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OUTLOOK

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Policy-Based Management
of Radio Resources and
Autonomic Computing in Cognitive/
Reconfigurable Networks and Systems

About this document

This document constitutes a white paper developed within WG6 of WWRP, concerning the management of radio resources in cognitive/reconfigurable networks and systems.

Policy-Based Management of Radio Resources and Autonomic Computing in Cognitive/ Reconfigurable Networks and Systems

Joint Editor Group:

Edited Prof. Panagiotis Demestichas (Univ. of Piraeus)

George Dimitrakopoulos (Univ. of Piraeus)

Yiouli Kritikou (Univ. of Piraeus)

Abstract:

This white paper presents some emerging concepts to support the advent of cognitive networks. In particular, it goes through the basic features of cognitive networks and their operation principles. Then, it focuses on their management, by splitting the overall management process into some autonomous components, i.e. the context acquisition, the profiles management and the policy-based management. These components constitute the inputs to the adaptation process of cognitive infrastructures. The output lies in the configuration of the behavior of the infrastructure (or the mobile terminal). Last but not least, the knowledge features of the management approach components are outlined.

In general, cognitive networking capabilities are a facilitator for the B3G vision, mostly targeting at the minimization of complexity associated with heterogeneous environments (and how they can be managed). To this effect, work on cognitive networks is ongoing and is believed to address even more innovative aspects during the coming years.

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1. INTRODUCTION

Wireless communications attract significant research and development effort, reflected on the progress of work performed in international projects [1], as well as on the discussions in international fora [2]. This work results in a powerful, high-speed infrastructure that offers versatile solutions to the digital information society. In this context, the technological focus is on the cooperation and coexistence of legacy Radio Access Technology (RAT) standards with currently emerging ones. The current wireless landscape is characterized by a plethora of RATs, which can be roughly classified in two major categories. The first one is the Wireless wide area networking (WWAN) technologies, which include, among others, 2G/2.5G/3G mobile communications [3], the IEEE 802.16 suite [4], WiMAX [5] and broadcasting technologies (DAB, DVB) [6]. Wireless short range networks (WShRNs) falls within a second family and includes wireless local and personal area networks (WLANs/WPANs), as well as wireless sensor networks (WSNs) [4], [7], [8].

This situation is depicted on Figure 1.

Regarding the backbone network architecture, legacy [3] or modern paradigms [9] can be followed. Moreover, the evolution of wireless access networks is frequently referred to as B3G (Beyond the 3rd Generation) systems [1], [2].

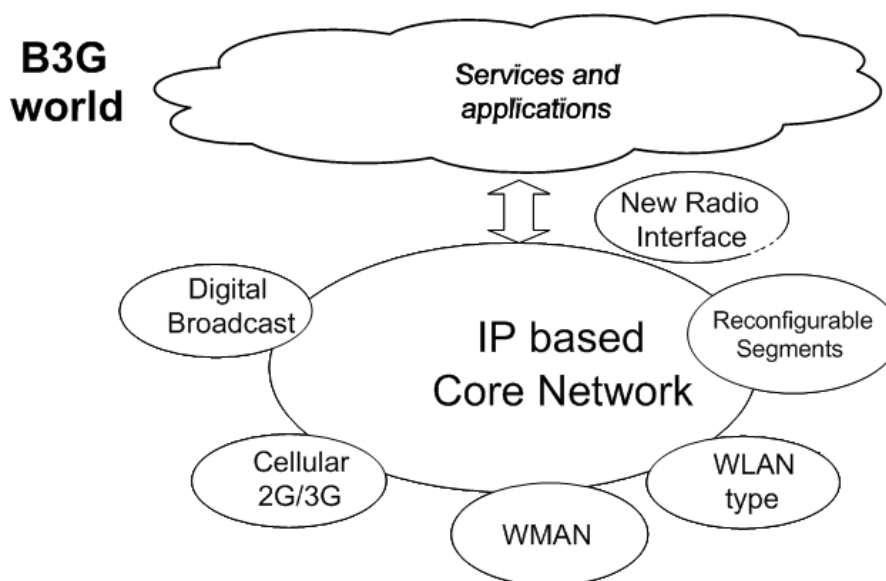


Figure 1: Overview of the Wireless World in the B3G Era

In the B3G era network operators (NOs) will have to address increased complexity, with respect to today. Complexity derives from two main sources. On the one hand, there is the inevitable heterogeneity of the network and terminal infrastructure, and on the other hand the user requirements that associate the B3G era with advanced services/applications, provided seamlessly and ubiquitously.

To meet these objectives, NOs have to deploy complex network topologies of heterogeneous nature. The different RATs will have to co-exist, and be complementarily (and efficiently) exploited. Each RAT has different capabilities, in terms of capacity, coverage, mobility support, cost, etc. Therefore, each RAT is best suited for handling certain situations. In this respect, a NO will have to rely on different RATs for raising the customer satisfaction, assigning the appropriate RAT to perform the respective task, so as to achieve the required Quality of Service (QoS) levels, cost-effectively. QoS refers to performance (e.g., bit-

An option for handling this complex situation is to design wireless B3G infrastructures by exploiting “cognitive networking” capabilities [11], [12]. In general, cognitive systems are able to retain knowledge from previous interactions with the environment and determine their behavior according to this knowledge, as well as to other goals and policies, so as to adapt to external stimuli and optimize their performance. In the case of wireless networks, cognition expresses the ability to dynamically select their configuration, through management functionality that takes into account the context of operation (environment requirements and characteristics), goals and policies [13] (corresponding to principles), profiles (capabilities), and machine learning [14], [15] (for representing and managing knowledge and experience).

As can be deduced from the above, cognitive networks consist of reconfigurable platforms and intelligent management functionality. In particular, they benefit from the existence of reconfigurable platforms that enable dynamic changes in their configuration, while they also require management mechanisms, capable of finding the most appropriate configurations. Accordingly, the scope of this chapter is twofold: on one hand to provide the basic characteristics of reconfigurable platforms and explain how they can support cognitive networks; on the other hand, policy-based management and autonomic [12] radio resources for B3G infrastructures that operate in accordance with the cognitive networking paradigm.

2. OVERVIEW OF COGNITIVE WIRELESS NETWORKS

2.1 Operation Principles

Cognitive networks have been proposed as a facilitator of the quest to offer seamless mobility to users, considering their ever-increasing demands. To do so, they contradict to legacy systems, since they are able to adapt their operation by (proactively or reactively) responding to external stimuli. This is achieved, as aforementioned, by disposing mechanisms that observe external conditions, retain valuable knowledge from interactions with the environment and plan their future actions accordingly. Their operation can be reflected on a feedback loop (see also [12]), like the one shown on Figure 2.

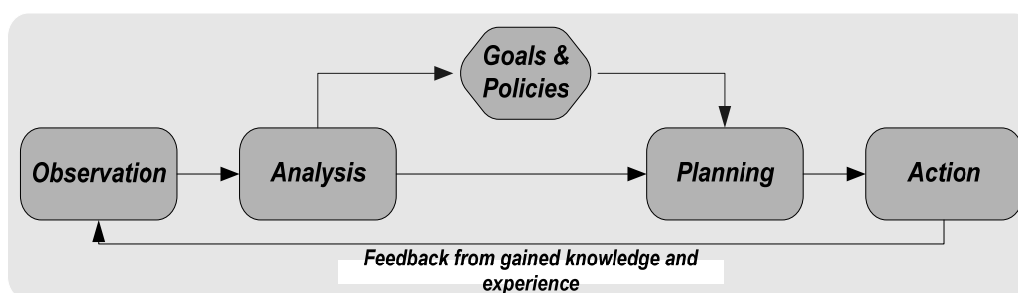


Figure 2: Cognitive Networks Operation Loop

A basic cognition principle foresees that the network continuously monitors the environment, looking for potential changes that can affect its operation. Observations form the basis for initiating machine-based reasoning to see if the reconfiguration process should be invoked. Once the decision is taken, the network acts accordingly. This loop is repeated inside a machine learning process, which leads to cognition. The loop is guided by a set of goals, which take the observations into account in planning actions.

At this point of time, a reasonable question may arise: “Which is the optimum way to manage the diverse entities that form part of a cognitive network”? The answer to this question might be complex. A potential answer to this is provided in the next subsection.

2.2 High-Level View of Management Functionality

The radio access networks have been classically designed and deployed to cover the traffic demand of the planned services in a static approach and by means of manual configuration of network elements, considering the busy hour traffic in each geographical zone. However, the continuously increasing demand also raised the need for the deployment of new technologies and networks which have to be optimally planned and managed by choosing among the options of finding new sites, co-locating sites or migrating to reconfigurable transceivers. Additionally, in the case of cognitive networks, novel functionality should efficiently plan and manage an ever-changing network, since it should adapt to external requirements that also change over time and space.

Furthermore, since a cognitive network consists of numerous elements and terminals of highly heterogeneous natures, located in different places, a centralized management approach becomes prohibitively complex and inappropriate. Hence, distributed management approaches, relying on pertinent technologies, e.g. autonomic computing, are currently in the focus (e.g., see [11]). This approach can offer scalability, stability and modularity (which provides low complexity). In this respect, this chapter is claimed to provide scalable answers to the question of managing (supporting) cognition. In the light of the above, each element may be multi-standard. A subset of technologies is used, namely those that are most appropriate for the context of operation. Network layer reconfigurations accompany the changes at the

The general definition of cognitive networks implies some very advanced capabilities, which spring from the necessity to encompass reconfiguration (change in the behaviour of the segment, reflected on parameters / infrastructure variations) features, enhanced by cognition capabilities. On the other hand, such changes should be performed in the best possible way for NOs and also the end users. In this respect, Regarding the management part, a modern research direction, in order to increase scalability and decrease complexity, is to comply with self-management paradigms, or in other words, to develop the management functionality in accordance with the autonomic computing principles [16], [17], [18].

Figure 3 provides the overall description of the management functionality proposed for managing a cognitive network segment.

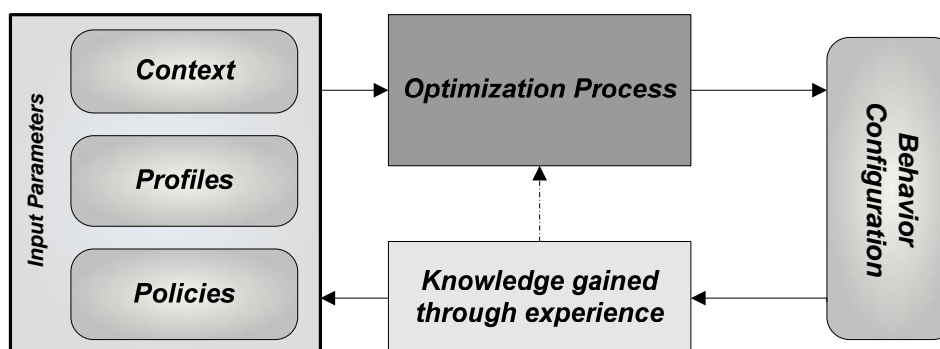


Figure 3: Problem Description for the Operation of Cognitive Networks

The proposed management mechanisms may refer either to the various parts of the input, to the optimization process, to the knowledge features (that accompany all parts), or also to the outputs of the management problem.

In the light of the above, the remaining sections of this chapter present several approaches for all parts of the problem, as shown on Figure 3.

3. MANAGEMENT MECHANISMS FOR COGNITIVE WIRELESS NETWORKS

Beginning from the analysis of the previous section with respect to the management functionality for cognitive wireless networks, this section aims at analyzing the parts of the problem as described before, emphasizing on their operability, as well as on their knowledge features (see also Figure 3).

3.1 Context Acquisition

This subsection presents the learning and adaptation method for robustly estimating the probability that (the selection of reconfiguration c is associated with a certain achievable bit rate and coverage capability. Details on the method have been published in [23].

3.1.1 Formulation through Bayesian networks

The Bayesian network that could be proposed for modeling the specified problem disposes some random variables, i.e. ABR and COV , which represent the achievable bit rate and coverage, respectively. CFG is another random variable representing configuration. CFG is the Bayesian network's predictive attribute (node), while ABR and COV are the target attributes. The goal is the computation of the maximum value of the joint conditional probability. Thus, given a configuration CFG , we search for the values of ABR and COV that maximize the aforementioned joint conditional probability. These values constitute the robustly estimated (i.e., the most probable) values of ABR and COV for this configuration. With reference to the above, the desired probability is equivalent to the product of the conditional probabilities. Hence, for performing the computations, two independent conditional probability tables (CPTs) can be organized, one for each random variable, which in this case are ABR and COV . Each CPT refers to a particular RAT. Each column of the CPT refers to a specific configuration (i.e., RAT and carrier frequency). Each line of the CPT corresponds to an ABR value, i.e. a discrete set of potential ABR values has been defined. Each cell (intersection of line and column) provides the probability that the configuration (corresponding to the column) will achieve the potential ABR value (corresponding to the line). Given a configuration, the most probable value of ABR is the value that corresponds to the maximum conditional probability.

3.1.2 Solution: learning and adaptation

In the previous subsection, we defined that the capabilities of configurations are modeled through the conditional probability tables (CPTs). The next step is to describe how to update the CPTs for illustrating this learning and adaptation process, which yields the robust methods for discovering the performance capabilities of candidate configurations. We focus on ABR , since the analysis for COV remains the same.

The process takes into account the system's measurements and, more specifically, the "distance" (absolute difference) between each candidate value and the measured value. The parameter nf is a normalizing constant whose value can be computed by requiring all the "new" probabilities to sum up to 1.

The system converges when the most probable candidate ABR value (i.e. the one with the maximum probability) is reinforced, while the probabilities of the other candidate ABR values are either reduced or reinforced less. After convergence, we limit the number of consecutive updates that can be done on the probability values associated with each ABR value. This is done for assisting fast adaptation to new conditions. For the same reason, we do not allow that a probability falls under a certain threshold. In such cases, the normalization factor, nf , is computed by requiring all the other "new" probabilities.

This method's goal was to show how a cognitive radio system could acquire interference and capacity estimations; and, secondly, by enhancing the above with a learning system, which is essential for obtaining a truly cognitive process. The proposed approach was to develop a robust probabilistic model for optimal prediction of the capabilities of alternative configurations, in terms of achievable bit rate. A short-term related future plan is to enrich the basic Bayesian model that has been described, by adding more nodes (random variables), including 'coverage' and 'context' (i.e., 'traffic' and 'user mobility'). The overall

future plan is to further employ probabilistic relationships and autonomic computing principles in the direction of realizing cognitive, wireless access, infrastructures. The goal is to develop an autonomic manager which will encompass the robust estimation scheme. The manager will consist of policies, context perception capabilities, reasoning algorithms, learning functionality and knowledge engineering, technologies for the representation of ontologies and semantics. All these will yield a system that hypothesizes on causes to a problem, and subsequently validates or falsifies the hypothesis.

3.1.3 Knowledge Features

Context information is obtained through interactions with the environment, which lead to reasoning and perception, through appropriate machine learning techniques. A managed network element is thus able to gain knowledge from those interactions and be aware of the optimum way to handle a given context. Specifically, a NO could know whether at a certain time of a day a service should be provided through a specific RAT, within the element. Alternatively, traffic conditions at a certain time or at a certain spot within the coverage area of an element could also direct a certain service provision manner. All in all, future decisions can be significantly facilitated through storing context information.

3.2 Profile Management

3.2.1 Overview of Profile Management Strategies

This section contains some preliminary considerations for managing the profiles of end-users, network elements, and terminals, in future systems, especially cognitive ones.

Regarding the access point's profile, an access point is assumed to dispose a set of transceivers. Each transceiver is capable of operating a set of RATs, whereas there is also a set of spectrum bands and/or specific frequency carriers, with which each RAT can operate, due to regulation or technological reasons. So, each transceiver has a set of candidate configurations, i.e. a combination of RAT and frequencies. Let it be noted that this part can also provide the access point's profiles (capabilities) that are dispersed within the access point, in terms of permissible RATs/spectrum, services, etc. However, in this paper all terminals are assumed capable of applying the self-management of cognitive access points' decisions.

Regarding the users' profiles, users are grouped into classes, each of which is characterized by specific preferences and requirements. These preferences are kept in special log files in the system's database. Such log files store important information about the users' preferences (such as software requirements, skills, level of knowledge, goals and expected outcomes from specific actions), their activity in the system, as well as the hardware (equipment) they most frequently use. Consequently, the log files are recovered every time the user makes a request for a service (application). This means that the system is in a position not only to recognize the user, but also to be aware of the user group he belongs to and his personal history. Therefore, it is able to predict at some point the preferences of this specific user and the potential requests he is going to address to the system and thus provide him with a certain set of services through network infrastructure, as depicted in Figure 4, aiming at satisfying his personal needs. Each service has a target QoS level and a set of RATs through which it can be offered. In addition, each service provided at a specific QoS level is associated with a level of importance (utility).



Figure 4: User – Service Communication, exploiting system's cognition for efficient and effective service delivery

3.2.2 Knowledge Features

The constant updates in the information provided by the “profiles” part of the functionality lead to significant knowledge gains with respect to user, and also network element behaviour. This is essential in providing services of maximum quality, tailored to individual user needs. E.g., network element capabilities can be associated with users of a certain class that require some service. This implies that the process of serving users in future cases may be facilitated and optimized through experience.

3.3 Policy-Based Management

3.3.1 Policy Management Strategies

In general, policies designate rules and functionality that should be followed in context handling. Policies are decided by the NO. Indicatively, a policy-based management approach can dispose the form shown on Figure 5.

High-level NO policies refer to business strategies for achieving some pre-set goals. These goals are usually related to the maximization of the NO revenues, either on a short-term or on a long-term basis. Moreover, NO agreements with other, cooperative NOs are also taken into account. For instance, as shown on Figure 5, the NO may select the offered services, as well as the RATs through which they will be offered. This information usually depends on the general NO strategies.

On the other hand, low-level NO policies are targeted at an optimal resource consumption. Indicatively, a NO may provide a policy to the cognitive infrastructure that prohibits the provision of a service at a certain quality level for users away from the transceivers, so as to reduce cost. Indicatively, the NO may select NOT to offer a specific service at some rate, due to short-term reasons, usually associated with resources.

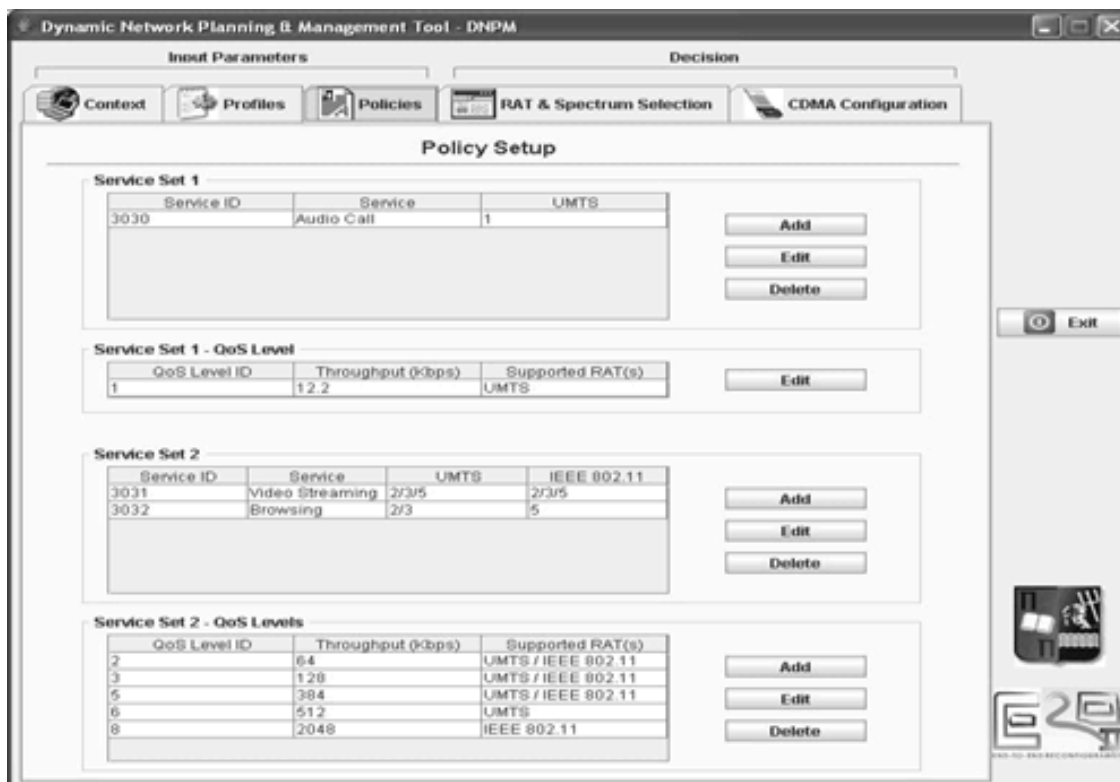


Figure 5: Representation of policy-based management

High-level, as well as low-level policies are designated by the NO, through the disposal of the requisite management functionality, a sample of which is provided on Figure 5, which depicts the capability of the NO to “add”, “edit” and also “delete” parts of a service, or the complete service offered to users, at a certain time period or location.

3.3.2 Knowledge Features

Cognitive features lie also in the “policies” part of the management functionality. Specifically, the suitability and efficiency of different policies possesses great importance in handling versatile contextual situations. E.g., a NO may get to know, through experience, that the provision of a service to users of certain locations may lead to overloading, or to increased cost. Additionally, a NO could also exploit knowledge on a potential increase in revenues when providing users of a certain class/location with very high QoS levels. Consequently, learning the most optimum policy and the most appropriate goals to be achieved may become valuable for NOs in successfully (transparently, fast and securely) handling difficult situations.

3.4 Configuration of Behaviour of Cognitive Infrastructures

3.4.1 Introduction

The configuration of behavior of cognitive infrastructures includes several aspects, such as the selection of the optimum configuration pattern, the download of software components, their validation and installation, as well as other issues that fall in the realm of the implementation of reconfiguration. This section contains exemplary data on the selection procedure for the optimum reconfiguration pattern, as well as for the download procedure of the necessary software components, during the process of reconfiguration.

3.4.2 Selection of Optimum Configuration Pattern

The configuration of cognitive infrastructures should encompass several decisions targeted at the optimization of QoS provisioning.

Indicative actions to be decided include the selection of operating RAT, spectrum band and/or carrier frequency, as well as other parameters (e.g. transmission power, modulation type). In addition, there will be actions related to the network elements interconnection, routing and congestion control. Finally, there will also be actions that involve the allocation of applications to the optimum QoS levels. Several solution approaches could be considered for tackling such a problem. A phased approach that could be utilized is described in the sequel.

The first phase includes the division of the problem in several sub-problems, which are subject to parallel processing. The sub-problems depend on the available configurations (mostly allocation of RAT and spectrum to the transceivers of the CgAP, but also other operating parameters). The second and third phases aim at exploring the capabilities of each configuration, in terms of achievable bit rates. This is performed at two stages, i.e. (i) through a first allocation of the demand to the transceivers of the CgAP, according to given policies and (ii) by attempting to provide the highest possible quality to the demand. Finally, the fourth phase includes the selection of the most appropriate configuration to handle the given contextual situation. This is performed by rating the available configurations through their potential provision of desired QoS levels. Specifically, the decision for the best configuration is achieved by disposing an objective function (OF) associated with the maximization of the total users’ utility, while requiring the least changes on the already established configuration.

Once the decisions are taken, there might be software components that need to be efficiently, transparently and securely downloaded. This is the subject of the next subsections.

3.4.3 Software Download

The overall software download procedure is divided into distinct phases and each phase is characterized by a duration time, thus in order to evaluate the efficiency of the overall radio software download procedure, it will be necessary to estimate the duration of the complete process. To this end, in this section a recall to the OTA Download technique and protocol description is reported. This will help to focus the attention on the particular aspects that could guarantee a spectrum efficient download of the software.

3.4.4 Over-The-Air (OTA) Download

The Over-the-Air (OTA) download is the software download technique with the maximum versatility. In this case, the software download operation occurs using a radio channel of a pre-existent cellular network or an additional infrastructure. Three different working modes are thus defined:

The traffic and control channels of the legacy cellular networks (GSM/GPRS or UMTS) are used. In this case the terminal has to be active on one of these systems and, using the channels provided by such standards, can receive the operative software related to another system.

A signaling or bootstrapping "universal channel" used for the download procedure is introduced. In this case, at the switch on the terminal automatically tunes itself on this "universal channel" and performs the operative software download related to the system present in that place.

A combination of the two aforesaid modes may be also envisaged: the negotiation phase of the download is performed, for example, using a legacy standard (first mode) while the software download procedure occurs with a specific channel dedicated to this operation (second mode).

3.4.4.1 Download Procedure

The radio software download procedure is divided into three distinct phases:

Pre-download Phase. This phase ensures that the radio software modules can be securely transferred on the basis of the current configuration, capabilities of the device, and user requirements. This phase includes service discovery, mutual authentication, capability exchange, and download acceptance exchange.

During-download Phase. This phase includes the transfer of software, the verification of its integrity, and retransmission requests in case of errors.

Post-download Phase. This phase includes the installation of software, the in-situ testing, the device reconfiguration, the non-repudiation exchange, and the recovery efforts in case of reconfiguration failures.

All the aforesaid OTA download methodologies are referring to the client/download path/ server architecture. Hereafter, the main steps of a generic procedure for download with any of the previously described methods are reported. The generic protocol for software download is client-server oriented, with the terminal assuming the client role and a generic node (software repository) assuming the server role.

The main steps of the procedure are graphically reported in Figure 6 and described in the following:

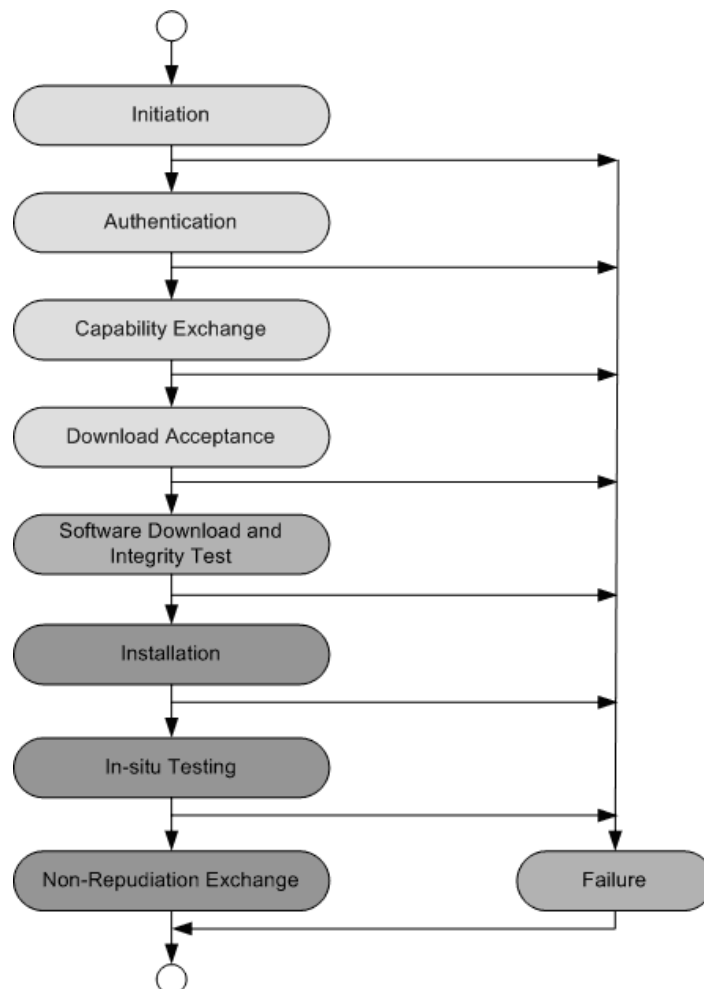


Figure 6: Software Download Procedure

Initiation: the terminal (or the server) triggers the start of the download procedure. In case the network or the terminal cannot operate the download (due to lack of resources or for other actions with higher priority) the procedure is interrupted.

Authentication: in this phase, the terminal and the server authenticate each other

Capability exchange: the server communicates the information related to the software to be downloaded; the terminal verifies if software can be charged in the memory, installed and started, on the basis of its own characteristics and parameters

Download acceptance: the server communicates to the terminal the characteristics of the download (e.g. dimension and number of segments/blocks), of the installation and of the billing; the terminal, eventually with the user interaction, states if the server indication can be accepted or not.

Software download and integrity test: the download of the operative software and data checks takes place; as the software is downloaded, an integrity test is run: the terminal requires the retransmission of radio blocks not correctly received.

Installation: during the installation step, billing and licensing data are provided by the server.

In-situ testing: before running the new operative software, the terminal runs a test.

Non-repudiation: the terminal confirms to the server the correct installation; after the reception of the confirmation by the server, billing procedures are initiated.

3.4.5 Concluding Remarks

In conclusion, the configuration of the behavior of cognitive wireless infrastructures is of critical importance and should be carefully analyzed when considering future systems. This is justified through the fact that wireless communications are indeed migrating towards the B3G era, which can be efficiently realized through the exploitation of cognitive networking technologies. Intelligent, self-management functionality is necessary for directing networks that operate in accordance with the cognitive paradigm. In this respect, this subsection aimed at paving the way for detailed studies in the realm of decisions upon the most appropriate configuration pattern, encompassing learning techniques.

Regarding the the OTA software download procedure which accompanies such decisions,

In conclusion, for the UMTS system the software download procedure has good performances in both cases of patch and RAT download thanks to the power control algorithm that permits to maintain a constant C/I target at the receiver. In case of GSM/GPRS, the software download procedure strongly depends on the RRM scheme adopted. Such remarks should be carefully considered by network infrastructure designers.

3.5 Configuration of Behaviour of Cognitive Terminals

Anything, anywhere, anytime, the query is not new. Still, today ubiquitous broadband wireless communication bringing multimedia services is not yet available. One of the major bottlenecks is the need for Software Defined Radios (SDRs) for wireless terminals, which could enable the user's dream to have access to a large variety of standards at low cost. The combination of the increasing need for functional flexibility in communication systems and the exploding cost of system-on-chip design, will indeed make implementation of wireless standards on multi-purpose reconfigurable radios the only viable option in the coming years. These devices being battery-powered, the performance requirements are coupled with severe constraints on energy efficiency. This is becoming a key concern: there exists a continuously growing gap between the available energy, resulting from battery technology evolution, and the steeply increasing energy requirements of emerging radio systems (Figure 7). Technology scaling, platform improvements and circuit design progress are not sufficient for bridging this energy gap. A clear need for holistic system-level strategies exists.

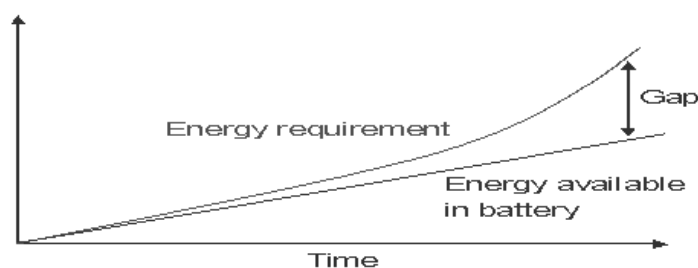


Figure 7: The energy gap is growing

Given the energy gap discussed above, a major challenge is to enable low energy reconfigurable radio implementations, suited for handheld multimedia terminals and competitive with fixed hardware implementations. To make such terminals a reality, a two-step approach is advocated. First, effective energy scalability is enabled in the design of the radio baseband and front-end. Secondly, the scalability is exploited to achieve low power operation by a cross-layer controller that follows at run-time the dynamics in the application requirements and propagation conditions (Figure 8).

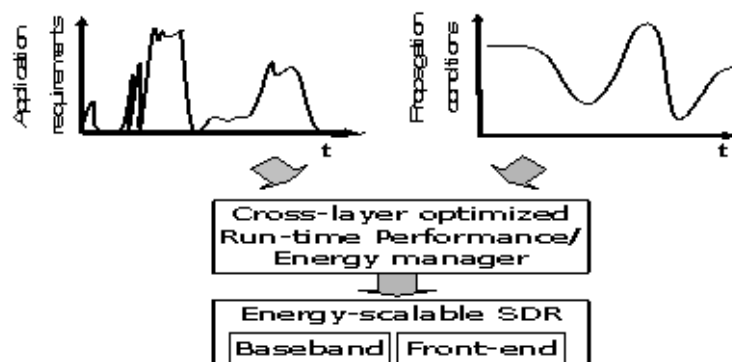


Figure 8: Energy scalable SDRs achieve low energy operation through cross-layer QoS and energy management.

Design step to enable flexibility. To enable the translation of functional flexibility into energy scalability, the reconfigurable radio (algorithms, architectures, components and circuits) should first be designed accordingly.

For the reconfigurable digital baseband engine, one has to carefully tradeoff flexibility and energy efficiency: flexibility should only be introduced where its impact on the total average power is sufficiently low or where it offers a broad range of control options that can be exploited effectively later in the control step (targeted flexibility). The required sub-functions of the wireless modem should be designed according to their nature (i.e., control or data processing) and flexibility/energy efficiency requirements. This calls for heterogeneous multi-processor system-on-chip (MPSoC) platforms. In [20] for instance, a heterogeneous MPSoC platform is proposed that builds on this concept of targeted flexibility.

For the reconfigurable analog front-end, architectures and circuits should be designed for a broad range of requirements in carrier frequency, channel bandwidth and noise performance with minimal penalty in power consumption, while also offering energy scalability. In [21] for instance, such a reconfigurable zero-IF analog front-end was implemented. All building blocks in the RF front-end are equipped with configuration “knobs” that allow them to adjust their performance to the requirements of the considered standards, but also to scale their energy consumption to the actual requirements. As an example of such energy scalable component is the power amplifier introduced in [22]. The proposed circuit flexibility enables significant trade-offs between the transmitter output power and linearity and the corresponding energy consumption. The resulting trade-off between the link signal-to-noise-and-distortion ratio and the transmitter power consumption is shown in Figure 9 (left part), for path losses ranging from 60dB to 90dB.

Control step to exploit flexibility. To exploit flexibility for saving energy, it is mandatory to control the reconfigurable radio system as function of the operation conditions. The key observation here is that wireless communications systems typically face very dynamic conditions (in terms of propagation environment and of application requirements). By carefully adapting the system to these dynamics at run-time, capitalizing on the energy scalability discussed above, much energy can be saved compared to conventional design. This problem has to be addressed from a cross-layer perspective, as measuring performance requires taking into account the characteristics of the protocol stack, whereas optimizing energy expenditure assumes detailed knowledge of the low-level radio hardware.

As an example, the above energy scalable radio was combined with smart cross-layer control, considering data transmission over an 802.11a WLAN link. An energy-efficient run-time radio link controller was designed based on a generic cross-layer optimization methodology. The resulting trade-off between the

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average net data rate (on top of the MAC) and the energy efficiency is reported in Figure 9 (right part). When compared with traditional WLAN radio link control schemes, where the data is transmitted at the maximum achievable data-rate and the transmitter is shut down when no data has to be sent, the proposed scheme can improve the energy efficiency by up to 40%, by properly adapting to the rate requirements and channel conditions.

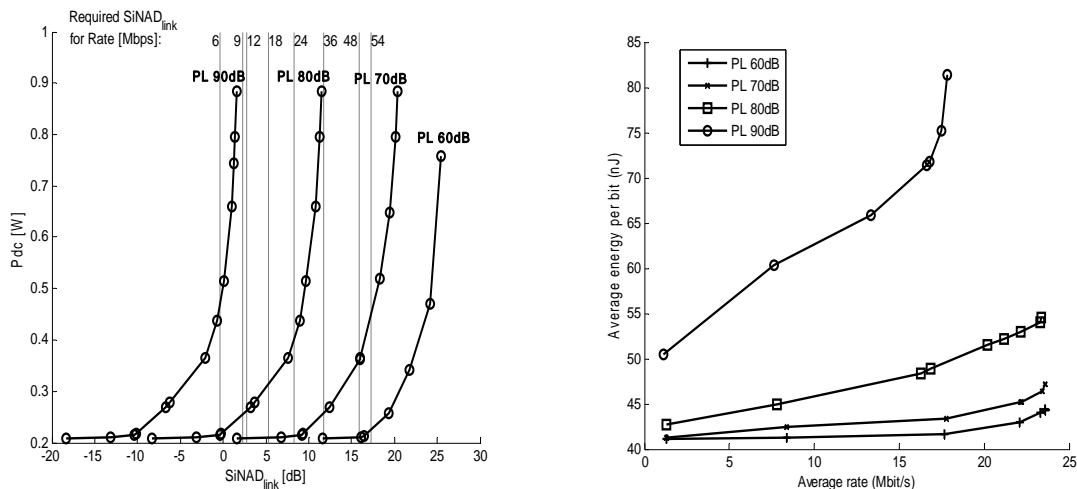


Figure 9: Power consumption versus link SINAD trade-off enabled by scalable front-end (left); average net MAC data rate versus energy efficiency trade-off enabled by cross-layer energy management (right)

4. SUPPLEMENTARY KNOWLEDGE FEATURES IN SUPPORT OF COGNITION

The solution of problems related to the configuration of behavior of cognitive infrastructures could be facilitated if knowledge features are integrated therein. This has been constructively described regarding the individual parts of the problem anticipated. Additionally, this section shows why knowledge feature are needed, indeed and how they could facilitate problem solutions.

The problems described in the previous could be solved either at the network segment level (more centralized manner) or at the element level (more distributed manner)

A significant advantage of the centralized functionality is that anticipates problems through a holistic view.

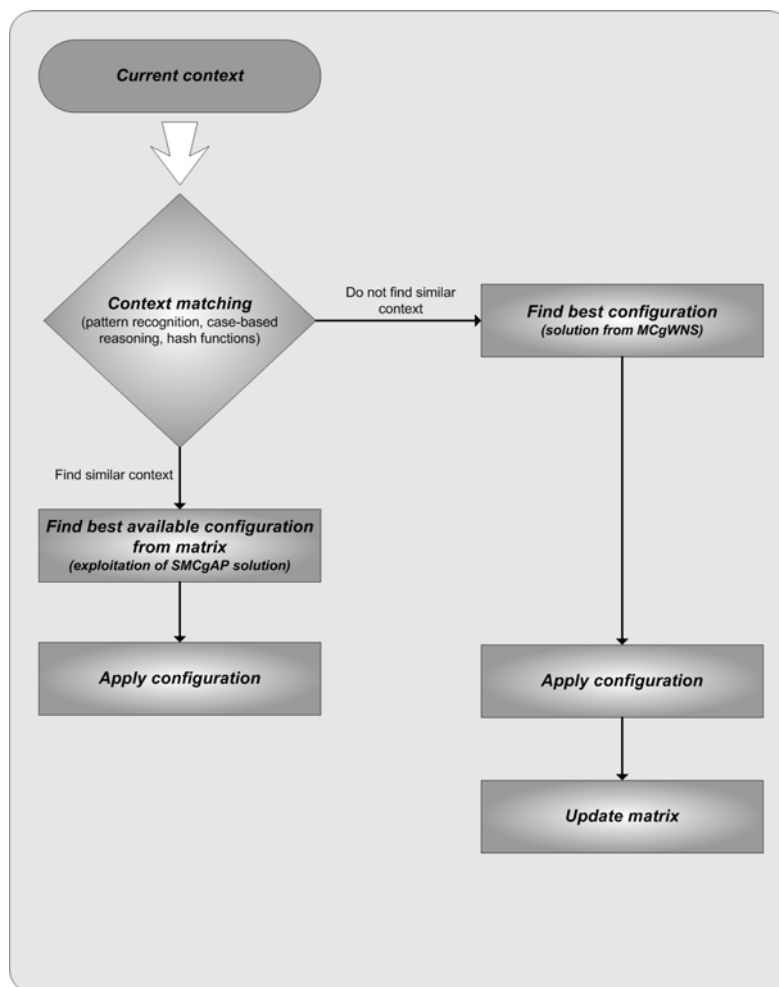


Figure 10: Approach for obtaining knowledge useful for decisions at the network segment level

However, it requires an increased amount of time to solve them, since it has to tackle with high complexity levels. Complexity derives from the fact that the configuration of behavior of numerous elements (access points) falls within the realm of a centralized functionality and thus the situation to be resolved is of multiple difficulty, compared to the one faced at a single element level. Therefore, an only real-time solution of the problem sounds almost unfeasible. On the contrary, the knowledge provided through the solutions achieved at the element level should be effectively exploited. This shall be achieved by retaining a rating of the different configurations in a matrix. Searching within this matrix will reveal the optimum

solution. A process that conforms to the above, which is based on machine learning, analyzed in the following (Figure 10).

The first step is to read the current contextual situation. This situation is then compared to some reference context situations that are available, in the matrix. This matrix describes the performance of several available configurations (e.g. utility based OF values, as described before), in a number of given contexts. In other words, the matrix exploits the solutions at the element level, which have revealed the efficiency of the alternative decisions to be taken, regarding the element behavior. The comparison procedure for the identification of a clearly or almost identical context situation can be based on techniques such as case-based reasoning or pattern recognition.

If the current context comprises aspects that cannot be matched to the available reference contexts, the problem must be faced without the support of machine learning, just by finding the optimum configuration at the network segment level, applying several times the method presented for individual elements. At this point, the complexity increases significantly and this calls for the consideration of signaling and other cost factors, so as to reduce the overall number of alternative configurations that need to be tested. In any case, after the optimum configuration has been found, it can be implemented. Finally, the matrix has to be updated with the information retrieved by the current context handling manner. In doing so, its information is gradually improved, leading to more efficient decisions.

On the other hand, if the current context has been faced in the past, information has been kept in the matrix and can be matched with the reference contexts available. Then, the most appropriate configuration is selected. This might not be the “real” best one in terms of performance, but a lower-priority one, due to the fact that the decision made takes into account also the previous state of the network segment. In addition, context matching shall not always result in a level of 100% similarity. Then, the selected configuration can be applied.

In general, learning techniques can help the wireless network gradually obtain knowledge, so as to improve the efficiency of the decisions. They are thus currently under intense research focus and are expected to significantly improve.

5. CONCLUSIONS AND SUMMARY

This chapter has presented some emerging concepts to support the advent of cognitive networks. In this respect, it has gone through the basic features of cognitive networks and their operation principles. Then, it has focused on their management, by splitting the overall management process into some autonomous components, i.e. the context acquisition, the profiles management and the policy-based management. These components constitute the inputs to the adaptation process of cognitive infrastructures. The output lies in the configuration of the behavior of the infrastructure (or the mobile terminal). Last but not least, the knowledge features of the management approach components have been outlined.

In general, cognitive networking capabilities are a facilitator for the B3G vision, mostly targeting at the minimization of complexity associated with heterogeneous environments (and how they can be managed). To this effect, work on cognitive networks is ongoing and is believed to address even more innovative aspects during the coming years.

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7. APPENDIX 1: CONTRIBUTING AUTHORS

NAME	COMPANY	E-MAIL ADDRESS
George Dimitrakopoulos	University of Piraeus	gdimitra@unipi.gr
Panagiotis Demestichas	University of Piraeus	pdemest@unipi.gr
Yiouli Kritikou	University of Piraeus	kritikou@unipi.gr
Eugenia Adamopoulou	National Technical University of Athens	jenny@cn.ntua.gr
Kostantinos Demestichas	National Technical University of Athens	cdemest@cn.ntua.gr
Didier Bourse	Motorola France	Didier.Bourse@motorola.com
Markus Muck	Motorola France	Markus.Muck@motorola.com
Klaus Moessner	University of Surrey	K.Moessner@surrey.ac.uk
Paolo Goria	Telecom Italia Labs	paolo.goria@telecomitalia.it
Alessandro Trogolo	Telecom Italia Labs	alessandro.trogolo@telecomitalia.it
Enrico Buracchini	Telecom Italia Labs	enrico.buracchini@telecomitalia.it
Antoine Dejonghe	IMEC	dejonghe@imec.be
Jan Craninckx	IMEC	cranincj@imec.be
Liesbet Van der Perre	IMEC	vdperre@imec.be

8. APPENDIX 2: GLOSSARY

ACRONYM	EXPLANATION
B3G	Beyond the 3rd Generation
CPT	Conditional Probability Table
DAB	Digital Audio Broadcasting
MAC	Medium Access Control
MPSoC	Multi-Processor System on Chip
NO	Network Operator
OTA	Over-The-Air
QoS	Quality of Service
RAT	Radio Access Technology
RNC	Radio Network Controller
RRM	Radio Resource Management
SDR	Software Defined Radio
SINAD	Signal to noise and distortion
WiMAX	Worldwide Interoperability of Microwave Access
WLAN	Wireless Local Area Networks
WPAN	Wireless Personal Area Networks
WShRNs	Wireless Short Range Networks
WSN	Wireless Sensor Networks
WWAN	Wireless Wide Area Networks

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Wireless World Research Forum
Othmarstrasse 8
CH-8024 Zurich
Switzerland

Secretariat:
Vinod Kumar
Alcatel-Lucent France
Centre de Villarceaux
Route de Villejuste
91 620, NOZAY
France
e-Mail: vinod.kumar@alcatel-lucent.fr
Phone : + 33 1 30 77 27 37
Fax : + 33 1 30 77 61 75

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