A Phased Model for Network Selection based on Context

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Chapter 1

Introduction

Nowadays Internet access has almost been turned into a need. At home, at work and everywhere we need Internet to read a mail, make a bank transfer and other type of communications. More and more usage of all these applications, together with a current ubiquitous mobility requirements, generates a scenario with a lot of networks to choose from. The aim pursued is to achieve self-configuration, self-management and self-adaptation with decisons based on context.

Whereas a network is selected by a user, requirements and capabilities are changing according to many tunable parameters corresponding to avalilability, quality and capacity that we can obtain in the environment. It would be interesting to know which of all the networks available is the advisable option after a certain period of time, when the environment has changed. We want all this without the human intervention, to find out a system that provides us the possibilty to work with guarantee to avoid wasting time on selecting the ideal network operating state.

The main challenge is to develope a decision mechanism that carries out a task like vertical handover between technologies. This integral component of the cognitive network permits to the user be kept connected to the network in the best possible mode at all times.

Once the overall goal of the study is clear, it is aimed to obtain a technology to carry it out. In the scope of the autonomic communications, current research cognitive networks can be helpful to achieve it. Cognitive networks can dynamically adapt their operational parameters in response to user needs or changing environmental conditions. They can learn from these adaptations and exploit knowledge to make future decisions based on perceiving current network conditions and then planning, learning, and acting according to end-to-end goals. Cognitive networks are motivated by the complexity, heterogeneity, and reliability requirements of the future networks, which are increasingly expected to self-organize to meet user and application objectives.

Cognitive networks arise as a response to the limited available spectrum and the inefficiency in the spectrum usage needs a new communication paradigm to exploit the existing wireless spectrum opportunistically. In order to achieve an ideal seamless communication, emerges the counterpart Autonomic Communication which aims to reduce the operational cost and management by self-management network devices.

On the one hand, we have the technology to characterize our work through cognitive networks, while on the other hand we must to set up a specific scenario. We make use of the original concept of *Always Best Connected* developed by [Gus03] to define our scenario. A system that takes care of selecting the best network and reducing the need for manual intervention and management.

This work examines the current state of the art of cognitive cycles developed within research fields on autonomic communications. Section two describes the functions of different models previously explained. The next section explaines our own approach. Finally, the last section presents the conclusions and some directions for future work.

Chapter 2

Autonomic and Cognitive Networks

The cognitive networks emerge as an alternative to the current networks, significantly limited in the ability to adapt and to improve specially the performance of their resource management within the increasingly complex, heterogeneous, dynamic and unpredictable environments.

Furthermore, the selected literature sources emphasize on scalability, mobility and diversity in order to provide the necesssary requirements that make possible to perceive current network conditions that enable the entity to plan, decide and act. Cognitive networks can dynamically adapt their operational parameters in response to user needs or changing environmental conditions. Moreover these networks can learn from these adaptations and use them to make future decisions exploiting this knowledge while taking into account end-to-end goals.

The initial and original concept of cognitive networks arises on getting inspiration from biological systems and their distributed and autonomous behaviour. For instance, how the brain coordinates the nervous system and their correspondingly actions. The ability of self-organization is based on a continuous feedback with the environment and helps to evolve the structure and to regulate the adaptations.

Similarly, within the scope of the computer science, IBM develops the concept of autonomic computing oriented towards application software and management of computing resources. This contribution is based on computing systems that can manage themselves given high-level objectives from administrators.

2.1 Models

The following section describes the features of the main technical models of cognitive networks. The first approach, the Sense-Think-Act, cannot be properly considered as part of the cognitive networks, but its simplicity is the basis for the other existing models. This analysis leads to a better understanding of the existing concepts on the field, which is essential in order to design a more simple model that encompasses the main functionalities.

2.1.1 Sense-Think-Act

The first model that we have taken into account is developed around the practical architecture and philosophical fundations of robotics. Since its emergence as an embryonic academic discipline around 1980, the sense-think-act paradigm was developed as a revolutionary progress towards the evolution from the pick-up industrial robots to mobile robots [Sie03].

The author mentions briefly the definition of the robot as a machine that gathers information about its environment and uses that information to follow instructions to fulfil a task. In the following paragraph we will explain the different parts that compose this model.

In the first place *Sensing* is the process that enables to get information about their surrondings. Many different forms of sensors measure aspects of the environment and produce a proporcional electric signal. Once the information is collected, the trouble is to define which of those are useful. Consequently, the following task consists in seeing what is important and ignoring what is not.

Ruled-based systems use the knowledge acquired in the *think* state. The machine stores and manipulates the information according to a set of preprogrammed rules to carry out its algorithmic reasoning. That is the equivalent of the human heuristic thinking.

The last step,*act*, just consists in executing the action for each rule. It is the simplest process after which the system is once again ready to receive new stimuli.

Recently revised paradigm tries two decades later to append the capacity to communicate. The main idea is to provide robotics with this ability to exchange information with other more complex elements such as networks, servers...

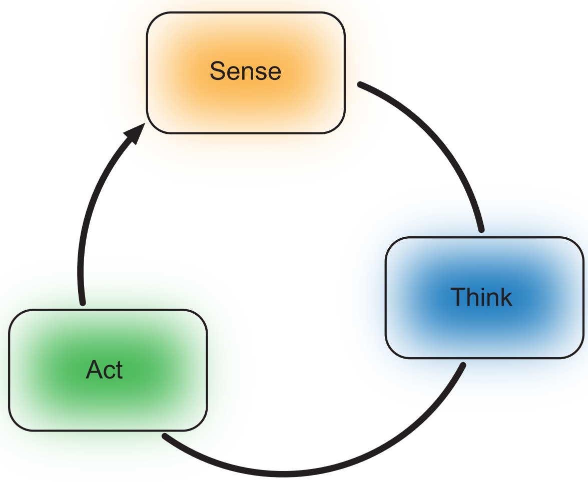

Figure 1: Schema of Sense-think-act loop

The author also comments the difficulties to supply the the computer with both cognition and perception. In this incremental development cycle is critical the human intervention in order to appreciate the richness information provided by the sensors. Thus, the information gathered gives only a partial knowledge about the world. The sensors and displays used must have similar technical specifications that the corresponding human senses.

2.1.2 Mitola Cognition cycle

The outside world is continuously changing and consequently the radio implements alternatives by adjusting its resources and performing the appropiate signaling.

Mitola offers the first view about cognitive cycle by employing cognitive radios to modify their actions in response to changes in the environment. through the use of state machines[Mit00]. Within the cognitive cycle, a radio receives information about its operating environment through direct observation and signaling. This information is evaluated and classified attending to importance by observing the different possibilities for each case, and choosing the best in a way to improve the performance.

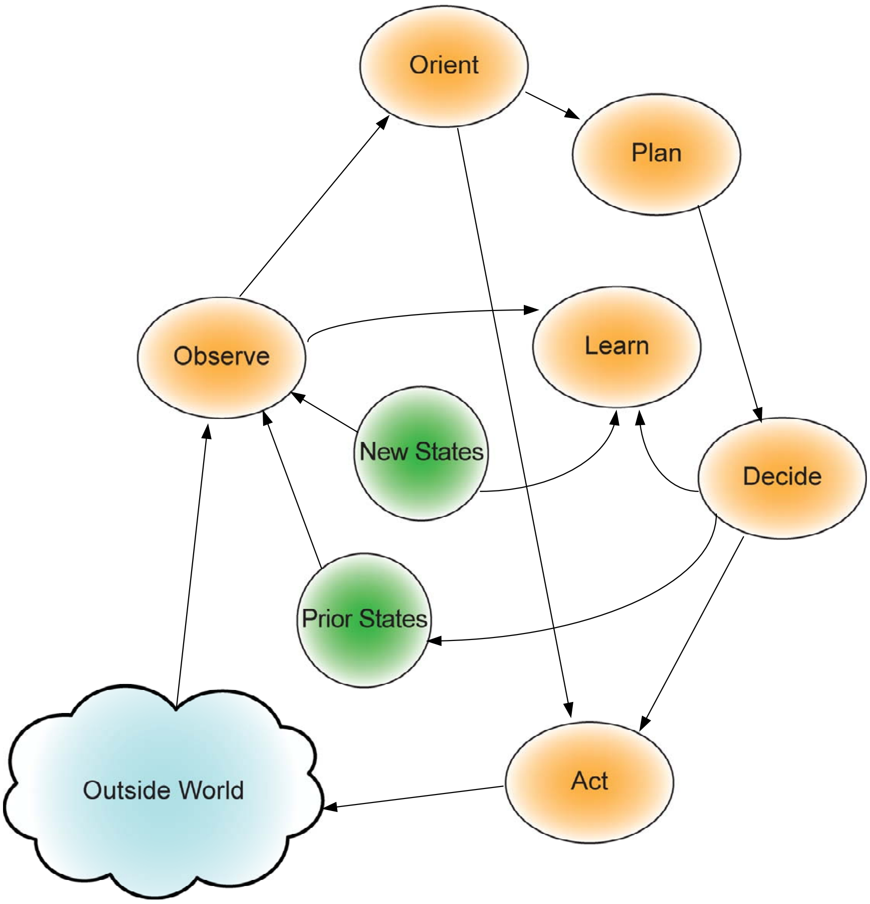

Figure 2: Mitola's cognition cycle, extracted from [Mit00]

The author includes the different control states, also called epochs, to keep an inference hierarchy and temporal organization within the network infraestructure [Mah07]. The first, wake epoch, is a large period of time to reactive the environment. The receipt of a new stimulus on any sensors or the completion of a prior cognition cycle initiates a new cognition cycle. The cognitive radio observes its environment by parsing incoming information. Any type of source that can provide environment awareness information may be also parsed. On the other hand, the dream epoch comprises the higher computational resources of the system by working on the pattern recognition and learning stages. In contrast with the sleep epoch, which is a statement of no activity, the prayer epoch works on the interaction of a higher authority with the complex domain.

In the *observation* phase, multiple stimuly in many dimensions are simultaneously received to generate plans for action. Remembering and rapidly correlating current experience against everything known previuosly.

Orient phase is the first collection of activity in the cognition component. Is based in the human short-term memory, providing an information that has not yet been assimilated at the current sleep cycle, but that will be saved with a whole degree of knowledge in the next sleep cycle.

When a current stimulus is received, it immediately is compared with previous experiences through the *binding* process. All the features of both situations are checked to take advantage of the prior experience to elaborate the ideal behaviour for the actual situation. *Binding* also determines the priority associated with the stimuli.

In response to the need to generate and evaluate the alternatives, *planning* gives a deliberate response to each stimuli, made up from a simple or complex planning system. The *plan* phase should include reasoning about time to accomplish accurately possible changes.

Among the possible plans, the *decide* phase selects the most appropriate for each case in a way that presumably would improve the validation. Finally, it carries out the definitive answer, where the radio implements the alternative by adjusting its resources and performing the appropiate signaling.

To improve the operation of the radio, based on all the observations and corresponding decisions the system as a whole can develope the ability to *lear* by creating new alternatives, generating new validations or creating new modeling states.

2.1.3 IBM: MAPE-cycle

IBM defines a control loop within the area of the autonomic computing based on a structured set of policies, rules and functions to check if the current state is desirable or not. The goal is to achieve standards for systems that are self-configuring, self-healing, self-optimizing and self-protecting. Nowadays a system without human intervention is still ideal and the goal is to minimize it as possible. This evolutionary process leads to an autonomic manager that uses shared knowledge to perform autonomic functions.

The authors in this research approach talk about the organization of the internal structure [IBM06] in parallel with the new concept of maturity levels[Wor04]. On the one hand, this last innovate type of classification helps us to undestand this evolutionary process in order to achieve these self-x capabilities. The most simple levels, basic and managed, don't offer awareness of the environment, and basically review the information gathered to take decissions[Wor04]. The next step through predictive and adptative tools is to obtain a set of policies to respond situations as they arise according to their relative priorities. Finally, the last aspect of the maturity is autonomic, which facilitates the infrastructure to learn as well as to predict and adapt. This new management approach is founded on the realization that multiple networks as well as networks with different functionalities will use multiple control mechanisms that are not compatible with each other.

On the other hand, the model here developed is called MAPE cycle loop, which stands for Monitoring, Analysing, Planning and Executing [Jac05]. These four parts work together to govern the control loop functionality, communicating with one other and exchanging knowledge. The autonomic manager is the responsible to automate these management functions and to control their internal relationships and communications with other autonomic managers.

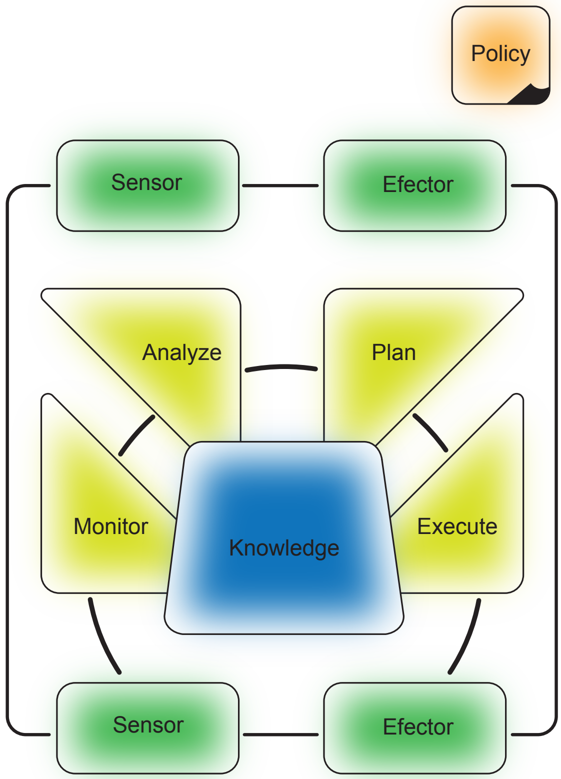

Figure 3: The MAPE loop cycle, extracted from[Jac05]

The main function of the first phase, i.e. monitoring, consists in being aware of the state of the system. Thus, the task is based on collecting information from the managed resources and correlating them to facilitate the next analysis. The information gathered is aggregated and filtered attending to their differents metrics and topologies[IBM05]. In order to cope with a great amount of information a rapid organaization and analysis is required from the autonomic manager.

Analyse function uses the job previously made by the monitor and provides mechanisms to observe and parse situations. In order to realize the necessary changes, the correlation analysis uses rules and relationships influenced and helped by stored knowledge data. This phase is responsible to determine if the autonomic manager can abide the established policy now and in the future. This function uses prediction techniques that allow to learn about the environment and help to predict the future behaviour. When modifications are required, this function develops a change request that contributes advising on the necessary or desirable modifications.

Following function, i. e. planning, creates or selects a procedure to enact a desired alteration in the managed resource, generating the appropiate change plan, which represents a desired set of changes. Mainly his task is to structure the actions needed to achieve objectives.

The execute function provides the mechanism to schedule and perform the necessary changes to the system. It is responsible to carry out the procedure that was generated by the plan function through a serie of actions and taking into account the necessary dynamic updates.

At the end of this section we find the link among the four parts prior explained. The knowledge block is certainly the brain of the whole system and provides access to knowledge from one or more knowledge sources. It shares and manages all type of information as well as policies and actions.

2.1.4 Dobson Model

Within the scope of the increasing autonomic systems, the author focus his work on the way to establish the main issues in order to design a model that provides the properties required for the networking methods[Dob07a]. The challenge consists on deriving benefit of individual, complex and adaptative components and their behaviour in the corresponding domains.

Furthermore, the author keeps the lately common proposal inside autonomic communications area to obtain the well-known self-capabilities (self-manafement, self-configuration...). As a response to all these requirements he designs the autonomic control loop, where decisions reflect the impact of previous decisions. The main point consists in achieving the feedback nature of adaptivity, the most valuable requirement in addition to flexibility. [Dob07b].

The system analyses the information gathered from all type of sources, and builds a model prepared to interact with the networks and its services within its reach. The author understands the system as a whole, and characterizes his approach by the behaviour of the components among themselves and by the way they affect its overall behaviour. An envelope of behaviour is implemented to keep a certain control of the system . This mechanism execute a control boundary in order to achieve high levels of precision and correctnes. Consequently it is not possible to say what it would happen in detail with a certain application, but it could guarantee user quality. It could also be added the difficulty to get the correct choice due to it could change over time and with context.

Dobson points out confidence and stability as one of the most desirable properties. Moreover, diversity gives the possibility to search the most effective solutions. Additionaly, the author emphatizes responsiveness as a manner to supply

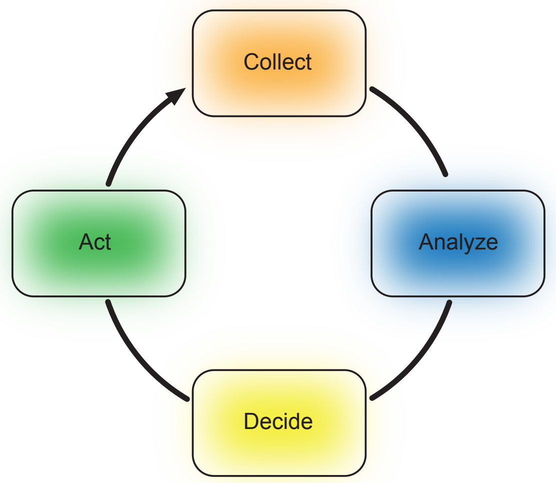

Figure 4: The autonomic control loop, extracted from, [Dob06]

responsive change. When a highly priority event happens the network must be able to deal with it by itself.

The author distinguishes four strong interconnected blocks: collect, analyse, decide and act. In the first place, by means of sensors, the system picks up information of the network's environment and the user context and also information concerning to applications requirements and network instrumentation and environment. The author suggests to use a *standard ontologies of sensing information* facilitating the interchange between subsistems.

On the other hand, the author also explains the analyse block as a way to deal with the previoulsy gathered sensor information. This step encompasses all the methods and techniques available to handle the uncertain information in order to deduce the best possible solution. The key of this concept is based on a set of rules and policies developed within the cognitive process to achieve a certain reasoning.

The decision aspect of the control loop is closely related with the abovementioned analysis and takes into account the current state of the system and the behaviour and responses carried out before. Different hypothesis are dynamically generated and evaluated to choose the correct result according the suitable decision theory.

The author defines acting as the last stage of this system, where the tasks of the whole process are executed. It is the most operational part of the control system and it usually informs about the actions executed to the users or administrators.

2.1.5 Georgia Institute of Technology

The computer science research group is focused on solving the problems of the scarcity and inefficiency of the spectrum [Ian06]. In the scope of the next generation networks, the authors state the development/appearance of cognitive radio technologies as the key to share the spectrum in an opportunistic manner, enhancing the flexibility of personal wireless services. Their teories have the main goal on discovering which portions of the spectrum are available as well as on detect the number of users, trying to satisfy the requirements of maintaining a seamless communication and sharing fairly the spectrum.

The basis of their work involves two concepts: cognitive capability and reconfigurability. The object of study is the cognitive cycle within the cognitive capability, which developes the ability to capture the information from its environment and to find the unused portions of spectrum also called *Spectrum holes* or *white spaces*.

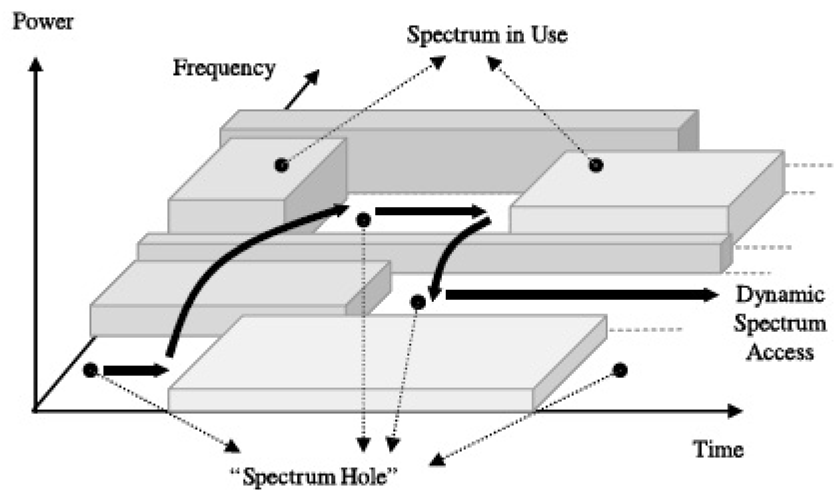

Figure 5: Spectrum hole concept, extracted from [Ian06]

The cognitive cycle is composed of spectrum sensing, spectrum analysis, and spectrum decision. Spectrum sensing techniques are designed to be aware of and sensitive to the changes in its surrondings, detecting the *spectrum holes*.

Once the information is gathered, spectrum analysis tries to select the appropiate band to each user according his requirements. *Spectrum holes* are characterized by time-varying radio environment, primary user activity and spectrum band information. Simultaneously, these *white spaces* are defined by parameters such as interference level, channel error rate, path-loss, link layer delay, and holding time.

The last step of this this cycle spectrum decision is the selection of the appropiate operating band for the current transmission, considering the QoS requierements and the spectrum characteristics.

Reconfigurability enables the cognitive radio to adapt to the dynamic radio environment, adjusting operation parameters for the transmission on the fly without any modifications on the hardware components. Operating frequency, modulation, transmission power and communication technology, viewed as the most important of these parameters, can be reconfigured not only at the begining of a transmission but also during the transmission.

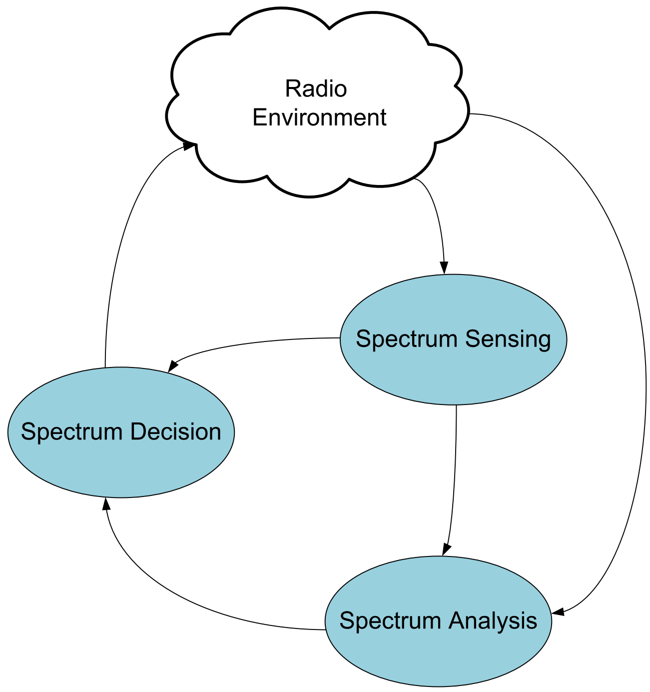

Figure 6: Cognitive cycle, extracted from [Ian06]

2.2 Psychological and pedagogical contribution

Within the cognitive science there is an empirical discipline focused on the field of the computer science, that involves the study of cognitive phenomena in machines. In this section it is only interesting to take a look at the features of that human methods of behaviour and learning to evaluate the possible applications in the networking field.

2.2.1 Background

We use a technical model to represent the real world: the behaviours, circumstances and iteractions of their own elements with the environment. There are many different possible ways to do it, but all these models are only approaches with more or less precision.

According to our limitations, a probable source to understand the surrounding environment information is to use the knowledge of human behaviour to build an approach based on this experience. Cognitive phychology tries to understand, diagnose, and solve problems. We are interested in finding a solution to structure the functional organization of a complex system of networks and all their interconexions.

As a result of using all the possible knowledge and process types, the educational objective is to achieve rationality as far as possible, keeping the beneficial aspects and rejecting the rest.

Learning and developing are processes by which knowledge and information is acquired over time. One task is take the methods used with children in order to put into practice in our approach.

2.2.2 Cognitive Approach to Student Learning

As a consequence of the latter, here the present study takes a look at a student learning model in order to get ideas to educate a cognitive system. This job made by David Hallowell in the educational psychology area consists in improving the performance through a structured use of the available skills[Hal08].

The author defines the cognitive load theory and working memory as the keys of learning. Many different aspects meet when it comes to analysing the capacity of learning such as motivation, personality, preferences and faculties. Furthermore, the author proposes strategies to improve this learning process, solving the problems as possible and consequently increasing the performance. The result is a managing cognitive load based on focusing attention and avoiding split information in order to reduce working memory load and use segmentation for progress gradually later.

2.2.3 Reflective Learning Model

Reflective learning and reflective practice have been hallmarks of professionaly-oriented learning in many fields. Moreover reflection involves thinking about and critically analysing the experiences and actions with the goal of improving the practice [KM88]. It allows to adapt general guidelines to particular contexts and disciplines enhancing strengths and preferences. Within the initial and most important proposal to mantain a global knowledge around all the dynamics and integrated networks, this tool helps to keep a continuous self-direct development and capable of making informed decisions through the capacity of learning. It provides the abilities for developing and sharing a commun and own collection of strategies and techniques related to learning.

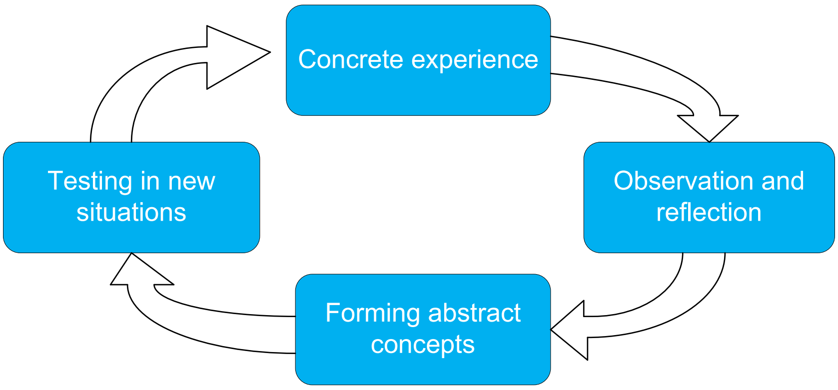

Figure 7: Reflective learning model, extracted from, [Hal08]

In the same way, the author [RAC+05] stresses the intereseting idea to develope processes and integrate techniques in most scenarios, in order to be able of supply counselling, assessment, planing or a combination of the three. Although the author refers here to the student and his knowledge, we can make an analogy and use this concept to improve the relations of all the processes and their corresponding knowledges in the same domain.

The same authors describe informal learning in the case of a learner is motivated to follow some self-direct learning. They explain the challenges and opportunities for informal learning involve three interrelated aspects: personal environment, educational environment and technical environment.

2.3 Assessment of Models

Seen different models for Cognitive Networks in the autonomic communication and computing fields together with the contribution from other systems coming from robotics makes possible an evaluation to the technical properties. Moreover nontechnical influences from psychology assist to redesign more intelligent future models in their learning capabilities with the influence of human models.

At the time to evaluate the properties of the corresponding models, it is interesting to compare some of the qualities presented. In order to mantain an updated architecture, it is advisable present extensible and flexible features for supporting future improvements. In addition, one of the most valuable features presented by the Sense-Think-Act, Dobson and Georgia Institute of Technology models is their simplicity, which leads to systems which are easy to implement. In spite of this advantage, we consider the more complex approach of Mitola as very useful and a remarkable reference.

Furthermore, all the models use context as a resource of information from the environment except the Sense-Think-Act, which lacks of any interaction with the environment. This is the most significant weakness of this robotic approach, as in a context-aware environment, different systems of the same domain should interact between each other to act according to others' decisions.

An interesting feature that provides intelligence and speeds up the performance of the system is the well-known learning. From all the cases examined, only the MAPE and Mitola models offer this quality. Moreover, the MAPE system offers a new vision in the development of the system introducing maturity levels, based on predict, adapt and learn. Other strengths are predictability, mentioned by Dobson, and reconfigurability, suggested for the cognitive cycle developed by the Georgia Institute of Technology.

In addition to all the technical contributions, the psychological influences offered by the Cognitive Approach to Student Learning and the Reflective Learning Model provide a new and different point of view to improve the current research. On the one hand, the first reference talks among other things about cognitive load and split information, very related with the desired properties and which will be more thoroughly described in the next chapter. On the other hand, the pedagogical model based on reflective learning suggests features such as counselling, assessment and planing, all of which are essential to achieve a better management.

Chapter 3

Common tasks and function blocks

After looking at existing approaches, many similarities in these models can be found. In this chapter, functions are grouped into blocks to see what can be used for a new model.

3.1 Sensing and Monitoring

Sensing and monitoring are considered as the first requirement of any context model with the purpose of capturing information.

The cognitive networks sense the spectral environment over a wide frequency band and exploit this information to opportuniscally provide wireless links that best meet the user communication requirements.

One of the greatest advantages of cognitive radio is that it can be operated in licensed bands without license as stated by the authors in [CMB04]. Secundary users can use the licensed band, but when they detect the presence of primary users they must vacate the band for them. Hence, they need to continuosly monitor the spectrum to detect the presence of primary users.

Cognitive networks offer the opportunity to use dynamic spectrum management techniques to help to prevent the interferences and to adapt to immediate local spectrum availability.

The acquisition process is based on a continuous collection of data for the different networks available (GSM, WiFi, UMTS, WIMAX). Network sensing is a key idea to obtain information regarding human behaviours with appropiate reliability.

Current spectrum sensing methods in cognitive networks mainly employ cooperation to improve detection capabilities and agility. The authors in [GL05] investigate three digital signal processing techniques to improve the sensitivity of the sensing function: matched filtering, energy detection and cyclostationary feature detection.

The implementation of the spectrum sensing function requires a high degree of flexibility. Reliable sensing creates spectrum opportunities for capacity increase of cognitive networks.

Monitoring is of paramount importance to self-managing networks. Given the closed loop interpretation pattern an autonomic components exhibits, the component must be able to determine what, when and where to monitor. The monitoring data may be diverse in content and context, and the monitoring parameters are likely to be subject to frequent changes. Moreover, monitoring relates sensing to prediction and to provide support for learning.

Quality of context describing the properties of the context data is an important part of the context data objects and should therefore be included in the description of the context. The properties depend on the capabilities of 'underlying sensors / measurement devices and can be influenced by the requirements of clients. These properties are very important for the clients to be able to make decisions about suitable context data objects [TW08].

Moreover, sensing imports multiple types of measured data such as movement, networks and user applications, metrics and topologies. This function reports all this data collected from the managed resources to improve its model of the environment.

3.1.1 Data Aggregation

Sensors in the networks act as sources that detect environmental events and supply relevant data to the system. Dealing with the challenges from network scalability and complexity, data aggregation protocols offer a reduction of the communication costs and extend the lifetime of the sensors.

The inherent redundancy in raw data collected from the sensors can often be eliminated by data aggregation. An autonomic component can only monitor a small subset of environmental variables in its local environment at any given time. Thus, data aggregation emerge as an effective technique for optimizing the sensing operations, as it is developed for extracting specific information from raw data.

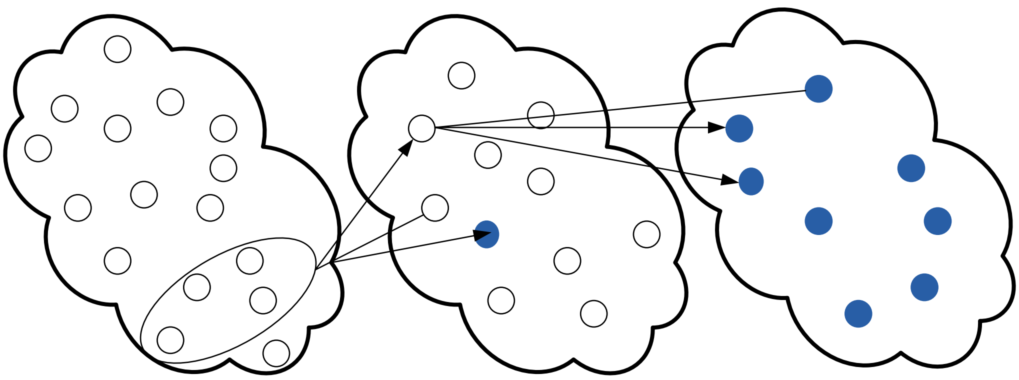

Figure 8: Concept of data aggregation, extracted from [TW08]

The aggregation offers the possibility to collect context-related data packets from proximity nodes in order to get a more precise information about a certain event. It is interesting to create a situational description through monitoring for significant changes. The authors in [TW08] mention data aggration as a tool that formally speeds up the system to describe a situation.

3.2 Analyse

Given the complexity of all the models examined, one component must be in charge of managing and processing the retrieved information. This module plays a similar role as a human brain, as it is the central node of all the system operations.

First, it must choose the suitable necessary mechanisms to interprete and summarize the received sensor data. The previously obtained sensing data is correlated and filtered to describe a situation. In this complex process the data turns into information and subsequently into knowledge. Data refer to a collection of facts usually collected as the result of observation processes within a computer system. This may consist of numbers, words, or images, particularly as measurements or observations of a set of variables. Data are often viewed as a lowest level of abstraction from which information and knowledge are derived. In addition, information is data that has been given meaning by a relational connection. Finally, knowledge is the appropriate collection of information, such that it's intent is to be useful.

One of the fundamental principles of the analysing function is to meet the needs of the system and dynamically update the corresponding changes. In addition, it is precised an accurate control of the context changes to use the suitable policies to ensure and guarantee a correct result. When the system appreciation of the environment changes, the current set of policies probably changes too, and this module must determine the state of this new situation. The configuration of policies and rules are also developed in this stage.

Furthermore, this module makes use of a central ontology for the representation of the reality and to share knowledge and to interoperate using a common semantics with multiple systems. In addition, ontologies are used to analise sensed data to determine the current state of the managed entities being monitored.

Moreover, the analyse block must evaluate the impact of the decisions made and draw conclusions for future situations and events. It is also responsible for controlling and adjusting the functionality of each of the components. Other tasks carried out by this module is the anomaly detection.

Finally, to achieve system-wide objectives, the analyse module is resposible to coordinate the interactions among all the autonomic systems and to manage the overall behaviour.

3.3 Context

Recently, the term context has become essential as the basis for decisions in many systems. Nowadays a large body of the research into context is focused on the provision of information and content in order to achieve a better knowledge.

Within the concept of context, we can find different definitions attending certain approach. On one hand, [BDR07] defines context *"as any information that can be used to characterize the situation of any entity, where an entity can* *be a person, place, physical or computational object"*. In this instance, the author of this reference, Dey and Abowd, give a specific explanation focused on the user and applications.

On the other hand, it is also well-known a extended definition of context in network, where [TW08] *Context information is any information that can be used to characterize the situation of an (networked) entity, where an entity can be a person, place, physical or computational object.*

Within the E2R project, context is view as the information that surrounds and gives semantic meaning to an entity [BPA06]. In order to describe the reality or state of the "world", the concepts ontology and context are complementary defined. In addition, ontology is defined as a "'shared model of the reality"' interpretable by all the artefacts.

3.3.1 Context-Aware Systems

Context-aware systems are able to adapt their operations to the current context without explicit user intervention and thus aim at increasing usability and effectiveness by taking environmental context into account [BDR07]. The authors emphasize that programs and services react specifically to their atributes and adapt thier behaviour according to the changing circunstances as context data may change rapidly. The main properties that we can observe are:

- *Simplicity*: the used expressions and relations should be as simple as possible to simplify the work of applications developers.

- *Flexibility and extensibility*: the ontology should support the simple addition of new context elements and relations.

- *Genericity*: the ontology should not be limited to special kind of context atoms but rather support different type of context.

- *Expressiveness*: the ontology should allow to describe as much context states as possible in arbitrary detail.

Ontology based models

Ontologies represent a description of the concepts and relationships. Therefore, ontologies are very promising instrumnent for modelling contextual information due to their high and formal expressiveness and the possibilities for applying ontology reasoning techniques [BDR07].

The recently increased popularity of ontologies has led to the appearance new-ontology based models of context. According to the author, these models aim to better support interoperability between entities sharing common concepts and also have the potencial to support sophisticated ontology-based reasoning.

For instance, in the SPICE project, ontologies define the basic contextual conceptualizations of classes of object in the platform to describe relationships between classes [JS06]. The authors explain the scope of the ontologies developed in this project as a way to make a useful support context aware application.

Ontologies in Autonomic Computing

According to the authors in [BPA06], the term ontology arises as a shared model of reality interpretable by all the components of a domain. Moreover, the authors define onlogy languages in order to conceptualize the world in term of objects and relations among those objects.

In addition, the author in [Mah07] proposes ontologies as a way to implement a common lexicon, mapping all the existing data models in a single common model. The result of this work encompasses a set of definitions for each term as well as a set of relationships between each term. Conceptually, the use of ontologies also help the construction of knowledge choosing the appropiate definition in the current context. Furthermore, ontologies provide a set of formal mechanisms that allow unambiguously identify syntatic and semantic areas of interoperability between each language and model used.

Ontologies use inference engines to answer queries about the data. They are used to define mappings between terms of knowledge and their intended meanings.

3.4 Decision Making

The raw information gathered needs to go through various levels of abstracion so that they can be input to the decision making process. The correct interpretation of this information helps to identify the characteristics and to describe a situation. An extensive database of policies and their associated action sets are stored in

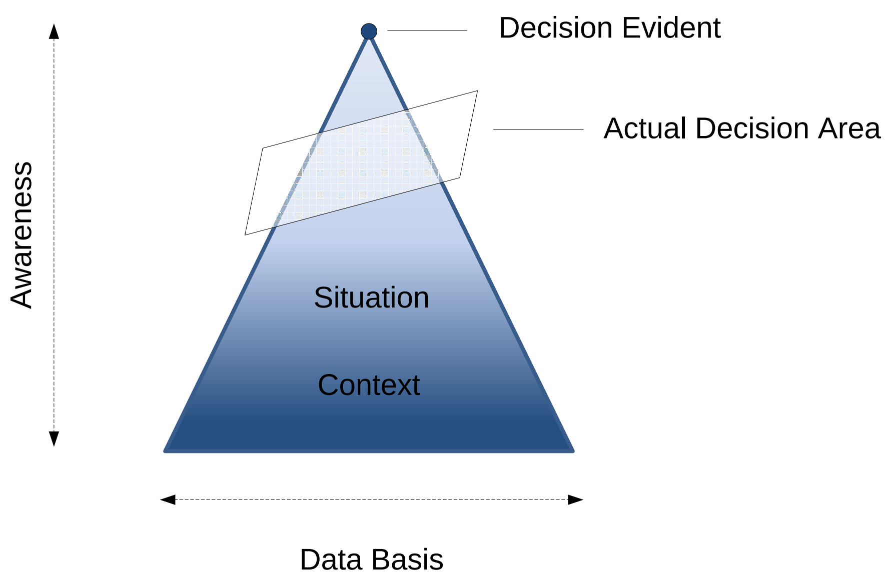

Figure 9: Situation awareness pyramid, extracted from [TW08]

a knowledge base. This set of considerations are designed to guide the decisions that affect the behaviour of a managed resource task, and uses context to speed up the performance and to supply flexibility. Therefore, a set of mechanisms are required to determine whether a particular enforced policy condition is met. These mechanisms encompass tasks such as application of policies, constraints, evaluation of alternatives and optimization.

Within the autonomic communications systems, different type of algorithms are used to: genetic algorithms, fuzzy logic, Markov Models. The attached Figure 9 shows how the situation awareness provides the basis of the corresponding decisions.

3.4.1 Learning

According to the existing literature within the cognitive networks, some similar characteristics such as awareness, perception, reasoning, judgement and learning are related to the term cognitive. They are all used trying to solve problems like capacity maximization and dynamic spectrum access [CHSO07].

The authors in [LL08] report learning as a set of mechanisms that use knowledge structures to predict future situations. This definition also includes the ability to learn predictive models from experience and to redefine them over time.

Learning is an important capability required for a cognitive system to improve performance through experience gained. Together with the use of effectiveness of past decisions under a given set of conditions, it establishes an effective and practical technique for discovering relations and extracting knowledge.

Many different learning algorithms such as hidden Markov model and genetic algortihms can be implemented to achieve a network that can learn from adaptations and use them to make future decisions, while taking into account end-to-end goals.

The goal of the learning engine is to determine wich input state will optimize the objective function. Learning is a long-term process consisting in the accumulation of knowledge based on the perceived results of past actions.

3.4.2 Act

This is the most operational function and supplies the mechanism to schedule and performe the necessary changes to the system. The available actuators change the behaviour of the managed resources and carry out the tasks ordered by the decision making module. Moreover, this block informs of the actions executed to users or administrators and stores the strategies used via learning mechanisms.

3.5 Context and Decision in European Projects

In this section we observe the importance of context and its behaviour within different projects developed in the Sixth Framework Programme (FG6) of the European Union.

3.5.1 Ambient Networks

The authors in [MSB+07], define Ambient Netowrks (AN) as dynamic networks that can change according to the environment. In the same way, they emphasize the novelty by which ANs can compose and descompose with other ANs extending the network's capabilities to give/offer new different services to end users.

Ambient Networks also enable co-operation between heterogeneous networks, in order to provide ubiquitous connectivity to end-users. The authors define the Ambient Control Space (ACS) as the main entity that gathers all the information and links it, strengthening a control plane overlay to integrate and interoperate seamlessly any existing network [MSG+07]. Moreover, the ACS supplies abstraction of resources and enables the service delivery for ANs. Functional entities, inside the ACS, deal with every type of AN features and communicate between each other using web services, and specifically SOAP. Furthermore, the Ambient Service Interface (ASI) is an "upper layer" interface of the ACS which is accessible to the applications whose tasks are based on defining requirements and specifing how to deliver the service.

On the other hand, the Overlay Management, create and mantain a service-specific overlay network to fulfil the service provider requirements. Moreover, it manages the service delivery to end-users while adapting to user and network context. The entity responsible to adapt automatically the context is the Service Context, whereas Context Source offers Context Information and Context Client uses it.

The authors inside this project introduce a specific overlay called Service-aware Adaptative Overlay (SATO). This mechanism has the self-adaptative ability and allows dynamic re-configuration when changes in network context have taken place.

The Context Coordinators enables aggregation and selects dynamically a node, or a set of nodes, to collect and analyse the retrieved information. The authors suggest for this election the dynamic and scalability advantage of the approach based on DHT. In order to identify the different types of aggregated information as context the Context Coordinators use Universal Context Identifier (UCI).

3.5.2 SPICE

SPICE is a research project whose main goal is to achieve unified and seamless way to deliver services over heterogeneous execution platforms, network and terminals. On the other hand is necessary to focus this challenge around the context concept, and how to take advantage of the context information acquired from heterogeneous context sources [ZZM+06].

The authors in [JS06] emphatize the idea of exploiting this contextual information, and the methods to obtain entailed information as a result of sharing knowledge from a combination of knowledge sources. The Knowledge Management Framework (KMF) use rules, recommendations, facts, preferences and semantic levels to handle the knowledge previously discovered and exchanged to provide it the interested parties.

The authors in [CDvK+08], consider the Personal Information Management (PIM) enabler as a mechanism used to personalize services based on user prefereces. Moreover this entity aims to manage information of end-users and to share them between different services. The task of the Knowledge Interpretation consists in adapting the needs and requirements of the end-users. This mechanism

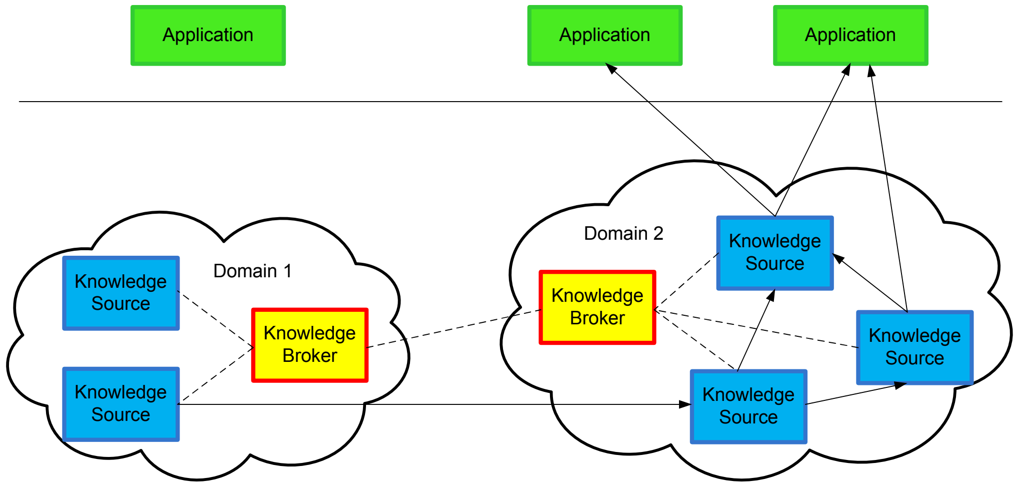

Figure 10: Knowledge Management Framework overview, extracted from [Mit00]

takes care of the interests and behaviours of the users and takes the corresponding actions based on the previously learnt knowledge and open the next possible and advisable options.

The Attentive Services are mechanisms that reacts to the changes of the service context or the knowledge on time in order to provide better solutions/properties to the end-user and notify the correspondings changes. The Distributed Communication Sphere (DCS) collects communication resources in the vicinity of a user than can potentially be used to provide high-level services.

The primary design principle of the context ontology is based on the realization that context is a relationship between multiple entities. Knowledge subscriptions are implemented by setting up a network context sessions using SIP/IMS mechanisms.

3.5.3 E2R

The End-to-End Reconfigurability (E2R) devise, develop and trial architectural design of reconfigurable devices and supporting system functions to offer an expanded set of operational choices to the users, applications and service providers, operators, regulators in the context of heterogeneous mobile radio systems.

The researchers devise end-to-end reconfiguration management and control architecture together with optimal split of intelligence and functionalities between cognitive network elements and reconfigurable end-user equipment. Specific end-to-end mobility and Quality of Service (QoS) protocols and mechanisms will be explored to achieve flexible traffic exchange.

The developed protocols and mechanisms exploit emerging concepts of autonomous systems as an evolutionary step from reconfigurable towards cognitive communications, characterised by self-learning, self-configuring, and self-managing attributes. The users will benefiting from these capabilities by reaching required service at times and places when and where needed at affordable cost.

In this project, the perspective of context is viewed as information that surronds, and gives semantic meaning to, an entity.

The authors in [BPA06] define a Context Manager as a part of their Self-ware Reconfiguration Management Plans (S-RMP), that uses context to trigger autonomic reconfiguration actions. This S-RMP comprises a modular, intermediary, multi-plan-based solution allowing independent evolution pahts and refinements to the legacy control and management planes.

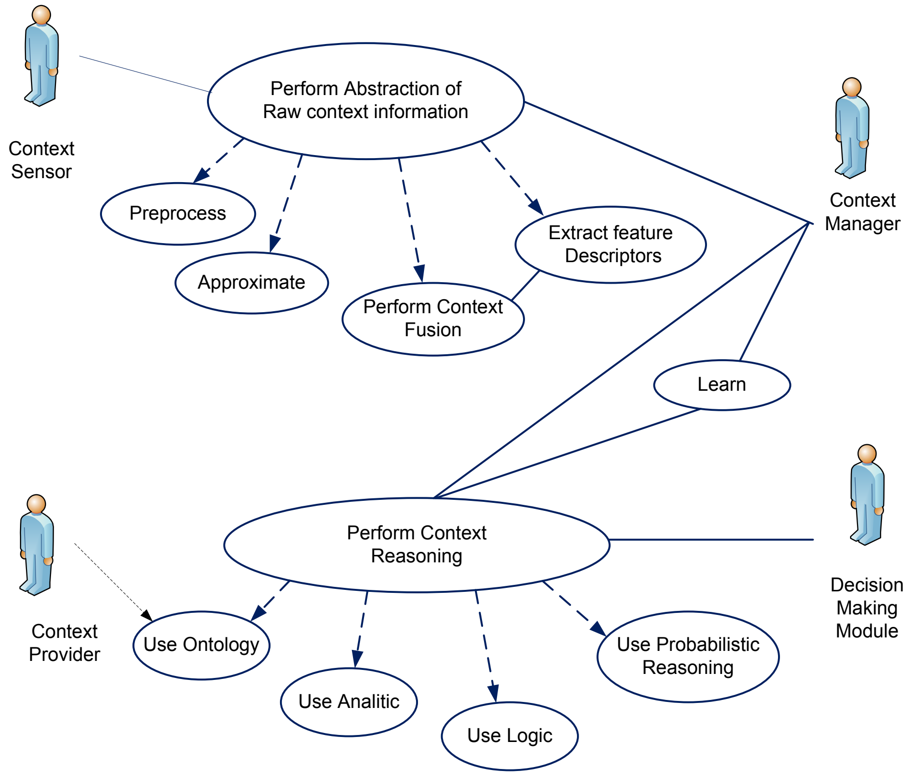

Figure 11: Use-case diagram from Context Interpretation, extracted from [KBB+05]

The Knowledge and Context Management module within the E2R consists of:

- *Performance Management function (PeM)*: monitors resources that are provisioned and controled by RsM.
- *Profile Management fucntion (PrM)*: is resposible for management, aggregation and evaluation of profile information. It carries out the reconfigurability Classmark, the main indicator describing the appropriate knowledge of any reconfiguration event.
- *Resource Management function (RsM)*: manages generic resources that are not associated with a specific RAT and device.
- *Reconfigurability and Autonomy Classmark module*: evaluates all the profile

handled by PrM and generates a dynamic label with capabilities of the entity in order to support reconfigurability actions and autonomy levels.

Finally the Context Interpretation module create high level composite context information required for autonomic decision making and it is responsible for abstracting raw context data.

3.5.4 MobiLife

MobiLife Integrated Project aims to bring advances in mobile applications and services to users in their everyday life by innovating and deploying new applications and services based on the evolving capabilities of the 3G systems and beyond. In doing so, it provides a new context-aware and proactive services and applications[CDD+05].

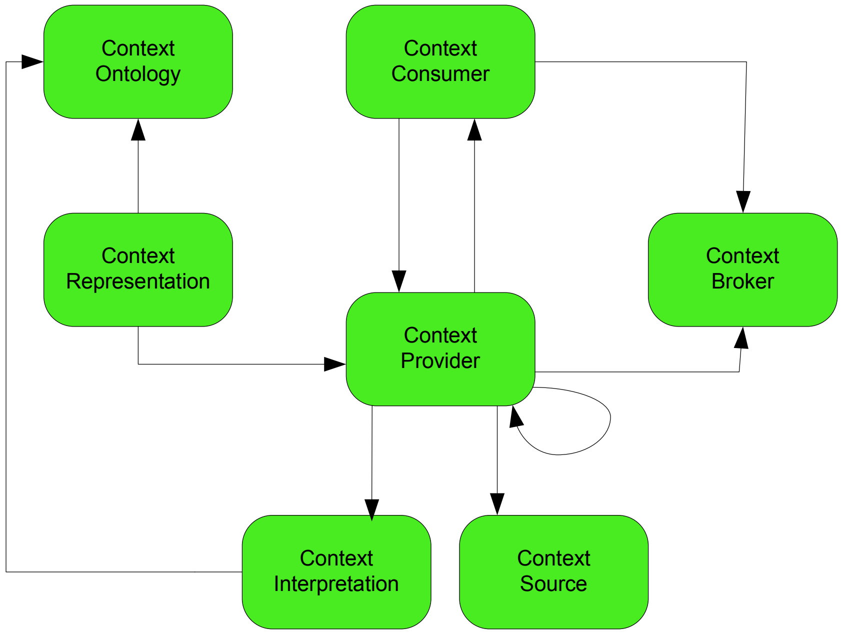

Figure 12: MobiLife cycle, extracted from [KBB+05]

The authors present a system architecture built to provide new services and applications to the user through a personalised and tailored information. The architecture is called Contex Management Framework (CMF), and is focused on two points, on the one hand self-awareness, to bring solutions to users in their local environments and the other hand, to make possible to share information between users through a group awareness. Its main task are: standardise context exchange between providers and consumers, enable the discovery of context providers and share a common undestanding about context information elements.

Furthermore, the authors describe the differents blocks that are the CMF are formed: Context Consumer, Context Provider, Context Broker, Context Representation Framework, Context Watcher and Context ontology.

Firstly, the Context Providers are software entities that produce context information from:

- *Internal*: information in a certain node (e.g. GPS location, BER).
- *External*: information about the network (e.g. Traffic congestion is a set of nodes).

The Context Representation Framework is a set of specifications used to describe the context provider advertisements and the interfaces to exchange context information. The Context Source provide an extra information store to deliver more complex information to the context consumers. Furthermore, the autor explain the Context Broker as a powerful query and repository service used to discover the context providers and their interfaces. The Context Watcher is a mobile application that aims is to make automatic recording, storage, and usage of context information easy for the end-user. The Context Interpretation has the responsability to describe group situation and context. It aims to provide semantically descriptions at different confidence levels and produce new interpretations to refine the descriptions of the group context. Finally the Context Ontology describes the qualitative context information elements and their interrelations.

Chapter 4

A Straightforward four-phases Model

4.1 Motivation

Given the increasing complexity of the communication networks, the main interest of this work is to design a system able to take decisions based on context. The continuous changes of the environment modifies the circumstances in the decision making process, and the use of context is an essential tool to be able to make a reliable decision. Historically, managed or static systems and subsequently adaptative systems have been developed to manage different applications and technologies. Nowadays, cognitive networks devices are permanently self-aware and context-aware and their challenges are to manage complexity and to make an efficient use of the available resources.

The key motivation behind the proposed approach is to replace users decisions in network selection, optimizing the self-government of the system and allowing a better service. In order to achieve the best preformance possible, the idea is that the user can be connected regadless of the location.

We present a framework of cognitive network management by means of an autonomic reconfiguration scheme. We propose a network architecture that enables intelligent services to meet QoS requirements, by adding autonomous intelligence, based on reinforcement learning, to the network management agents. The system is shown to be better able to reconfigure and manage the different areas of interest in order to adapt changes.

4.2 Scenario

Once the initial idea of the system is established, it is necessary to allocate it within the scenario. In this case, there are three different points of view for always best connected scenario: from the operator, the user and the service provider. In this design, we only consider the scenario from a user's viewpoint.

4.2.1 Always Best Connected (ABC)

The Always Best Connected concept provide a person with connectivity to applications using the devices and access technologies that best suit his or her needs, thereby combining the features of access technologies to supply an enhanced user experience[Gus03].

An always best connected scenario, where a person is allowed to choose the best available access networks and devices at any point in time, generates great complexity and a number of requirements.

In an environment of multiple access technologies, the concept of being always connected refers not only to being always connected, but also being connected in the best possible way.

For a user, always best conected means to be connected through the best available device and access technology all the time. Depending on the preferences, a user can be connected over one access at time or over multiple accesses in parallel. All type of access technologies, fixed and wireless are included in this concept.

Moreover, the two key components uppermost in users' minds defining better and best will be price/performance ratio and comprehensive service access. It is mportant to the user to control the best billing option available at any time [GMN+03].

Furthermore, the best connectivity solution can be chosen only after accurate analysis of cost and benefits of each access solution. This analysis requires contributions from all the involved parts such as users, operators and service providers.

Accordingly, the user should always be connected through the access solution, satisfying one of the following conditions: minimizing a cost function, maximizing the level of perceived QoS or minimizing cost provided that a certain QoS constraint are satisfied.

4.3 Phased Approach

Given the contributions previously examined within different research fields together with the description of the scenario and the initial proposal, the foundations of this work are laid.

In order to guarantee a seamless transition of a multimode device from one network interface to another, this approach uses a vertical handover. This integral component of the cognitive networks permits to the user, to be connected to the network in the best possible model all the times.

The designed model is composed by four blocks: sensing, analysing-decision making, acting and learning.

First, **Sensing** provides to the system all the information collected by sensors to give an overall and detailed explanation over the environment. This block is continuously monitored to notice the constant changes in the environment. Moreover, sensing supplies a clear conceptual understanding of the set of context as a crucial task to represent and analyse the cognitive system.

Furthermore, the job made for this function is important in the sense of providing updated information of the actions carried up for all the systems inside a domain. In order to accomplish the application requested by a user, e.g. videoconference, a set of requirements such as delay, link speed or BER, are needed. Therefore, this information is obtained in a close cooperation with the analyze block, that consequently request to the sensing. All the changes generated are saved in a data base.

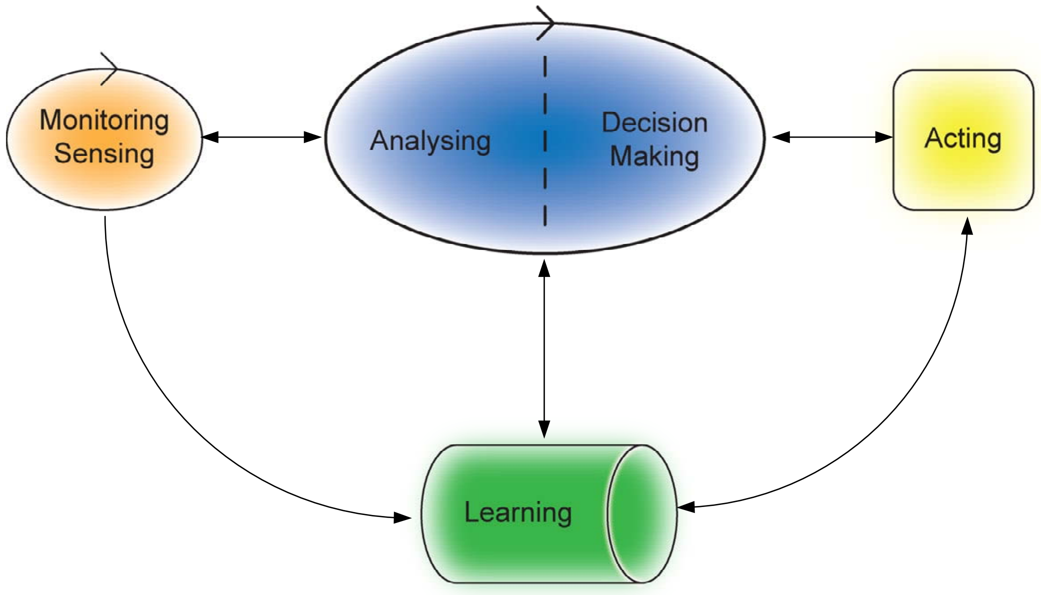

Figure 13: Phased Context Model for Network selection

Given the fact that the **Analyze** and **Decision Making** modules have a strong coupling in many common processes, the phased approach proposes a single block that carries out the functionalities of both entities. This module is in charge of the "intelligence" and management of the whole system, supplying the corresponding algorithms to each decision.

The use of ontologies is useful to analise and identify the gathered sensed data and to determine the current state of the system. This complex module checks the consistency of the global system and predicts constantly future situations and their correspondig responses.

There is a periodic communication between sensing devices and analyse block in order to work in the identification of suitable oportunities, always depending on the limitations, as well as on the user and application demands. Usually sensors collect information related to certain parameters. In case of an eventual change in the user or the current situation, new data is needed and it is immediately requested by the analyse via sensing tools.

This block tries to mantain the equilibrium in each state and optimize the performance and efficiency, and proposes reconfiguration as an important capability for adaptations and optimizations. Moreover, this compact module must understand, negociate and interact with the different control loops in the same domain.

Finally, this module makes use of all the algorithms available in the database to use them in any decision making process. The Act module is reported with the chosen algorithm, which can be combined with additional algorithms if necessary. In case of find a new algorithm to solve any new situation, it is immediaty saved in the database via learning mechanisms. To conclude, it evaluates the success of the learning operation within the feedback loop between both blocks.

The major breakthough of **Learning** is that it offers the possibility to take advantage of past decisions to better respond to current changes.

It is essential the use of learning techniques as an effective way to deal with the dynamic environment and uncertainties. A very interesting aspect to achieve learning could be use a feedback loop, which use past interactions with the environment to solve current and future interactions.

Decision making use the work made by analyse to carry out the optimal decision and the result is directly communicated to learning. The learning module consists of a database periodically monitored.

The ability of learning can be seen as a way to improve a system and probably enable to carry out a larger numer of tasks. It would be interesting to supply these capabilities developed through simple methods for students, as viewed in 2.2.3, into this model as far as possible.

Finally, **Act** executes the action based on the recommendations given by the Analyse-Decision Making module. This module sends an error-back signal to the analyse-decision making block when a solution is not found in order to establish a control loop with other systems, which give another solution to provide estability to the system. In addition, it mantains an updated database with all the algorithms used by means of the learning capability.

Chapter 5

Conclusions and future work

Cognitive networks and the use of context have a vital role within the current development of autonomic communication. Much of the existing research focuses on both to achieve the desired self-capabilities in the way to reduce the human intervention and mantaining or even enhancing the performance and capacity of the autonomic systems.

These networks, initially developed to solve current network problems like the limited available spectrum and their inefficiency, are currently considered as the basis for exploiting the spectrum management functionalities.

The *Always Best Connected* scenario represents an easy and suitable example to use context in collaboration with the cognitive networks. The user can use the computer with no worries about the network selection. The system with the usage of context information such as location, application required, topologies, can selected the best option by itself.

The examined models from autonomic communication and autonomic computing represent the basis of the current research of context models. All of them have a similar structure and functions, but each one introduces some novelty. The contributions developed in robotics and computer science offer a different and valuable approach in the same direction. Simplicity, use of context, ability of learning and reconfigurability become essential characteristics in this field. In the same way, the influences developed in psychological and pedagogical fields can be useful as a inspiration to design more complex systems.

Context provides an "intelligent" interpretation of the gathered information and is useful in the formalization of the relationschips of the events and situations that have taken place. Accuracy and correctness are the main characteristics to define the quality of the context information, which helps in predictions and hypotheses permitting the recognition of elements based on a partial knowledge.

Moreover, the use of ontologies supplies interoperability, which is fundamental to communicate all the components of the system. It describes the qualitative context information elements and their interrelationships. Therefore, it is obvious the relation between both terms in order to make an efficient use of context information to equip current networks with self-management and service adapting properties.

Ambient Networks, SPICE, E2R and MobiLife are projects developed within the Sixth Framework Programme (FG6) of the European Union. All of them work in different areas (application, networks, middleware and radio network), and use different ontoligies and transport, but they all have in common context as a object of research. The main goal of these studies is to take advantage of context to benefit end-users.

The ability of learning in addition with reasoning and others similar, try to contribute "intelligence" and the ability to solve new problems and learn from the errors.

A further work can be done to include more complex context information from multiple users with different types of context with the aim to combine services and applications in a dynamic and heterogeneous network.

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