Autonomous Functionalities for Cognitive Radio

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Abstract: This paper provides an overview on the research activities in autonomous functionalities for cognitive radio and networks, carried out in FP7/E[3]-project. The identified main research areas within this topic include opportunistic spectrum access and autonomous self-x functionalities for communication nodes. Opportunistic spectrum access delineates innovative topics concerning distributed cooperative spectrum sensing, collaborative MAC algorithms, distributed radio resource management algorithms, and control mechanisms for the opportunistic spectrum access. In autonomous self-x functionalities the research covers cognitive device management, autonomous RAT and operator selection and self-x features for autonomous elements, including autonomous decision making functionalities for RAT protocol configuration, negotiation on missing RAT protocol components, and functionality for dynamic configuration of RAT protocol components.

Keywords: Cognitive radio, autonomous functionality, autonomous decision making, distributed algorithms.

1. Introduction

FP7 project E[3] (End-to-End-Efficiency) carries out research on the utilisation of cognitive radio and networking technologies in heterogeneous wireless environments. The research topics in the project cover system and functional architecture, solutions and algorithms for cognitive radio, technical enablers for cognitive radio, and associated business models and regulatory issues. In the solutions and algorithms part of the E[3] project, research work is carried out on two complementary areas: i) collaborative solutions and algorithms with centralized decision making mechanisms, and ii) solutions and algorithms with distributed, autonomous decision making mechanisms. This paper focuses on the latter area, providing an overview of research activities within the project on functionalities utilising autonomous decision making mechanisms.

There is a multitude of motivations for utilising autonomous functionalities. In heterogeneous wireless environments with multiple operators offering competing and complementing services in the same area, the complexity of centralised control

functionalities reaches unmanageable levels as the number of players increase. In contrast, autonomous solutions distribute the decision making complexity across the network nodes resulting in a management and control framework that scales nicely as the network grows.

Figure 1 describes the autonomous operating scenario leveraged in this paper. In this scenario, cognitive devices apply collaborative and cooperative mechanisms to autonomously measure, analyse, and make decisions. The associated autonomous functionalities include e.g. cognitive device management, autonomous protocol re-configuration, autonomous RAT selection, and opportunistic spectrum access.
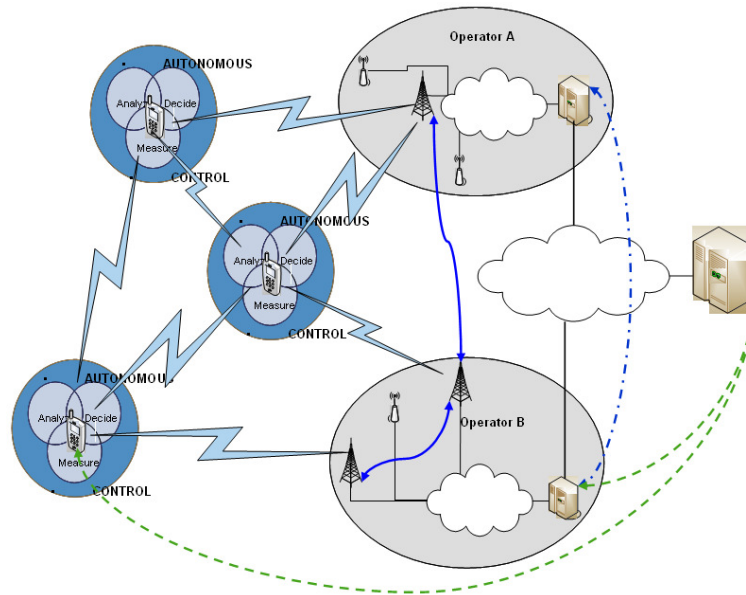

Figure 1 : Autonomous operation of nodes

In the rest of the paper, section 2 summarises the work on autonomous algorithms for opportunistic spectrum access. Section 3 provides an overview on the different autonomous functionalities utilising the self-x principles. Section 4 concludes the paper.

2. Opportunistic spectrum access

Advanced cognitive capabilities can improve spectrum utilisation by allowing (secondary) users to opportunistically access licensed and unlicensed spectrum bands. Spectrum sensing – a key enabling technology for opportunistic access – is necessary for detecting unused/under-used portions of the spectrum. Regarding autonomous functionalities in E^3, the focus is on cooperative spectrum sensing mechanisms, which distribute the sensing operation in frequency, time, and space dimensions between the participating nodes. Based on the measurements obtained from other cooperating nodes, each node can autonomously infer current spectrum utilisation. Distributed cooperative spectrum sensing schemes have several benefits over centralized solutions, including e.g. inherent measurement diversity, mitigation of the hidden node problem, energy efficiency (the amount of time and bandwidth a certain node needs to sense the spectrum can be limited) [1], [2], [3].

Coordinated access among secondary users to spectrum opportunities is a key issue to attain high efficiency, maintain fairness, and deliver QoS guarantees. The local availability of spectrum resources is one of the key reasons why distributed autonomous wireless networks can achieve higher spatial spectrum utilisation/reuse than currently deployed wireless systems. The distributed RRM has to cope with three time-varying stochastic variables, the radio channel, the user capacity demand, and the interference temperatures/spectrum opportunities. WP4 in E^3 aims to develop a general concept and

algorithm for RRM in autonomous self-x networks. A very rich R&D literature exists on channel allocation, transmission power control, and multi-channel MAC (Medium Access Control) in wireless networks in the OSA (Open Spectrum Access) context. Each approach proposed in the literature is valid for a specific set of scenario descriptors, a sample list of which is given below.

- Air-interface; i.e., (T/F/C)DMA, fixed/variable bands, half/full-duplex, omnidirectional/directional transmission, fixed/variable power control, etc.
- Number of radio transceivers per node. Single/multi-hop topology. Location information availability. Clock synchronisation.
- Protocol vs. physical interference model. Centralised vs. distributed control.

Strong emphasis is observed in more recent literature on autonomous and distributed operation. Particularly, it is assumed that the primary users (legacy systems) are oblivious to the opportunistic use of their licensed bands by secondary users. Examples of distributed mechanisms in the literature are fast-converging power control in physical interference model [4], proportionally-fair local-bargaining channel allocation in protocol interference model [5], and multi-channel, cognitive MAC protocols [6][7]. The majority of solutions proposed in the literature consider radio nodes with continuously backlogged buffers. Actual user demand, however, is inherently a random and time-varying process. Further, resource utilisation gains depend on whether or not the access mechanism can handle statistical multiplexing of the time-varying and random user demands. In other words, spectrum utilisation can be further improved if resource allocation and MAC among secondary users can be driven by the time-varying user traffic and QoS. An example to this approach can be found in [8].

A final note has to do with the agility of resource allocation and MAC mechanisms in future cognitive radio networks with opportunistic spectrum access. The approaches mentioned in the preceding paragraph are acceptable first-order solutions for the sharing of white spaces with long expected availabilities. However, these solutions may fail to converge fast enough to exploit white spaces with short availabilities. Of particular importance is the speed by which the secondary users evacuate spectrum upon primary user re-appearance. A sample solution can be found in [9].

3. Autonomous self-x operation of nodes

Figure 2 provides a summary on the different autonomous self-x functionalities covered by E^3. More specifically, cognitive device management, addressed in section 0, focuses on designing and developing management functionalities that will enable a wireless device to determine its configuration and behavior, in a reactive or proactive manner. In this context, autonomous decision making plays a key role to choose the most suitable reconfiguration action to be followed, in accordance with a set of decision and optimisation criteria. One of the particular decision making cases is the autonomic RAT and operator selection, covered in section 3.2. Finally, a natural consequence of the autonomous decisions will be the self-configuration of the protocol stack of mobile devices and the self-organisation of the different systems, which will be addressed in section 3.3.

3.1 Cognitive device management

The availability of a multitude of access technologies in evolving B3G/4G wireless systems will enable users to enjoy wireless services at any time, at any place. In order to truly enhance the experience of all users, including even technology agnostic ones, functionality is required, not only on the network but also on user-device side. The aim of cognitive device management is to provide the "always best connection" in a transparent manner, focusing more on requirements and preferences of individual users.
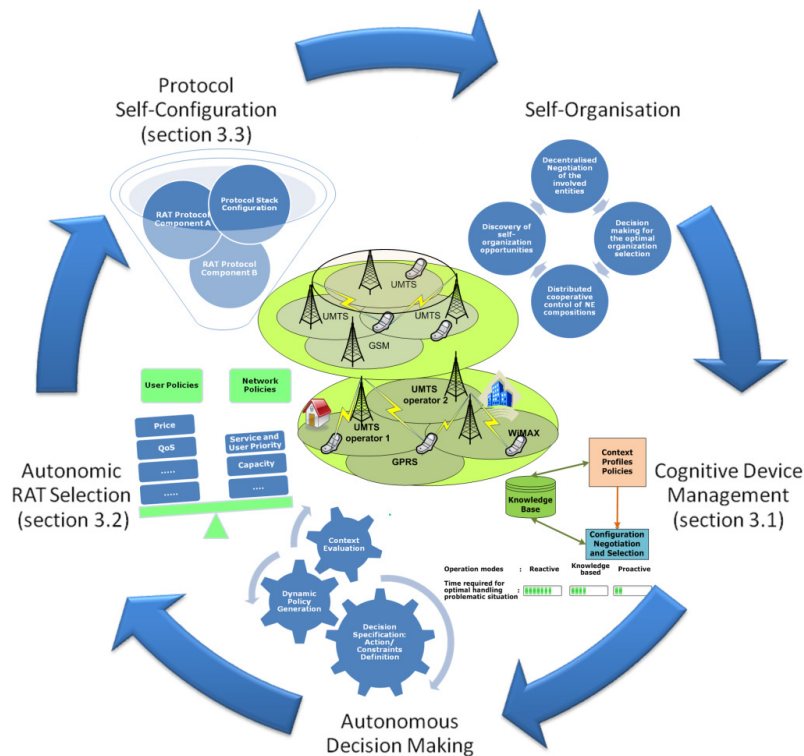
Figure 2 : Summary of autonomous self-x functionalities in E^3.

Cognitive devices should comprise capabilities for dynamically selecting and adapting their operation, taking into account user preferences and requirements, user device environment characteristics, policies, and experience, established through machine learning mechanisms. Mechanisms for the management of cognitive devices should augment devices with the following features:

- *Acquiring and learning profile information*, by obtaining data related to user behaviour, preferences, requirements and constraints as well as equipment capabilities [10]. Indicative information includes (i) the set of potential configurations (such as the RATs and the associated spectrum and power levels), (ii) the services that can be used and the QoS levels associated with them, (iii) the utility volume (i.e. user satisfaction) associated with the use of a service at a particular quality level, and (iv) the maximum price that the user is willing to pay to use certain services at specific QoS levels.
- *Acquiring and learning context information* [11],[12]. This includes mechanisms for the device to perceive its current status and the conditions in its present environment, as well as estimating the capabilities of configurations. Context information should include data about available access technologies and operators in a given area and their corresponding status (e.g. frequencies, available resources, coverage), information about the device status (e.g. coverage at the current location, power available), information about the status of other devices in the area (e.g. activity, ability to cooperate).
- *Acquiring and managing information on policies* of various entities (network operator, etc.) [13]. Certain policy specifies a set of rules that the user device must follow. The goal of policies is to refine the input provided in the profiles and the context. In case negotiations are realised, policies may also define a list of networks that can be negotiated with. Policies influence available services and respective QoS levels, as well as the available device configurations.

- *Selecting the optimal device configuration action(s)* taking into account current context, profiles, policies and knowledge [13]. This may be triggered either as a reaction to a situation currently encountered or in a proactive manner, by making use of experience obtained over time. This includes functionality for negotiations of the device with network entities regarding configuration policies. A significant aspect is the specification of learning functionality in the context of decision making. The aim is to build knowledge related to the decisions made in certain problematic situations so as to be able to measure the effectiveness of a solution applied and speed up the decision process.
- High level views of the Cognitive Device Management functionalities as well as of the corresponding prototype are depicted in Figure 3.
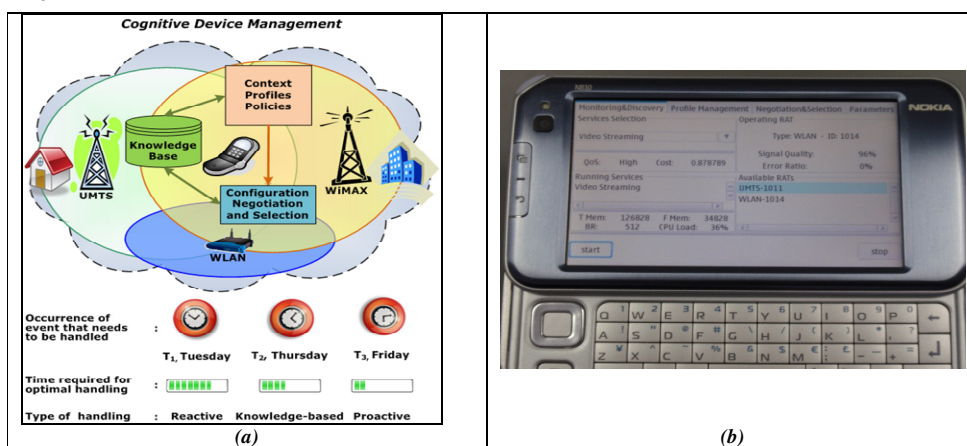-

Figure 3: (a) Overview of Cognitive Device Management mechanisms
(b) View of prototype implementation running on NOKIA 810

3.2 Autonomous radio access technology (RAT) and operator selection

Current wireless scenarios are characterized by a multiplicity of RATs, each having different protocol stacks and supporting applications and services with different QoS levels to be provided to mobile devices. To cope with this, Joint Radio Resource Management (JRRM) strategies consider the amount of resources in all RATs as a whole in order to assign the most suitable ones to each mobile device. Traditionally, these functions have been centralized because a central network node may have a more complete picture of the radio access status. However, a centralized implementation has drawbacks in terms of increased signalling load and transfer delay. Consequently, wireless technology evolution exhibits the trend towards decentralising these functions to radio access network edge nodes and even to the mobile devices. A decentralised RAT and operator selection executed at the mobile device involves a set of functional requirements covering the creation of awareness (i.e. how can the terminal acquire the needed information to take decisions) and the awareness networking (i.e. how the awareness information can be exchanged between nodes). The following functionalities are identified:
- *Acquisition of context information*: This includes the available RATs/operators in a given area and their status (e.g. frequencies, available resources, coverage), the mobile device status (e.g. coverage at the current location, power available, technology capabilities) and the status of other devices in the area (e.g. activity, ability to cooperate). Context information can be acquired either by the mobile device itself (e.g. by measurements) or through the interaction with other nodes based on the awareness networking functionality described later on.

- *Acquisition of user information*: This function obtains the user preferences in terms of the RATs and operators. This can be locally obtained from interaction with the user, who can configure the settings of network selection for different applications, as well as preferences with respect to the desired QoS.
- *Acquisition of policy information*: For an efficient operation, it is possible that the network can guide the autonomous access network selection by providing appropriate policies to mobile devices. In this case, this functionality will handle the derivation and management of these policies for the terminal.
- *Awareness networking*: This provides the means to exchange information between the different nodes, either between terminals or between terminals and base stations, giving support to the acquisition of context information functionality explained above (e.g. to obtain information about the RATs/operators available in other areas of the network that cannot be directly obtained by a terminal in its current position, and could for instance be advertised by other terminals that have passed through these other areas). This functionality could make use of radio enablers such as IEEE P1900 [14], the Cognitive Pilot Channel (CPC) [15] or the Cognitive Control Radio (CCR) [16] to enable communication exchange among terminals.
- *Distributed decision making for RAT selection and protocol configuration*: This functionality implements the specific algorithm to decide and select at the mobile device the access provider/access technology that better fits its service requirements and cost constraints. In accordance with this RAT selection strategy, the mobile device may have the need to reconfigure its protocol stack to operate with a new selected RAT.

In E^3 project novel solutions for autonomous RAT selection algorithms are proposed, covering the above functionalities. In particular, for services without stringent delay requirements a specific solution can be found in [17].

3.3 Self-x features for autonomous elements

The interworking of multiple RATs and the continuously growing user needs in the continuously evolving telecommunication environment pave the way towards new networking trends, including the reconfigurability notion and the autonomic networking concept. One of the objectives of such areas is the incorporation of adaptation capabilities in the protocol stack of mobile devices [18],[19]. The following high level required functionalities are derived for cognitive RAT protocol reconfiguration:
- *Distributed/autonomous decision making functionality for RAT protocol configuration*: Such functionality concerns the analysis of new requirements (network/mobile device context changes) and the specification of concrete reconfiguration actions evaluating policy rules and context data, e.g. selection of suitable RAT protocol configurations. [20]
- *Negotiation on missing RAT protocol component(s):* Such functionality concerns the selection of the most suitable RAT protocol components for two cases: the protocol stack bootstrap, and dynamic protocol adaptation following a change in the environment. The latter includes the selection of a new component that should replace an existing one following handover to a new RAT or increased service requirements.
- *Functionality for dynamic configuration of RAT protocol components*: This includes: intra-layer management functionality for a single RAT protocol layer, which is responsible for the realization of reconfiguration operations in a specific protocol layer including the control and coordination of the dynamic

binding and replacement of RAT protocol components; generic/cross-layer management functionality responsible for the overall control of the whole protocol stack operation.

The target of this work is to examine how the introduction of protocol self-configuration features in mobile devices affects the network side, considering the produced decision making requests. One of the key issues is the computation of the performance bounds of the system in terms of bottlenecks identification for the system computational resources. In this direction, a system model has been specified, which uses multiclass queuing networks to model the requests to the network as transactions between the system entities [21]. Specifically, we model a reconfigurable system as a distributed transactional system with two classes of mobile devices: reconfigurable and semi-autonomous; their difference lies on the support of decision making functionality (Figure 4). The outcome of this model is the derivation of global bounds for the asymptotic network response time per class of mobile devices versus the number and frequency (think time) of reconfiguration decision requests.
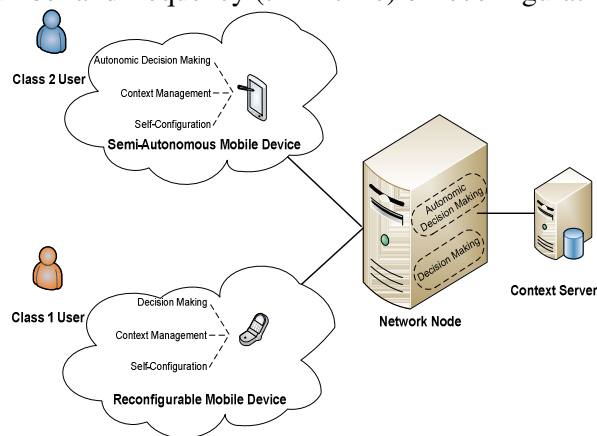

Figure 4 : System model for analysis of network overhead

4. Conclusions

This paper provided a high level overview of the research activities on autonomous functionalities for cognitive radio and networks carried out in FP7/E^3-project. The presented research topics highlight those functionalities where the benefits of utilising autonomous decision making mechanisms (instead of centralised decision making) are the most significant and concrete. Examples of further technical details of the associated work can be found e.g. in the following recent articles: collaborative spectrum sensing [1], [2], and [3], awareness networking facilitating autonomous, distributed decision making [16], cognitive device management functionalities [10]-[13], autonomous RAT selection algorithm for non-real time services [17] and self-x features for autonomous elements as regards self-configuration and autonomous decision making functionalities [18],[20]

Acknowledgment

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