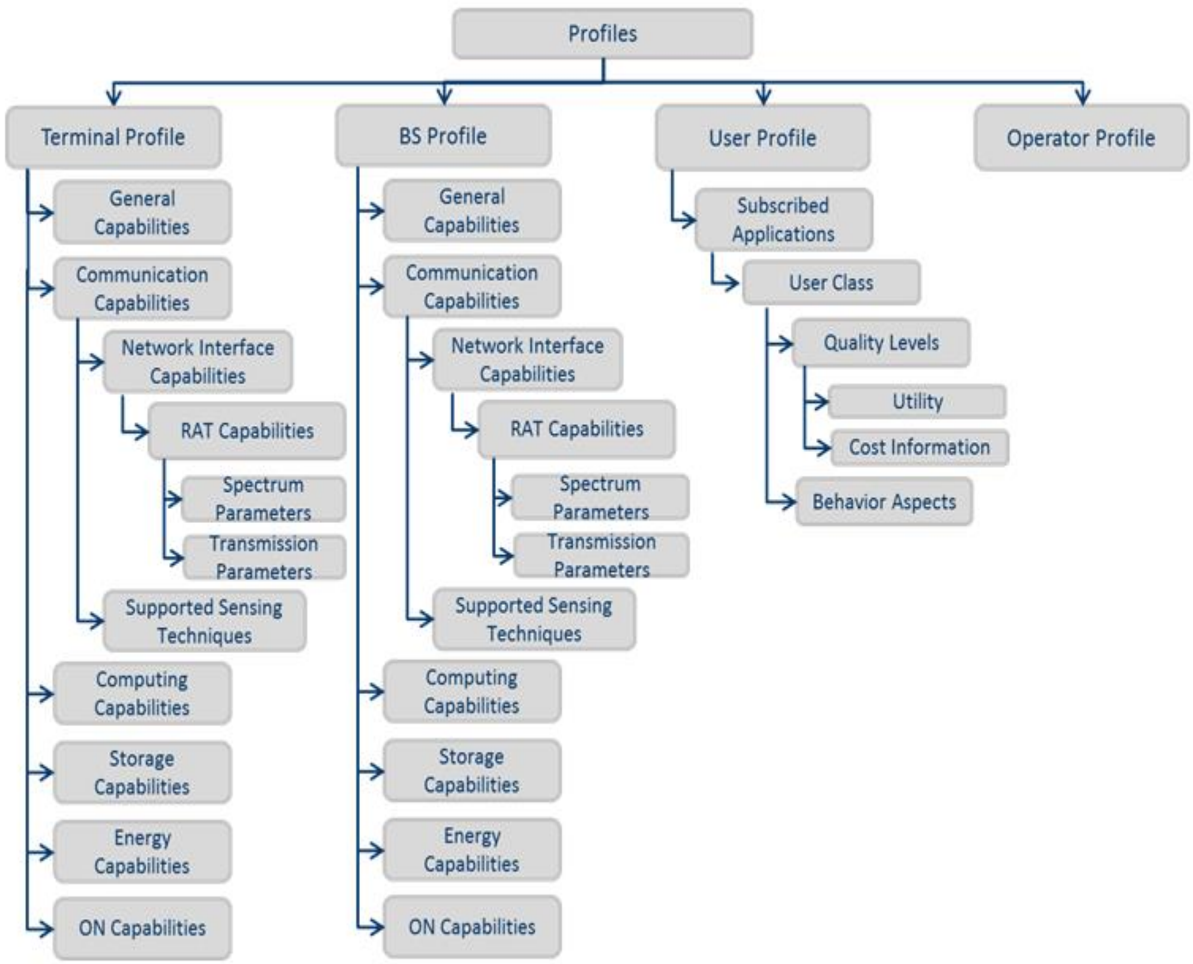

Figure 5-2: Profile-related information

Table 5-1: Terminal/BS Profile

Terminal/BS_Profile
General Capabilities
• *Node_ID* (Node's unique ID – Integer) • *Node_Type* (Type of device e.g., terminal, BS, small cell – Integer) • *Localization_Support* (Set of localization systems (e.g. GPS) supported by the device – Boolean) • *Display_Resolution* (Screen resolution available in terminals – Enumeration)
Communication_Capabilities
• *Network_Interface_Capabilities*

- *Interface_ID* (Set of network interfaces of the device – Integer)
- *RAT_Capabilities* (Set of RATs supported by each network interface of the device - Class)
  - *RAT_ID* (Integer)
  - *Spectrum_Parameters* (Set of spectrum capabilities for each RAT, of the network interface of the device – Class)
    - *Spectrum_Block* (Class)
      - *Central_Frequency* (Integer)
      - *Bandwidth* (Integer)
    - *Transmission_Parameters* (Set of transmission capabilities for each RAT, of the network interface of the device – Class)
      - *Transmission_Power* (Integer)
      - *Maximum_Supported_Velocity* (Integer)
      - *Maximum_Capacity* (Integer)
      - *Spectrum_Aggregation_Capability* (Boolean)
    - *Supported_Sensing_Techniques* (Class)
      - *Detector_Types* (Enumeration)

Computing_Capabilities

- *CPU_Frequency* (The frequency of the CPU of the device – Integer)
- *Memory_Size* (The memory size of the device – Integer)

Storage_Capabilities

- *Cache_Size* (The cache size of the device – Integer)

Energy_Capabilities

- *Battery_Capacity* (The battery capacity of the device – Integer)

ON_Capabilities

- *ON_Support* (Indication whether the device supports ONs or not – Boolean)
- *Routing_And_Relaying_Support* (Indication whether device supports data routing and relaying or not – Boolean)
- *Multiple_Connectivity_Support* (Indication whether device supports multiple simultaneous connections or not – Boolean)
- *Number_of_Participations_in_ON* (Indicates how many times the device has participated in ONs – Integer)
- *Remote_Connection_Setup_Support* (Denotes if other devices can trigger a connection setup procedure within the device – Boolean)
- *Incentives* (Set of possible incentives for the device e.g., discount on customer's bill, social networking awards, etc.)
  - *Incentive_Type* (Enumeration)
- *Gateway_Support* (Denotes whether the device has the ability to serve as a gateway towards other devices – Boolean)

Additionally, user profile provides information on the subscribed applications of a user, the user class of an application (i.e., the quality levels that the application can be provided to this user class. E.g., for streaming or browsing application type, a user that belongs to the 'High' user class the possible qualities of service shall be e.g., 2Mbps, 1Mbps or 512Kbps etc.). Also, the behaviour aspects of the user are taken into account. These aspects indicate the number of requests from a user in order to use an application and the usage characteristics. Usage characteristics include the estimated session duration and the estimated data volume transfer. For example a user may need to use an ON for 5 minutes or may need to download a small (e.g., 1-2MB) or a large file (e.g., 20MB). Usage characteristics are used to determine whether a user can be supported through an ON.

Table 5-2: User Profile

User Profile

General Capabilities

- *User_ID* (Identity of user – Integer)
- *ON_User_Preferences* (Set of ON user preferences. It comprises indication on the preferences for the status of a user in an ON -e.g. gateway, relay, end user, etc. – Class)
    - *Relaying_Interfaces* (Integer)
    - *Subscribed_Applications* (Class)
        - *Application_Profile* (Class)
            - *Application_ID* (Integer)
            - *Application_Name* (Octet_String)
            - *Application_Type* (Enumeration)
- *User_Class_ID* (Set of user classes at which application *app* can be provided – Integer)
- *Quality_Level* (Set of quality parameters – Class)
    - *Quality_ID* (Quality level identity – Enumeration. Each QoS level consists of a set of parameters which specify its utility value, bitrate, etc. For instance, a streaming application may be served through two user classes, namely "Gold" and "Silver". The "Gold" user class may provide the application at 3 possible quality levels, e.g. "High", "Medium" and "Low", which may correspond to utility value 10 and bitrate of 8 Mbps, utility value 8 and bitrate of 5 Mbps and utility value 5 and bitrate of 2 Mbps respectively.)
    - *Utility* (Class)
        - *Utility Value* (Integer)
        - *Bitrate* (Real)
        - *Latency* (Real)
        - *Jitter* (Real)
    - *Cost_Information* (Class)
        - *Cost Value* (Integer)

• *Behavioral_Aspects* (Behavioral aspects of a user, using an application with a subscription at a specific user class. It comprises parameters such as the number of times the user requested the application app and usage characteristics)
  ○ *Number_of_Requests* (Integer)
  ○ *Usage_Characteristics* (Class)
    ▪ *Estimated_Session_Duration* (Integer)
    ▪ *Estimated_Data_Volume_Transfer* (Integer)

Finally, operator profile shall include information on the elements (e.g., BSs) that the operator owns/ manages, its subscribers etc.

Table 5-3: Operator's Profile

Operator Profile
General Capabilities
• *Operator_ID* (Operator's identity – Integer) • *Operator_Name* (Operator's name – Octet_String) • *Infrastructure_Elements* (No. of equipment that the operator owns/manages – Integer) • *Subscribers* (No. of subscribers – Integer)

5.2.2 Context information

Context information (Figure 5-3) is divided into terminal and base station context. Terminal and BS context include parameters related to "General status", e.g., Node location, Context timestamp, Node mobility (in case of a terminal) etc.; "Communication status", e.g., interface status, RAT operated, demand and QoS offered per application, user class etc.; "Computing status", e.g., current CPU/memory usage; "Storage status", e.g., current cache usage; "Energy status", e.g., current battery level; and ON specific context, e.g., ON services offered, Supported ONs (ON paths from terminals to BSs –set of nodes and links), Potential ONs (neighbouring terminals that support ON) etc. The figure and the table that follow provide an analysis of the aforementioned parameters. The type of each parameter corresponds to the data types as proposed in the IEEE 802.21 specification.

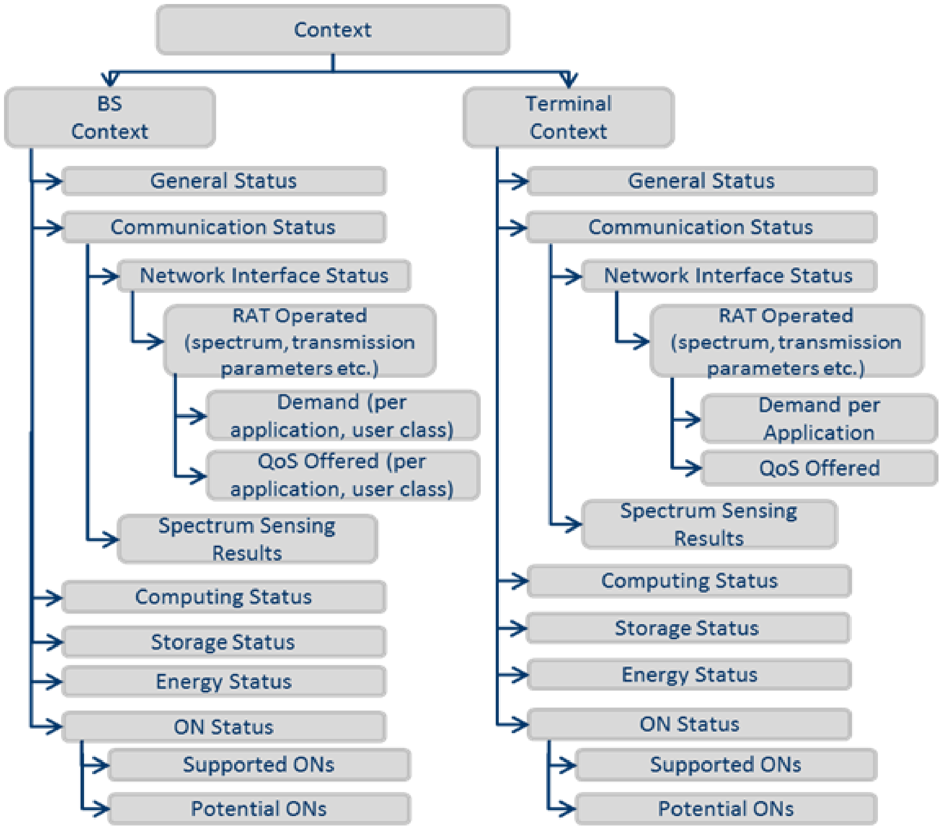

Figure 5-3: Context-related information

Table 5-4: BS/Terminal Context

BS/Terminal Context
General Status
• *Node_ID* (Identity of device – Integer) • *Node_Location* (Location of device – Location_Type) • *Context_Timestamp* (The timestamp of the specific context occurrence – Time_Date) • *Fitness_Value* (Fitness value of the device – Real) • *SG_Type* (Small cell operating at Open/Closed Subscriber Group – Enumeration) • *Mobility_Level* (Terminal related parameter related to the speed of the terminal – Integer) • *Currently_Served_Nodes* (Set of terminals that are currently served – Integer)
Communication Status

• *Network_Interface_Status* (Set of active network interfaces of the device – Class)
  ○ *Interface_ID* (Integer)
  ○ *Power_Consumption* (Real)
  ○ *Current_Load* (Real)

- *RAT_Operated* (The operating RAT of each network interface - Class)
    - *RAT_ID* (Integer)
    - *Demand_Per_Application* (Class)
        - *Active_Application* (Class)
            - *Application_ID* (Integer)
            - *UserClass_ID* (Integer)
            - *Quality_Level_ID* (Integer)
            - *Elasticity* (Integer)
    - *QoS_Offered* (Class)
        - *Active_Application* (Integer)
        - *Active_Time* (Integer)
        - *Data_Exchanged* (Integer)
    - *Broadcast_Transmission_Power* (Real)
- *Spectrum_Sensing_Results* (Spectrum status for each network interface of device operating at a specific RAT. Contains parameters which specify the spectrum's bandwidth, central frequency)
    - *Spectrum_Availability* (Enumeration)
    - *Estimated_Idle_Periods* (Integer)
    - *Spectrum_Block*
        - *Central_Frequency* (Integer)
        - *Bandwidth* (Integer)

Computing Status

- *CPU_Usage* (Current CPU usage of device – Integer)
- *Memory_Usage* (Current memory usage of device – Integer)

Storage Status

- *Cache_Usage* (Number of file/multimedia parts in caching – Integer)

Energy Status

- *Battery_Level* (Information on the energy that is left for the device – Integer)

ON Status

- *Supported_ONs* (Set of supported ONs for each network interface of the device)
    - *Interface_ID* (Integer)
    - *ON_Characteristics* (Characteristics for each supported ON. It comprises parameters such as the id of the ON, its location, the links that belong to the ON, the applications that are supported by the ON, etc.)
        - *ON_ID* (ON identity – Integer)
        - *ON_Location* (ON location – Octet_String)
        - *Path* (Available paths consisting of links and nodes)
            - *Links* (Octet_String)
            - *Nodes* (Octet_String)
        - *ON_Services_Offered* (Enumeration)
        - *Security_Support* (Boolean)
    - *Potential_ONs* (Set of potential ONs that can be supported by each network interface of the device)
        - *Interface_ID* (Integer)
        - *Neighboring_Nodes_That_ Support_ON* (Octet_String)

5.2.3 Decisions information

Information on decisions (Figure 5-4) is divided into ON decisions, infrastructure decisions and terminal decisions.

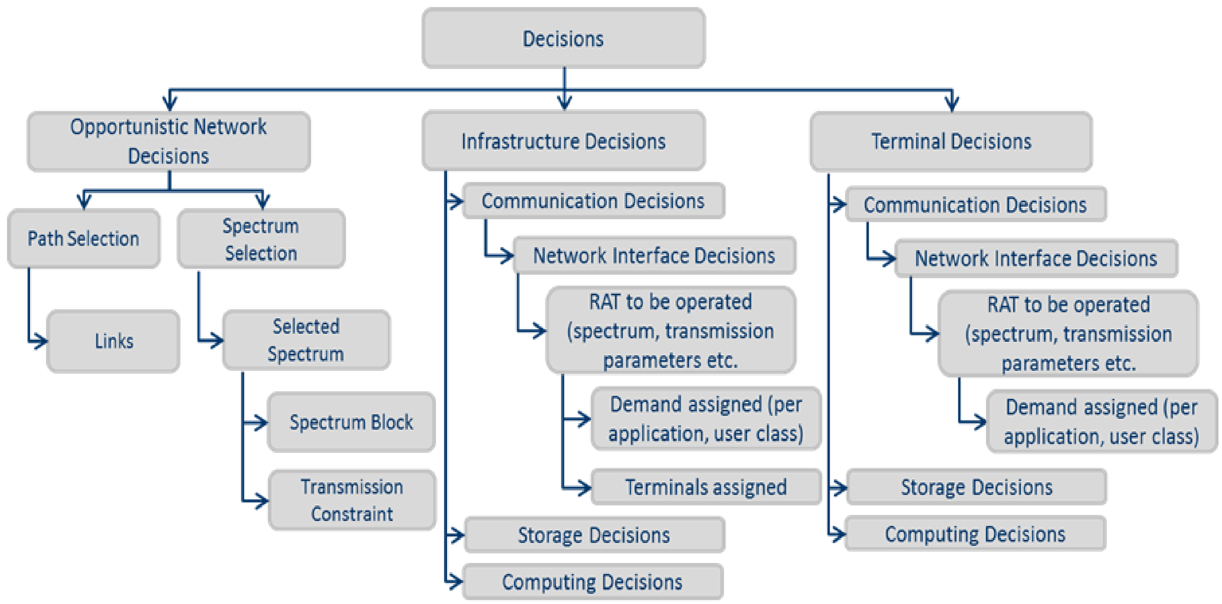

Figure 5-4: Decisions-related information

Specifically, ON decisions include parameters related to "Path selection" (covering selected nodes and links); and "Spectrum selection" e.g. selected spectrum block such as central frequency, bandwidth, selected sensing technique (e.g. sensing detectors etc.) and transmission constraints (e.g. maximum allowed transmit power etc.). Additionally, infrastructure and terminal decisions cover aspects on communication e.g., RAT to be operated (including assigned demand per application and user class, assigned terminals); storage e.g., amount of cache to be used); and computing e.g., CPU or memory amount to be used.

Table 5-5: Decisions

Decisions
Communication Decisions
• *Network_Interface_Operated (*Set of network interfaces of a device that will be operated/selected according to the decision made*)*   ○ *Interface_ID* (Integer)

- *RAT_To_Be_Operated*
  - *RAT_ID (*RAT at which network interface will operate – Integer*)*
- *Demand_Assigned*
  - *Active_Application*
    - *Application_ID* (Integer)
    - *UserClass_ID* (Integer)
    - *Quality_Level_ID* (Integer)
    - *Elasticity* (Integer)
  - *Broadcast_Transmission_Power* (Class)
    - *Transmission_Constraint* (Octet_String)
    - *Maximum_Allowed_Transmission_Power* (Real)
  - *Selected_Spectrum* (Class)
    - *Spectrum_Block* (Octet_String)
    - *Central_Frequency* (Integer)
    - *Bandwidth* (Integer)
- *Terminals_Served* (Terminals that are assigned to be served by the specific network interface operating at the specific RAT – Integer)

Computing_Decisions

- *CPU_Usage* (Decision on cache resources usage – Integer)
- *Memory_Usage* (Decision on memory resources usage – Integer)

Storage_Decisions

- *Cache_Usage* (Decision on cache resources usage – Integer)

ON_Decisions

- *ON_ID* (ON identity – Integer)
- *Selected_Path* (Class)
  - *Links* (Set of links that belong to the specific ON. Each link consists of L parameters that depicts the link's ending points, SINR, measured capacity – Class)
    - *Ending_Points* (Octet_String)
    - *SINR* (Integer)
    - *Measured_Capacity* (Integer)

5.2.4 Knowledge information

Knowledge (Figure 5-5) is related to acquired context and decisions made. For example, ON knowledge comprises information on the selected path between terminals and towards BSs, selected spectrum etc. (e.g., nodes and links used, spectrum used, QoS achieved etc.). Infrastructure-related knowledge includes: communication decisions (such as RAT operated, assigned demand per application and user class, assigned terminals etc.); storage decisions (such as amount of cache used etc.) and computing decisions (such as CPU/memory used etc.).

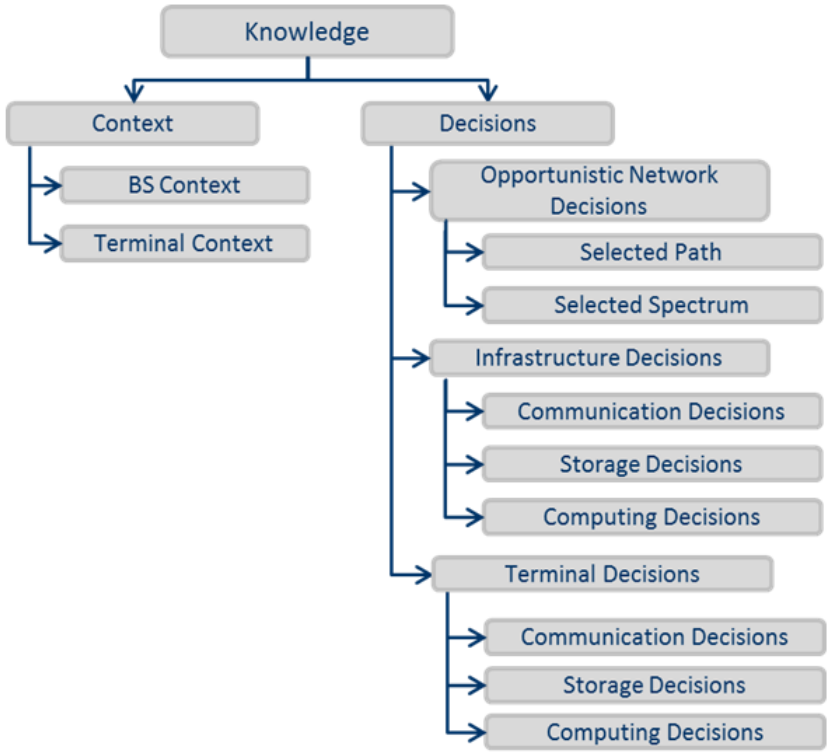

Figure 5-5: Knowledge-related information

Accordingly, terminal-related decisions include communication decisions (such as RAT operated, applications served, QoS offered etc.); storage decisions (such as amount of cache used by the terminal etc.) and computing decisions (such as CPU, memory used etc.).

Table 5-6: Knowledge

Knowledge

• *Network_Context* (Class)
  ○ *Terminal_Context* (Network context comprises a set of terminal contexts – Class)
  ○ *BS_Context* (Network context comprises a set of BS contexts – Class)
• *Decision* (Decision that was taken for network context)
  ○ *ON_Decision* (A set of ON-related decisions – Class)
  ○ *Terminal_Decision* (A set of terminal-related decisions – Class)
  ○ *Infrastructure_Decision* (A set of infrastructure-related decisions – Class)

5.2.5 Policies information

Policies represent rules of the network operator that are imposed for certain reasons (Figure 5-6).

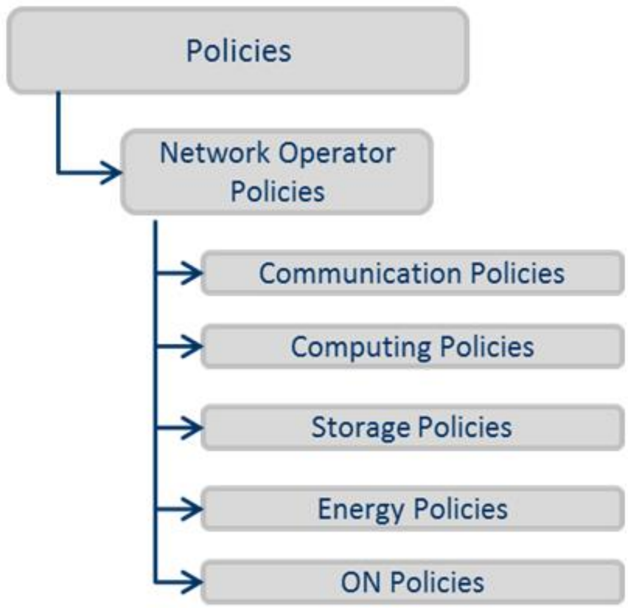

Figure 5-6: Policies-related information

Network operator policies shall include parameters related to "Communication-related policies" (e.g., allowed interfaces, allowed relaying capacity etc.); "Computing-related policies" (e.g., CPU usage, allowed memory usage etc.); "Storage-related policies" (e.g., allowed caching size etc.); "Energy-related policies" (e.g. allowed consumption etc.); "ON-related policies" (e.g., maximum number of nodes in an ON, maximum time to live, allowed applications and quality levels etc.);

5.3 Evaluation results and recommendations

5.3.1 Simulation parameters

In order to solve the coverage and capacity extension problems the network elements (i.e. terminals, APs, BSs) exchange control messages between cognitive management systems that comprise various information regarding the status and the capabilities of the nodes, as well as the computed decisions. The structure of the exchanged information is described earlier. For instance, when a device's context is conveyed it comprises general information (e.g. the device's ID, its location, the context timestamp, etc.), communication status (i.e. the status of the device's network interfaces, the operating Radio Access Technologies (RATs), the offered QoS to the applications, etc.), computing status (e.g. CPU and memory usage), storage usage (e.g. cache usage) and energy status (e.g. remaining battery level). Therefore, the goal of the signaling evaluation is to measure the size of the exchanged information that is transmitted through the control messages for different number of nodes (these nodes are the node that initiates the exchange of messages, the neighboring nodes and the APs).

The following test cases are considered for the evaluation:

Table 5-7: Considered testcases

Case	Considered Attributes
1	– Total BSs: 7 – Non-congested BSs: 6 – Congested BSs: 1 – Terminals in non-congested BSs: 15 – Terminals in congested BS: 40 – Terminals switching to ONs: 12 – # created ONs: 12 – # links per ON: 2 – # of interfaces in BSs: 1 – # of interfaces in terminals: 2 – # of RATs (per interface): 1 – # of subscribed apps: 1 – # of quality levels: 1 – # of active interfaces: 1 – # of active applications: 1
2	– Total BSs: 7 – Non-congested BSs: 6 – Congested BSs: 1 – Terminals in non-congested BSs: 20 – Terminals in congested BS: 80 – Terminals switching to ONs: 24 – # created ONs: 24 – # links per ON: 2 – # of interfaces in BSs: 1 – # of interfaces in terminals: 2 – # of RATs (per interface): 1 – # of subscribed apps: 1 – # of quality levels: 1 – # of active interfaces: 1 – # of active applications: 1
3	– Total BSs: 7 – Non-congested BSs: 6 – Congested BSs: 1 – Terminals in non-congested BSs: 25 – Terminals in congested BS: 160 – Terminals switching to ONs: 48 – # created ONs: 48 – # links per ON: 2 – # of interfaces in BSs: 1 – # of interfaces in terminals: 2

– # of RATs (per interface): 1 – # of subscribed apps: 1 – # of quality levels: 1 – # of active interfaces: 1 – # of active applications: 1

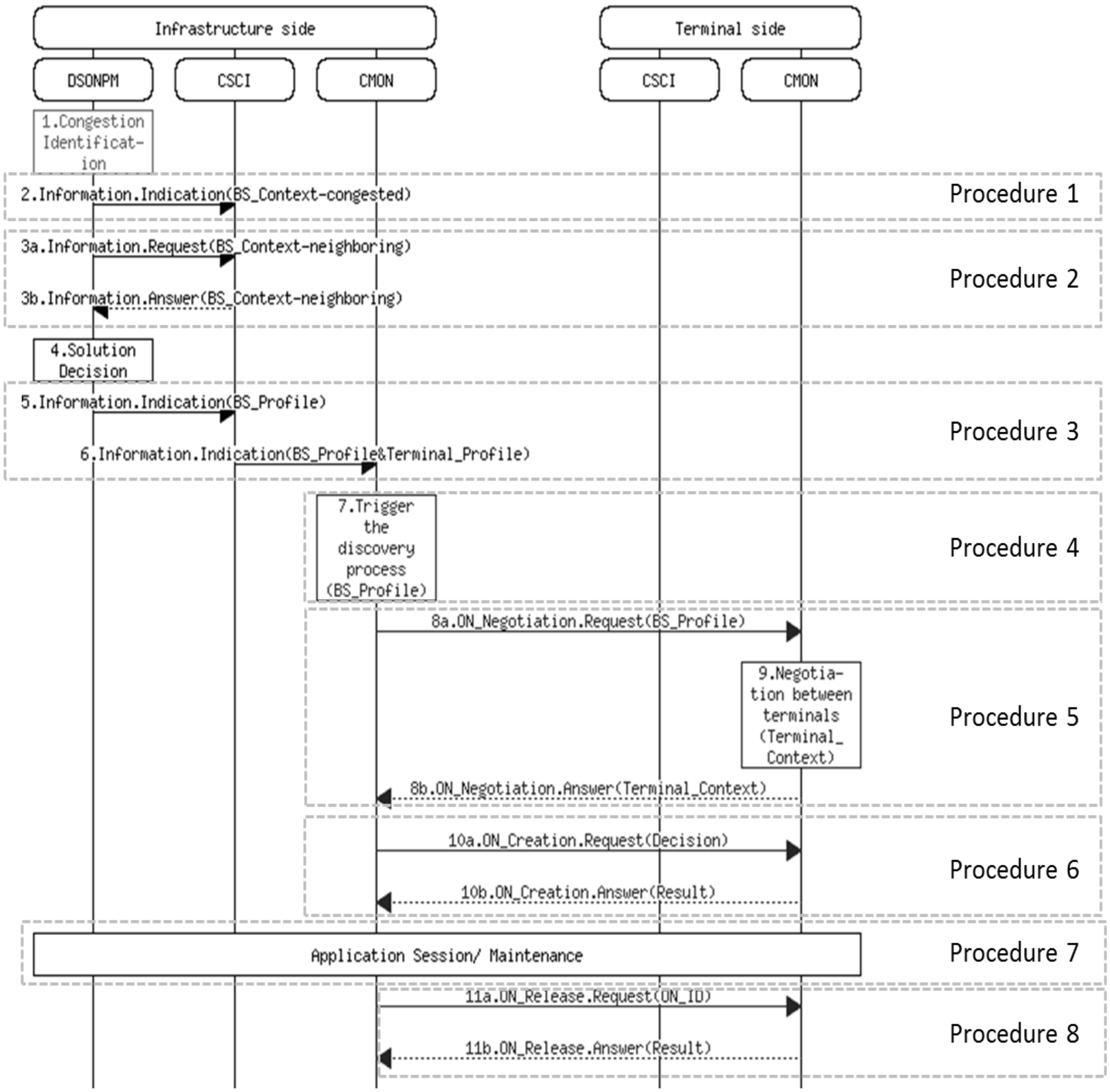

Figure 5-7: Mapping of messages and related information to procedures

5.3.2 Performance evaluation

The charts that follow provide associated signaling load for the creation, maintenance and termination of ONs according to the provided input parameters in Table 5-7. Sizes of messages and parameters are estimated by taking into account sizes of the basic data types according to the IEEE 802.21 specification. Figure 5-8 shows the minimum sizes of each data type according to the IEEE 802.21 specification.

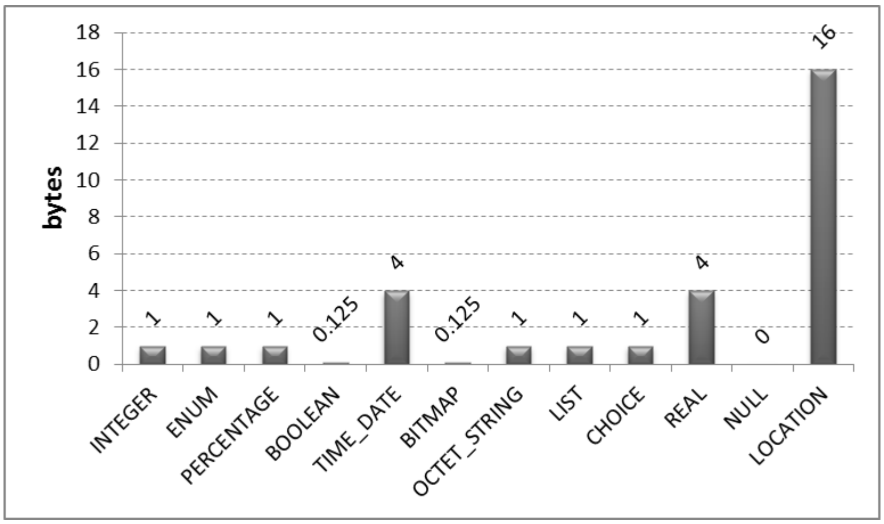

Figure 5-8: Minimum sizes of each data type according to the 802.21 specification

According to the specification, minimum sizes of data types of "Integer", "Enumeration", "Percentage", "Octet_String" are 1 byte (unless mentioned differently –e.g. we may use an "Integer" of 4 bytes, an "Octet_String" of 10 bytes etc.). Also, definitions of "List" and "Choice" add 1 extra byte to the contents of the "List" or the "Choice". "Boolean" and "Bitmap" data types are having minimum sizes of 1 bit (i.e., 0.125 byte). Finally, "Time_Date" and "Real" data types are having a size of 4 bytes each, while the "Location" data type is considered to be 16 bytes. Of course, "Null" requires zero bytes.

According to the information conveyed in the "BS/Terminal Profile" a specific formula has been developed for the calculation of it as presented in Relation 5.1.

$$\text{BS/Terminal\_Profile} = 35 + \sum_{i=1}^{a} (18 \cdot x_i + 1) \qquad (5.1)$$

where

$a =$ number of interfaces, $a \geq 1$

$x =$ number of RATs (per interface), $x \geq 1$

The data structure has been assessed according to the aforementioned test cases 1-3. It is shown that sizes may vary according to the number of interfaces and number of RATs per interface.

The "User Profile" data structure uses as arguments the number of available interfaces that could be potentially used for relaying, the number of subscribed applications, the user classes of each application and the number of available quality levels for each user class. It is calculated through the following formula (5.2):

$$\text{User\_Profile} = 26 + a + \sum_{i=1}^{app_s} (9 + 12 \cdot q_i) \qquad (5.2)$$

where

$a =$ number of interfaces, $a \geq 1$

$app_s =$ number of subscribed applications, $app_s \geq 1$

$q =$ number of quality levels, $q \geq 1$

The "Terminal Context" data structure uses as arguments the number of active applications, the number of file/multimedia parts that are available in caching, the number of links of each terminal and the number of ON-capable neighbouring terminals. It is calculated through the following formula (5.3):

$$\text{Terminal\_Context} = 105 + \sum_{i=1}^{a_{act}} (28 + 4 \cdot app_{act}) + 6 \cdot m + 44 \cdot l + 4 \cdot t_n \qquad (5.3)$$

where
a_{act} = number of active interfaces
app_{act} = number of active applications, $app_{act} \geq 1$
l = number of links of terminal, $l \geq 1$
m = number of file/multimedia parts in caching storage, $m \geq 0$
t_n = number of ON-capable, neighboring terminals, $t_n \geq 0$

The "BS Context" data structure uses as arguments the number of ONs currently supported by the BS and the "Terminal Context" of each terminal currently connected to the BS. It is calculated through the following formula:

$$\text{BS\_Context} = 117 + m \cdot 6 + \sum_{i=0}^{on_s} (22 + 44 \cdot l_i) + \sum_{j=1}^{t_{BS}} \text{Terminal\_Context}_j \qquad (5.4)$$

where
on_s = number of supported ONs, $on_s \geq 0$
l_i = links of each supported ON i, $l_i \geq 1$
m = number of file/multimedia parts in caching storage, $m \geq 0$
t_{BS} = number of terminals connected to BS, $t_{BS} \geq 1$

The "ON Decisions" data structure uses as arguments the number of links in the ON and it is calculated through the following formula (5.5). Message sizes may vary according to the number of links in each ON:

$$\text{ON\_Decisions} = 32 + 44 \cdot l_{ON} \qquad (5.5)$$

where
l_{ON} = number of links in the ON, $l_{ON} > 1$

Also, the "Infrastructure Decisions" have been calculated according to the following formula (5.6). Message sizes may vary according to the considered number of interfaces, the number of served terminals and the file parts in caching storage:

$$\text{Infrastructure\_Decisions} = 22 + 2 \cdot a + 8 \cdot t_{served} + 6 \cdot m \qquad (5.6)$$

where

$a =$ number of interfaces, $a \geq 1$

$m =$ number of file/multimedia parts in caching storage, $m \geq 0$

$t_{served} =$ number of served terminals, $t_{served} > 0$

The "Terminal Decisions" have been calculated according to the following formula (5.7). Message sizes may vary according to the considered number of interfaces and the number of file/ multimedia parts in caching storage.

$$\text{Terminal\_Decisions} = 30 + 2 \cdot a + 6 \cdot m \qquad (5.7)$$

where

$a =$ number of interfaces, $a \geq 1$

$m =$ number of file/multimedia parts in caching, $m \geq 0$

Also, "ON_Knowledge" data structure conveys selected information from the BS_Context, Terminal_Context, ON_Decisions, Infrastructure_Decisions or Terminal_Decisions. To that respect, the size of this data structure is linked to the sizes of the aforementioned context or decision structures.

For the suitability determination-creation and termination relevant procedures (i.e., procedures 1-6 and 8), triggered-based events are considered. On the contrary, for the maintenance phase (i.e., procedure 7) a periodic exchange of signaling messages is also considered.

The chart in Figure 5-9 shows the impact of each procedure 1-6 and 8 which involve trigger-based messages. Periodic messages are not exchanged during these procedures, because the procedures are executed only when they are instructed from the cognitive management system. Each procedure is evaluated separately for each one of the testcases. Also, the chart in Figure 5-10 illustrates the total signaling load for each testcase.

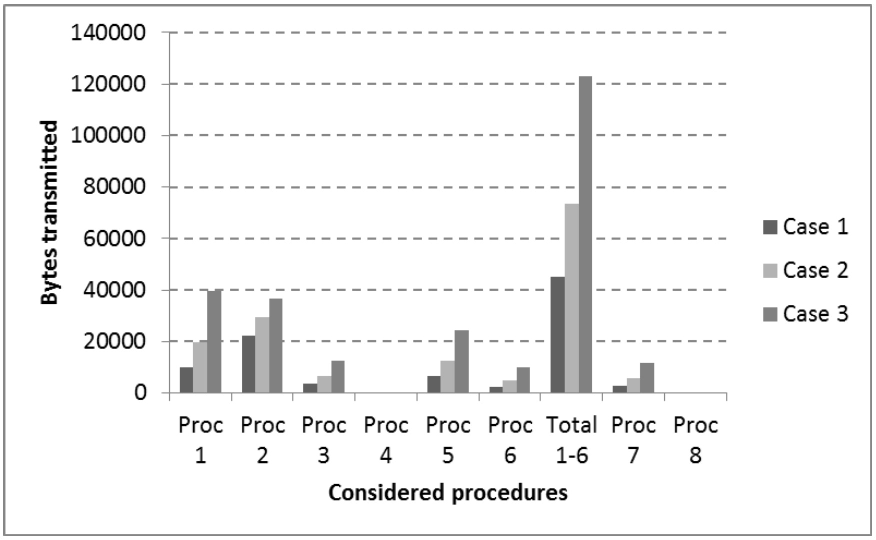

Figure 5-9: Signaling load associated with specific procedures

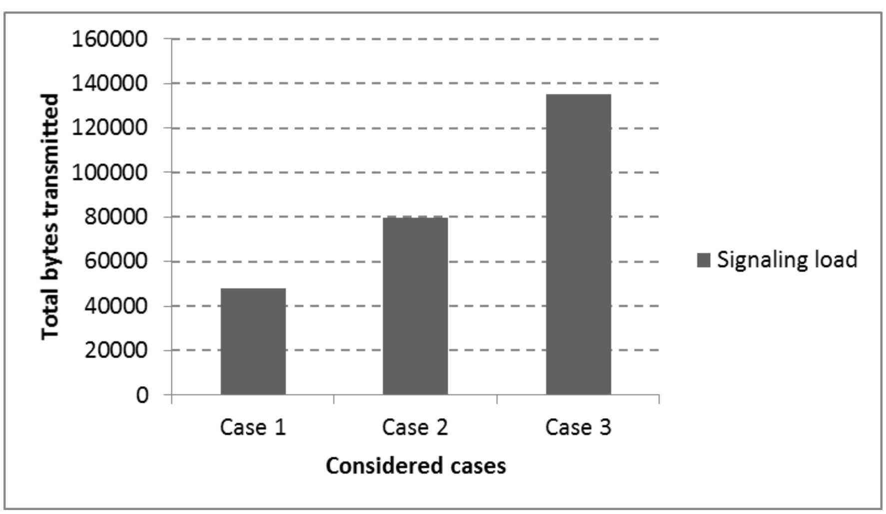

Figure 5-10: Total signaling load for each case

Figure 5-11 provides an estimation of the periodic signaling load which is considered to take place during the maintenance phase of the ON. Specifically, during this phase, terminal context is considered to be sent periodically (every 1, 5 or 30 seconds) in order to know the status of the nodes involved in the ON (e.g. their current location, current energy level, current links etc.). It is observed that as long as the intervals of transmission are more closely defined, the signaling load per second (bytes/s) is higher (for each case considered).

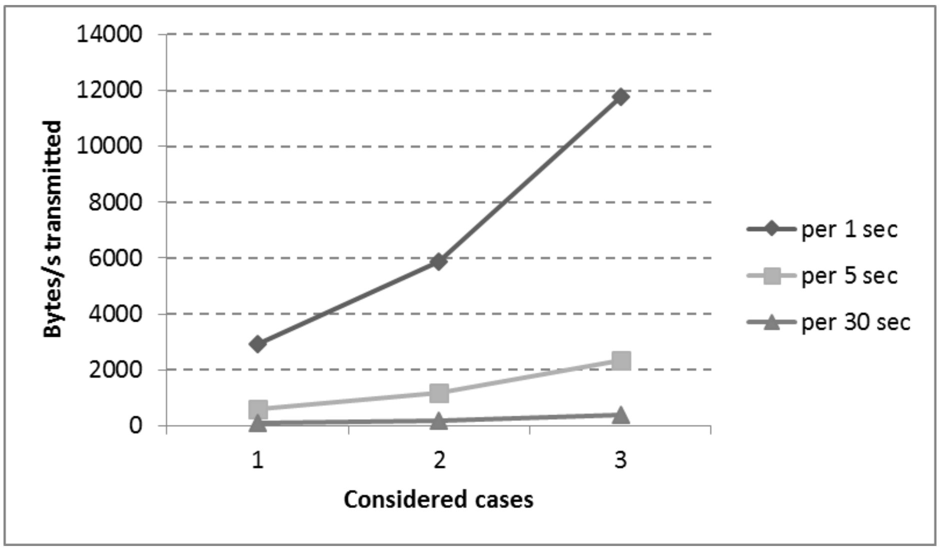

Figure 5-11: Calculation of periodic signaling load associated with procedure 7 (ON maintenance)

5.3.3 Key findings and recommendations

Through the numerical evaluation of the size of the exchanged information, it is observed that as more terminals are included in the opportunistic networks, this means that more information between these terminals should be exchanged. In general, as it was expected the signaling load was increased as more nodes were included in the network, due to the fact that more messages are exchanged during the discovery process, in order to find neighboring available nodes.

Moreover, parts of the aforementioned work related to control channels have triggered the pre-standardization work of a technical report of ETSI and more specifically ETSI TR 102 684 on “Feasibility Study on Control Channels for Cognitive Radio Systems” [3].

5.4 Chapter References

[1] ETSI TR 102 682 V1.1.1,”Reconfigurable Radio Systems (RRS); Functional Architecture(FA) for the Management and Control of Reconfigurable Radio Systems”, 2009

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6 Energy Efficient Device-to-Device Communications

Chapter Outline

This chapter focuses on the energy efficiency achieved when device-to-device communication is employed. Specifically, different levels of energy consumption are observed for intermediate terminals (in the middle of the ON 'chain') and edge terminals (at the end of the ON 'chain'). It should be noted that through intermediate terminals, traffic of edge terminals is also served, thus energy consumption of intermediate terminals is expected to be higher.

The rest of the chapter is structured as follows: Section 1 provides an introduction of the chapter. Section 2 proceeds to the main considerations, indicative scenarios and potential application domains which are taken into account for our evaluation. Section 3 proceeds to the performance evaluation and key findings of the chapter.

Keywords: energy efficiency; edge terminals; intermediate terminals; transmission power

6.1 Introduction

One of the main challenges of the evolving wireless world is to support a wide set of QoS-demanding services. However, the solutions that will be considered should not only take into consideration the optimization of the network performance, but should also be energy efficient both for the operator and the end-user. As a result, this chapter presents the energy efficiency of D2D communications by studying specific cases. The cases studied in this chapter comprise a congested macro base station, neighboring non-congested base stations and various ON-enabled terminals. The proposed solution will offload a proportion of the traffic of the congested base station to the neighboring un-congested ones, through the creation of an ON. The congested base station will consume less energy since terminals will be rerouted to the neighboring un-congested base stations. Therefore benefits for operators and end-users in terms of energy consumption will be provided as it will be shown in this chapter.

6.2 Evaluation scenarios and potential application domains

D2D communications can capitalize on the use of cognitive management systems and control channels as discussed in previous chapters of this dissertation in order to proceed to the efficient creation of a D2D network through the exchange of messages. As proposed in previous chapters two main scenarios will be considered where D2D communications are utilized in order to solve problematic situations through ON creation. These are the opportunistic coverage expansion of the infrastructure and the opportunistic capacity expansion of the infrastructure. In both scenarios, a problematic situation is occurred (e.g. an infrastructure failure, or infrastructure congestion respectively) and the terminals cannot efficiently served by the problematic infrastructure. Therefore, paths to alternative, neighboring, non-congested BSs are being identified. This can be achieved through the exploitation of neighboring terminals that will redirect the problematic terminals to alternative BSs.

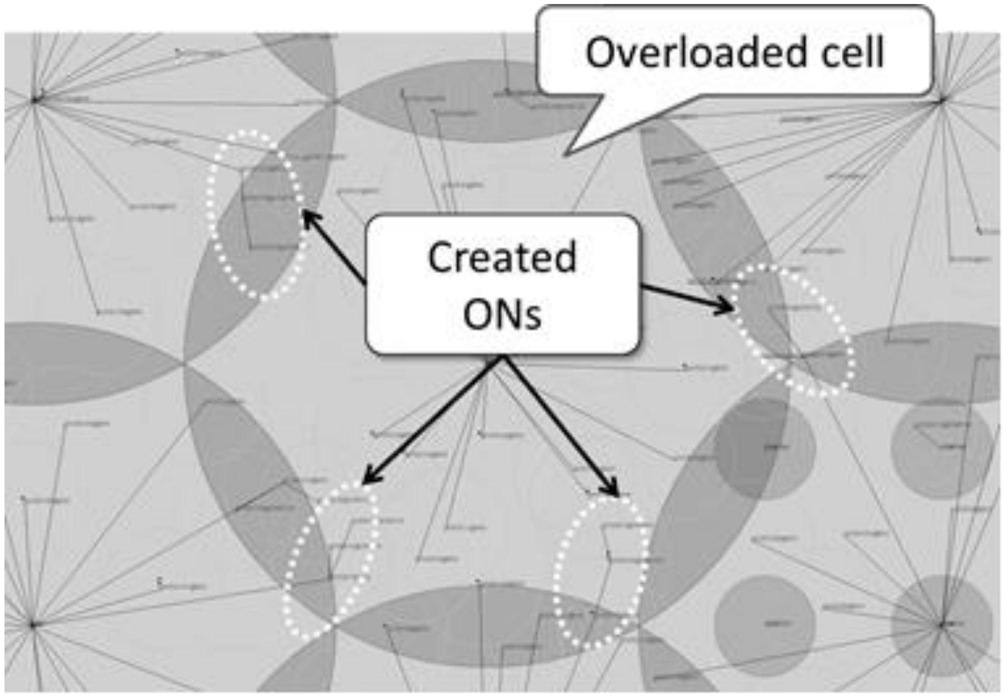


Figure 6-1: Indicative playground for testcases

Figure 6-1 presents the indicative playground which is considered for the evaluation of the energy efficiency. Specifically, the middle BS represents the congested BS and terminals which are currently served by this BS, need to be redirected to the neighboring uncongested BSs (which are represented in the figure by six (6) circles around the middle one).

In Figure 6-2 the blue circle corresponds to an indicative coverage of an Access Point, while the purple circle depicts the indicative coverage of a terminal device in order to create the ON/ D2D network in areas where ground morphology is challenging for traditional communications. Through this example it is possible to realize additional use cases with potential applications in defense domains and in remote areas which are posing certain limitations with respect to infrastructure coverage and quality of communication.

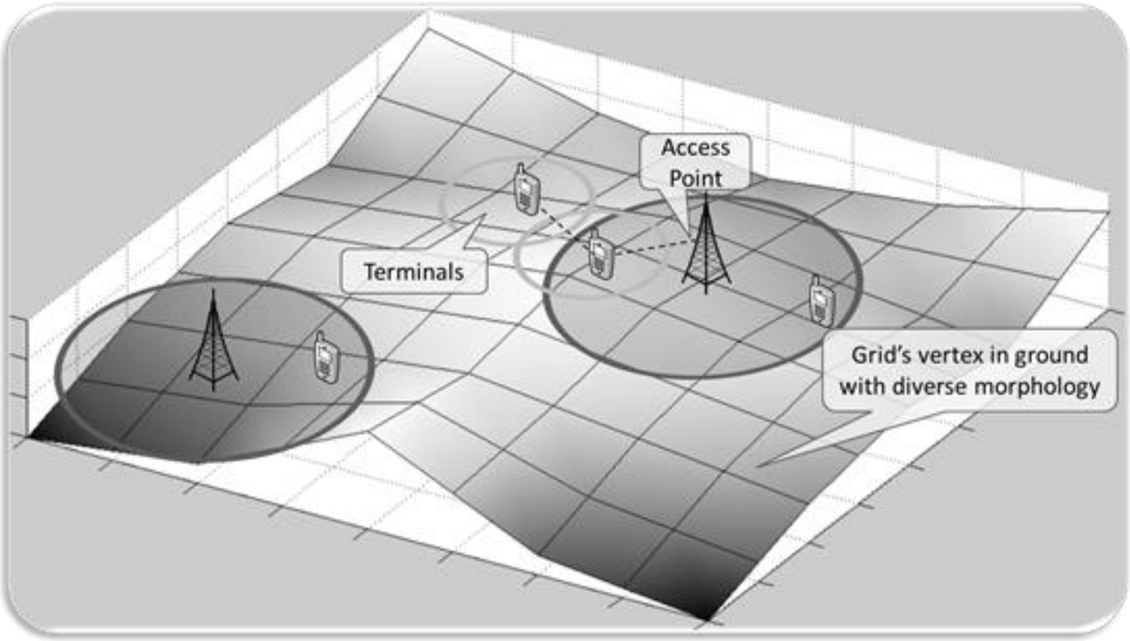


Figure 6-2: Situations where diverse ground morphology is challenging for traditional communications

6.3 Evaluation results and recommendations

6.3.1 Simulation parameters

Specific testcases have been evaluated according to Table 6-1. In terms of mobility, the Random Walk mobility model has been used and measurements have been performed for specific moving velocities ranging from stationary (0 m/s), 2m/s and 4m/s. Mobility is following a Random Walk model in order to maintain traffic distribution in cells.

Table 6-1: Definition of testcases

Testcase	**Moving terminals in non-congested neighboring BSs (and in congested BS)**	**Mobility level (m/s)**
1	0 (0)	0
2	6 (12)	1
3	6 (12)	2
4	6 (12)	4
5	3(6)	1
6	3(6)	2
7	3(6)	4

6.3.2 Performance evaluation

Figure 6-3 presents the impact of D2D communications through the creation of ONs in edge terminals. Edge terminals are considered to be terminals at the end of the D2D chain which are not served directly by a BS, but need to connect to nearby located intermediate terminals in order to gain access to neighboring BSs. It is shown that edge terminals are benefited from the proposed solution in all testcases due to the fact that short-range links are created with nearby intermediate terminals.

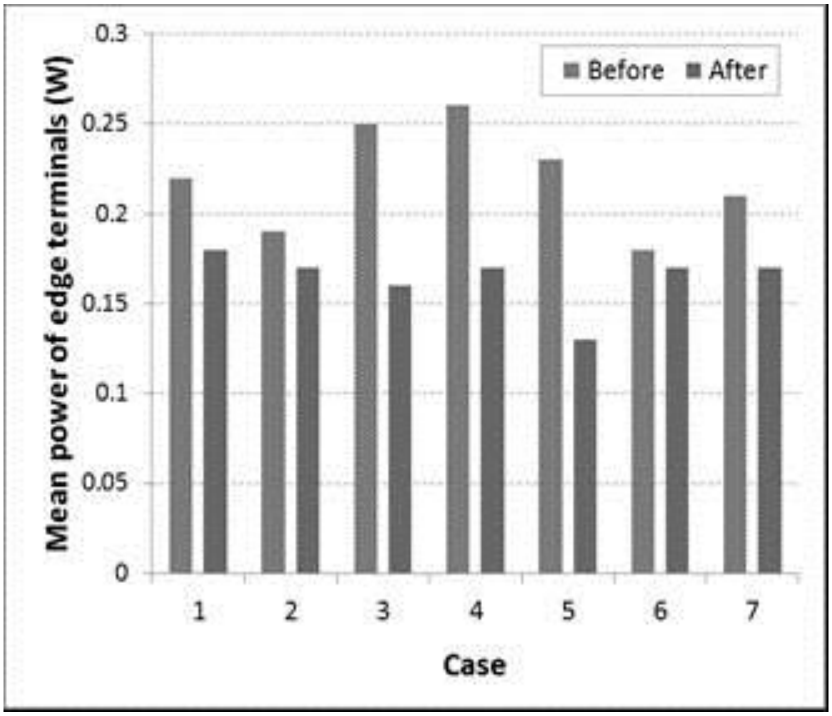


Figure 6-3: Decrease of mean energy consumption of terminals

Figure 6-4 shows the impact of ON creation to intermediate terminals. This category of terminals assists edge terminals in order to gain connectivity to a neighboring BS. In this respect, extra load passing through intermediate terminals leads to their light increase of their mean energy consumption in cases where no mobility or very little mobility (1 m/s) is used. On the other hand, when mobility is increasing e.g., 2-4 m/s, the mean energy consumption of intermediate terminals is slightly better even after the creation of an ON, due to the fact that an intermediate terminal is not staying for a long time in range of a nearby edge terminal and as a result is less stressed in terms of energy consumption, until it is replaced by another ON-enabled terminal that is passing by.

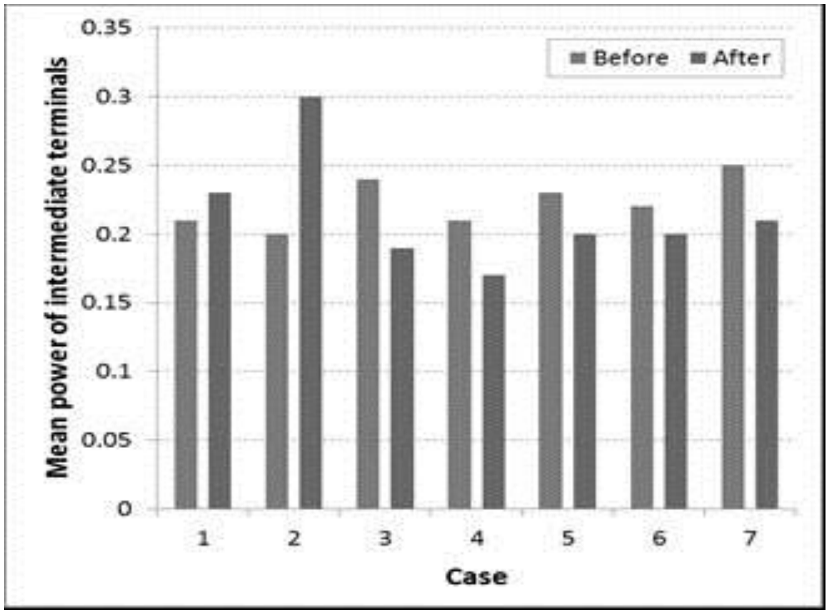
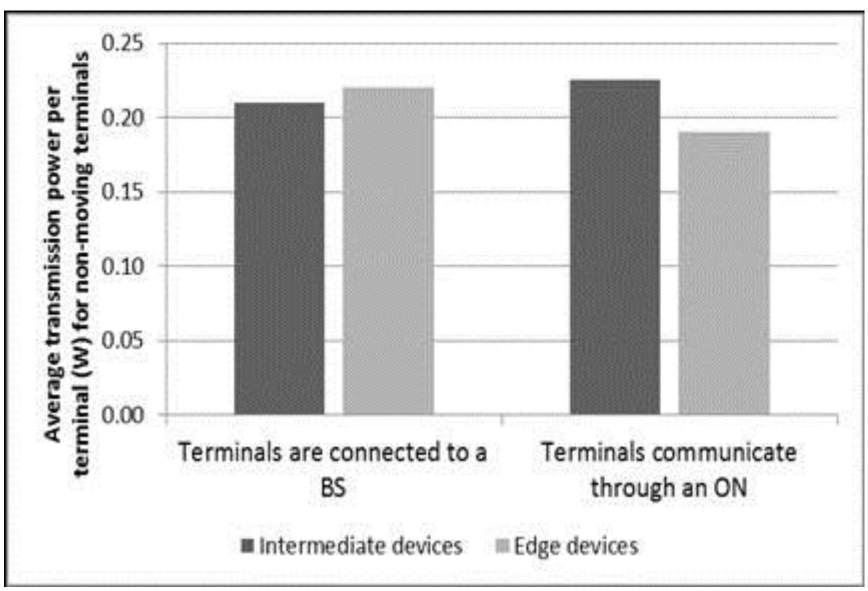
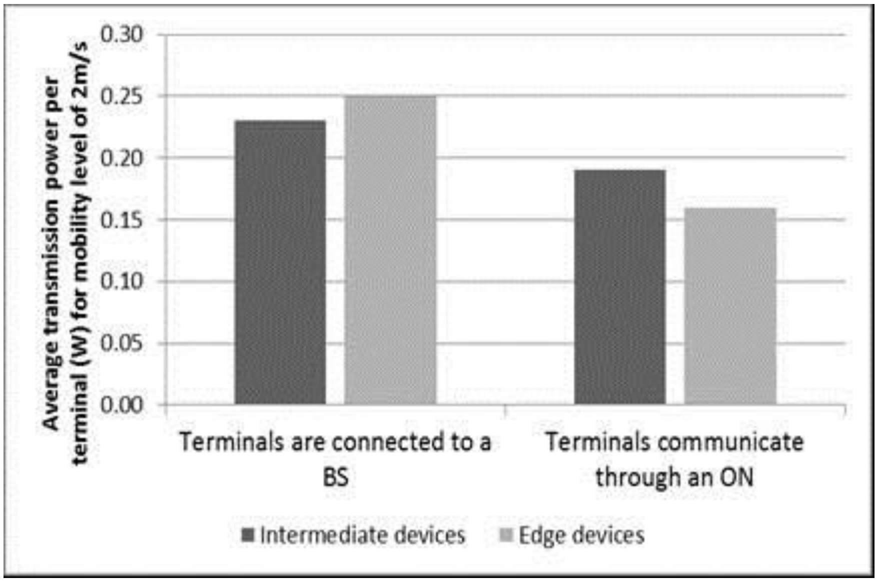


Figure 6-4: Impact of ON traffic traversed through intermediate terminals to mean energy consumption

Figure 6-5 illustrates an overall comparison of average energy consumption for terminals communicating directly with BSs and when an ON is formed in static conditions and in moving conditions. Both intermediate and edge terminals are evaluated in order to show the actual benefits of D2D communications and mobility.



(a)



(b)

Figure 6-5: Energy consumption comparison for terminals communicating directly with BSs and when an ON is formed in (a) static conditions, (b) moving conditions

Figure 6-6 shows the decreasing trend of the congested base station average transmission power after the creation of an ON, where less terminals are served by the previously congested base station.

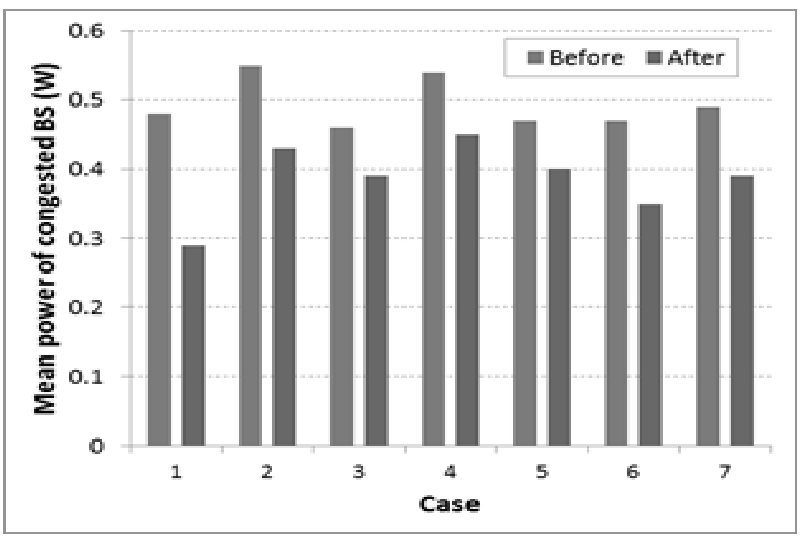
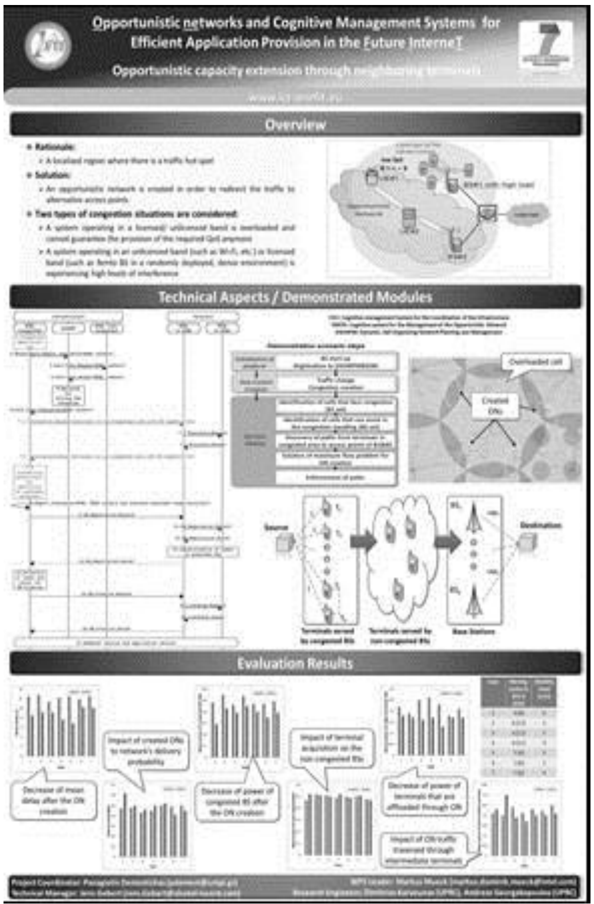


Figure 6-6: Mean energy consumption comparison of congested BS before and after the ON creation

Supported by the previously presented results, energy-related benefits for mobile operators and end-users are clearer in addition to the fact that coverage or capacity extension of the infrastructure is observed due to the introduction of D2D communications.



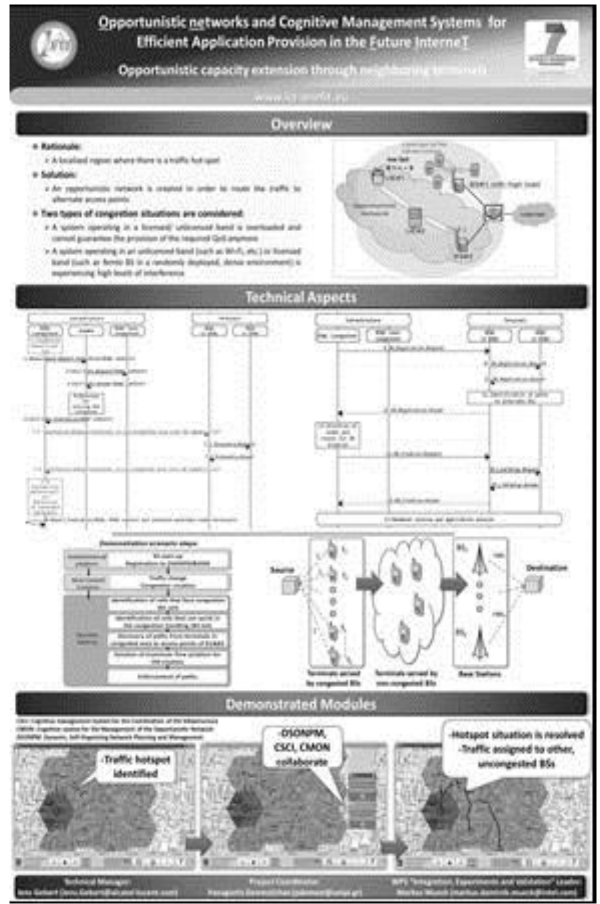


Figure 6-7: Indicative demonstration material during the events

6.3.3 Key findings and recommendations

From the aforementioned results it is evident that energy efficiency for terminals participating in ONs is supported by the fact that short-range links are created between terminals. Moreover, it is shown that as the mobility level of terminals increases, the overhead of intermediate terminals which are serving the edge, ON nodes, is limited due to the fact that their exposure to the ON lasts for a short time.

It is worth mentioning that this work has also being demonstrated during demo dedicated sessions in international events and conferences in order to strengthen the impact of the proof-of-concept. Specifically demonstrations have taken place in Future Network and Mobile Summit (FNMS) 2011 [1], 2012 [2] and 2013 [3], as well as during the Future Internet Week-ServiceWave 2011 [4] and the ACM 3rd International Workshop on Mobile Opportunistic Networks (MobiOpp) 2012 [5]. Also, Figure 6-7 illustrates indicative demonstration material which was presented during the aforementioned events.

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[1] A. Georgakopoulos, V. Stavroulaki, J. Gebert, O. Moreno, O. Sallent, M. Matinmikko, M. Filo, D. Boskovic, M. Tosic, M. Mueck, C. Mouton, P. Demestichas, "Opportunistic Networks for efficient application provisioning in the Future Internet: Business Scenarios and Technical Challenges", In Proc. 20th Future Networks and Mobile Summit 2011, Warsaw, Poland, June 15-17, 2011

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of Opportunistic Networks in the Future Internet”, Towards a Service-based Internet, vol.6994, pp.313-314, Springer Verlag, October 2011

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7 Summary – Ongoing Challenges

This dissertation provided an overview of the dynamic access networks in a wireless Future Internet beyond 4th generation and towards a 5th generation of systems by considering the current status and looking forward to the emerging challenges. Special emphasis was placed on the opportunistic networking paradigm in order to provide an insight on research regarding operator-governed ONs which are assumed to be coordinated extensions of the infrastructure. ONs can be used for providing coverage and capacity extension of the infrastructure in places where is needed in a temporary manner. For the coordination of operator-governed ONs, cognitive management entities are introduced and control channels have been evaluated in order to enable the exchange of necessary contextual information among the involved nodes.

In the context of this dissertation, the problem of the selection of most suitable nodes for their inclusion in an ON has been formulated and solved by providing certain performance evaluation results. In addition to this, the problem of selecting the most appropriate paths for redirection of traffic from congested base stations to neighboring non-congested ones (hence providing capacity extension to problematic areas) has been also formulated and solved.

In addition to these problems, the necessary contextual information which is needed for the creation of ONs has been categorized to certain groups, in order to be able to provide a more structured view. Also, the evaluation of transmitted information between such control channels has been provided as part of this dissertation.

Finally, the energy efficiency aspect of device-to-device communications (in which opportunistic networking is part of it) has been studied in order to be able to show that such solutions can provide savings for operators and end-users. Specifically, energy efficiency has been studied according to certain use cases which are taking into account neighboring users and the level of mobility of terminals.

However, there is still a plethora of challenges ahead regarding the topics described. In this respect, the results of this dissertation can provide a useful starting point for further and intensive future research.

Knowledge-based, intelligent management of networks

It is a fact that the achievement of optimality (acceleration of deployment of network elements, QoS/QoE, cost and energy efficiency), in demanding and variable contexts through the exploitation of the appropriate system capabilities can only be done through a constantly agile system behaviour. Therefore, essential advances in the management intelligence are necessitated. In addition, the development of knowledge can lead to the fast and reliable handling of future contexts, based on previous ones. The potential alternative handlings, and the respective efficiency of each handling (actually applied or alternate) is also assessed. The challenge here is to develop appropriate mechanisms in order to associate "good" solutions with each context.

Evolved RATs for 5G and beyond for addressing limitations of current cellular networks in terms of coverage, capacity and overall performance (including QoS/QoE)

New RATs are anticipated. Moreover, there will be evolved versions of legacy RATs, namely, potentially new, advanced versions of LTE-A, HSPA, and WiFi. Moreover, it is believed that also the evolutions of GSM continue to play a role (according to Ericsson reports), e.g., in lightly populated areas where it is already deployed or for serving certain classes of traffic. Typically, the goal is to devise technologies that maximize the amount of the user-plane data that can be carried through the system resources. Therefore, the challenge is to evolve the set of RATs and the mechanisms for their complementary use, in order to obtain configurations that are optimal at each tier with respect to QoS/QoE, cost and energy efficiency.

Determination of a novel 5G framework for addressing future requirements and challenges

A novel 5G framework would consist of main requirements and a set of technology trends. The framework will contribute to the solidification of technological foundations and longevity of 5G systems. Requirements include the proper provisioning of a large and rapidly expanding set of applications/services and a drastic improvement of the energy and cost efficiency. These requirements yield the needs for fast/reliable service deployment, offering all types of relevant QoS/QoE, handling demanding and changing contexts of operation (e.g., increased user traffic, high mobility etc.), providing means for the higher monetization of service provision, and drastically improving the cost efficiency.

8 Appendix A - Acronyms

Acronym	**Explanation**
3GPP	3rd Generation Partnership Project
AHP	Analytical Hierarchy Process
AP	Access Point
ASA	Authorized Shared Access
B4G	Beyond 4G
BS	Base Station
C4MS	Control Channels for the Cooperation of the Cognitive Management System
CAPEX	CApital EXPenditures
CC	Control Channel
CCC	Cognitive Control Channels
CCM	Configuration Control Module
CCR	Cognitive Control Radio
CMON	Cognitive Management system for the Opportunistic Network
CMS	Cognitive Management System

CN	Core Network
CPC	Cognitive Pilot Channel
CPU	Central Processing Unit
CSCI	Cognitive management System for the Coordination of Infrastructure
CUS	Collective Use of Spectrum
D2D	Device-to-Device
DAN	Dynamic Access Network
DSM	Dynamic Spectrum Management
DSONPM	Dynamic, self-Organizing Network Planning and Management
ETSI	European Telecommunications Standards Institute
FA	Functional Architecture
FDMA	Frequency Division Multiple Access
FI	Future Internet
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
JADE	Java Agent DEvelopment Framework

JRRM	Joint Radio Resources Management
KPI	Key Performance Indicator
LSA	Licensed Shared Access
LTE	Long Term Evolution
M2M	Machine-to-Machine
OFDMA	Orthogonal Frequency Division Multiple Access
ON	Opportunistic Network
ONE	Opportunistic Network Environment
OPEX	Operational Expenditures
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RFID	Radio Frequency Identification Devices
ROI	Return on Investment
RRS	Reconfigurable Radio Systems
TDMA	Time Division Multiple Access
UDN	Ultra Dense Network
UMTS	Universal Mobile Telecommunications System

WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network

9 Appendix B – List of Publications

9.1 Short CV

Andreas Georgakopoulos holds a B.Sc. from the University of the Aegean (2005) and a M.Sc. from the University of Piraeus (2008) in Greece. He conducts research as a research engineer at the Telecommunication Networks and integrated Services Laboratory of the University of Piraeus since 2009. His main interests include the specification of intelligent management mechanisms for the creation and maintenance of dynamic access networks beyond fourth- and towards fifth-generation. At a European and international level, he has been actively involved in various Framework Programme (FP7) and recently Horizon 2020 (H2020) projects, including Networks of Excellence and European Cooperation in Science and Technology (COST) Actions. In addition, he participates in various initiatives, such as GreenTouch and the Wireless World Research Forum, in the area of communication architectures and technologies, in a Greece-China collaborative project as well as in a project funded by the U.S. Office of Naval Research (ONR).

9.2 Publications in international journals

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2. P. Demestichas, K. Tsagkaris, V. Stavroulaki, Y. Kritikou, A. Georgakopoulos, “Technical Challenges for Merging Opportunistic Networks with Respective Cognitive Management Systems in the Future Internet”, in Proc. IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (IEEE-PIMRC), Istanbul, Turkey, September 26-29, 2010

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11. D. Karvounas, A. Georgakopoulos, D. Panagiotou, V. Stavroulaki, K. Tsagkaris, P. Demestichas, "Opportunistic Exploitation of Resources for Improving the Energy Efficiency of Wireless Networks", in Proc. IEEE International Conference on Communications (ICC) 2012, Ottawa, Canada, June 10-15, 2012

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14. P. Demestichas, A. Georgakopoulos, D. Karvounas, K. Tsagkaris, V. Stavroulaki, "Elaboration on the Necessity for Further Advancements on Cognitive Network Management for Future Wireless Infrastructures", in Proc. 29th Wireless World Research Forum (WWRF), Berlin, Germany, 23-25 October, 2012

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1. K. Tsagkaris, A. Georgakopoulos, P. Demestichas, “OneFIT Project: Envisaged scenarios and challenges”, 1st International Workshop of COST Action IC0902, 23-25 November 2010, Bologna, Italy

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