Topology Control in Self-managed Wireless Networks

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Abstract. The vision for future telecommunication systems is considered as a representative example of a complex adaptive organization, where several elements, with various computational capabilities and network resources, are interconnected. The increased complexity and the continuously changing network environment make more intense the need for automation and for localized network management tasks. Self-management will allow the execution of advanced configuration actions, such as the change of the wireless network topology under various performance criteria. This paper focuses on the description of the principles and the architectural framework for the cognitive management of future communication systems, considering a complex radio access environment. This framework is used in order to present a solution on the autonomic topology control of future communication systems, where multi-hop links are established using the available relays stations, under the energy consumption constraint.

Keywords: self-management, wireless systems, cognition, topology control, relays, energy optimization.

1 Introduction

Current control and management approaches of network systems are mainly centralized, and despite their simplicity, they are resulting in many cases in bottleneck or failure points, yielding for human intervention. There is a need for new ways to control communication systems, according to new management schemes and networking techniques without neglecting the advantages of current Internet. The specification of management schemes that will enable the adaptation of network's behaviour (i.e., self-management) following de-centralized and self-organized approaches is a major challenge. Furthermore, the introduction of cognition to next generation network elements is useful for increasing the system automation by providing them the self-management capability, as well as for the improvement of their performance.

Topology adaptation at the wireless edge is considered as one of the research challenges for next generation communication systems. The (self)-management of the wireless networks topology is a key operational capability for network operators, taking into account especially dense urban network environments, consisting of various base stations, relay stations and mobile devices of high mobility. In this paper the network topology is re-organized in an automatic and distributed way for the reduction of the

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energy consumption in the user equipment side, considering also the total energy consumption of the corresponding network area. The enablers that could be used in order to develop cognition and self-management capabilities are presented through the proposed Distributed Cognitive cycle for System & Network Management (DC-SNM).

The remainder of this paper is organized as follows: the related work for cognitive and self-organizing systems, which are fundamental pillars of self-managed systems, is presented in section 2. The principles and the framework for the DC-SNM are described in section 3. The process for the self-managed control of the wireless network topology for the energy consumption improvement is outlined in section 4. Finally, future research directives and conclusion are discussed in section 5.

2 Cognitive Systems and Self-organization

Cognitive systems, autonomic communications systems as well as self-organizing systems are interrelated scientific areas that are briefly surveyed in this section so as to identify functional requirements, recent advances, and proposed architectures, which attempt to establish the cognitive and adaptive behavior of computing and communication systems.

The fundamental features of an artificial cognitive system are embodiment, anticipation, adaptation, motivation, reasoning, and autonomy; these features are needed, since such architecture comprises a continue process of perception and action. Several research initiatives took place recently trying to introduce cognition in communication systems. A thorough review of artificial cognitive systems and cognitive architectures is provided by Cliff [1], D. Vernon et al. [2], and P. Langley et al. [3]. These architectures are classified into congitivist, emergent and hybrid models, taking into account their viewpoint on cognition and the different phases in cognitive science evolution. SOAR [4] and ACT-R [5], as well as SASE architecture [6] have inspired the present paper. According to Thomas et al. [7] a cognitive network bears a cognitive process that can perceive current network conditions, and then plan, decide, and act on those conditions [8]. The cognitive network can learn from these adaptations and use them to make future decisions. A framework is proposed in [9] to introduce cognition in the whole network taking into account end-to-end goals, and utilizing Software Adaptable Networks (SAN). Thomas et al. attempt to progress Mitola cognitive radio concept [10] by covering all aspects of communication networks, both wired and wireless/mobile. The introduction of cognitive capabilities in a communication system will continuously increase its intelligence, by viewing a problem in more than one ways, and by evolving its problem-solving process. In addition, the capitalization of cognition capabilities renders the system autonomous.

Apart from cognition, self-organization is another key feature of the next generation self-managed communication systems, which can be viewed as a capability that complements adaptive behavior of communication systems and contributes towards their autonomy. Self-organized systems have the capability to change their organization without any external or central dedicated control entity. Self-organization goes beyond mere distribution and may not be based on global state information [11], [12]. Multiple individual entities interact in a distributed, collaborative peer-to-peer fashion (at a microscopic level) on a common global objective, which leads to sophisticated organization and defines the behavior of the global system (at a macroscopic level), thus establishing emergent properties [13]. Self-organized systems are flexible, scalable, adaptive, robust to failures, and more reliable, since they degrade softly rather than break down suddenly. These features are necessary for future communications systems that operate in high dynamic and complex environments, considering the frequency of potential changes in their structure. Mobile Ad Hoc Networks (MANETs) and Peer-to-Peer (P2P) networks are examples of dynamic network environments, where self-organization has merit. Various algorithms and techniques have tried to solve networking issues for self-organized systems such as optimal path selection and service discovery [14].

As it is obvious from the above analysis various architectures and mechanisms for the introduction of cognitive and self-organizing capabilities have been proposed in several research fields. Thereinafter, it is necessary to transfer and adapt cognition and self-organization paradigms from other sciences or from nature to realistic use cases in communication systems, taking into account the specific characteristics of communication networks.

3 Distributed Cognitive Cycle for Network Systems Management

Future network systems design principles are based on high autonomy of network elements in order to allow distributed management, fast decisions, and continuous local optimization. The Generic Cognitive Cycle model, as it is depicted in Figure 1, is envisaged to be in the heart of Future Internet Elements (e.g., access points, base stations) and it leads to their autonomy [15], [16]. A Future Internet Element may be a network element (e.g., base station, access point, and mobile device), a network manager, or any software element that lies at the service layer. Future Internet Elements, with cognition embedded, will have a process for monitoring and perceiving network equipment's internal state and environmental conditions, and then planning, deciding and adapting (self-reconfiguring) on these conditions. Such an element is able to learn from these adaptations (reconfigurations) and use them for future decision making, while taking into account end-to-end goals.

The three distinct phases of the Generic Cognitive Cycle Model are the following:

- Monitoring process involves gathering of information about the environment and the internal state of a Future Internet Element. Moreover, the Monitoring process receives, internally or externally, information about the effectiveness of the Execution process that took place, after the last decision.
- Decision Making process includes the problem solving techniques for reconfiguration and adaptation, utilizing the developed knowledge model and situation awareness. The Decision Making supports the optimal configuration of each element, considering its hypostasis and the organization level that it belongs. Decision making mechanism identifies alternatives for adaptation or optimization and chooses the best one, based on situation assessment, understanding of the surrounding context, and the preferences of the element. After decision making, the execution process undertakes to apply the decision that will change the behaviour of the element.

- Execution process involves (self-) reconfiguration, software-component replacement or re-organization and optimisation actions.

The self-awareness of each network node is instantiated in the Knowledge Repository, which stores the necessary models that each network needs in order to describe the acquired environment, through the relative sensors and the interaction with other elements, enabling knowledge sharing. Knowledge is maintained utilizing three correlated types of memories: The semantic memory, the episodic memory and the procedural. Models about the environment, the tasks that each element supports and association of solutions at specific problems are examples of models that are available in the knowledge repository, utilizing the above memories.

Moreover the feedback (or appraisal) functionality helps the element to evaluate the result of its decision, based on problem solving experience. It assesses the result and the efficiency of an adaptation action and it is considered as as a complementary method of learning.

Fig. 1. Generic cognitive cycle model

A cognitive node recognizes events, and situations, and classifies them to known categories. Events recognition implies the ability to sense/monitor, to perceive objects and to interpret the environmental situation. Decision making models which solve arising problems and optimize the operation of cognitive nodes are necessary, taking into account the allowable actions and the available alternatives. Furthermore, planning and anticipation are required and are important features of an intelligent system. A plan specifies a future state description and the steps that should take place in order to achieve an identified goal or state. Anticipation mechanisms increase the intelligence of a network node, by predicting future situations as a result of certain actions on current status and facilitate problem solving because the system has the necessary time to organize and plan its actions. Moreover, reasoning methods (e.g., deduction, induction, abduction) enable a cognitive node to combine current knowledge so as to

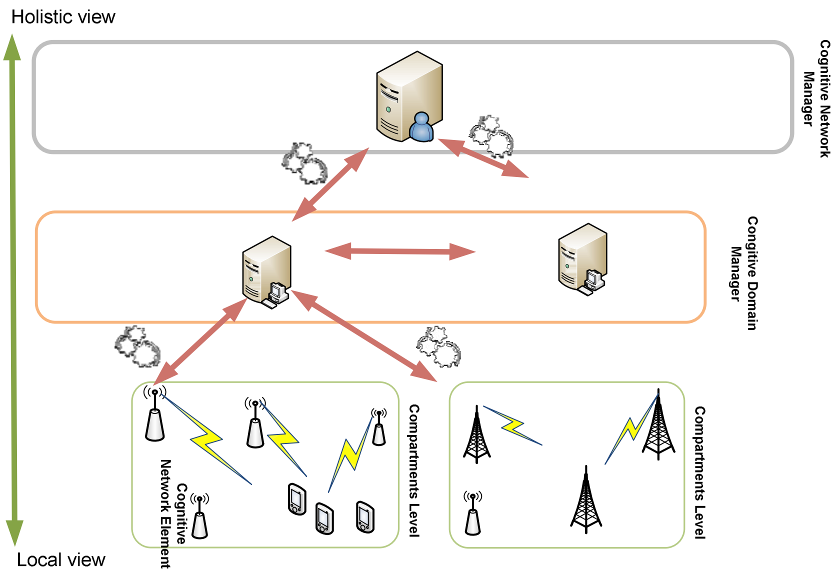

Fig. 2. Hierarchical distribution of the cognitive cycles

produce new knowledge or to draw conclusions. Learning techniques allow a cognitive node to acquire, manipulate, relate, and classify knowledge.

A Distributed Cognitive cycle for System & Network Management (DC-SNM) will facilitate the promotion of distributed/decentralised management over a hierarchical distribution of management and (re)configuration making levels to (a) (autonomic) network elements, then (b) to network domain types and (c) up to the whole network system (Figure 2). Hence, this will set the scene for one of the major design goals, which is high autonomy of network elements with cognitive capabilities aimed at fast localised (re)configuration actions and decision making. Such a distribution brings about the intriguing issue of orchestrating the cognitive cycles (M-D-E) of Monitoring, Decision Making and Executions at higher levels of the management distribution.

The logic behind the introduction of the DC-SNM is to serve as the conceptual template of introducing the Future Internet mechanisms advances in the overall system as well as a network management instrument. Hence, it is a formulated tool for addressing the complexity and capabilities of networks, services and management elements and their roles as providers of new paradigms that are emerging in the evolution of needs and mechanisms for Future Internet, service and network infrastructures in general. The Distributed Cognitive cycle for System & Network Management can be used as the guiding framework for constricting the architectural and functional features in relevant deployment scenarios.

The decomposition of network management into responsibility areas will provide the principle on which universal management architecture will be developed having as a main goal the efficient handling of complexity towards Future Internet environments. Such a decomposition combined with the introduction of cognitive functionalities at all layers will allow decisions and configuration at shorter time-scales. Each element at the identified layers has embedded cognitive cycle functionalities and also the ability to manage itself and make local decisions. For an efficient and scalable network management, where various stakeholders participate, a distributed approach is adopted. Dynamic network (re)-configuration in many cases is based on cooperative decision of various Future Internet Elements and distributed network management service components. Hints and requests/recommendations are exchanged among the layers, in order to indicate a new situation or an action for execution. The automated and dynamic incorporation of various layers requirements (e.g., SLAs) into the management aspects provides also novel features to network management capabilities. Moreover, the resolution of conflicting requests will be an issue of situation awareness and elements' domain policy prioritisation.

4 Wireless Access Systems Topology Control

Next generation wireless networks should have the capability to exploit the different advantages of cellular networks and ad hoc networks. Various types of hybrid wireless network using multi-hop approaches could be adopted in order to enrich configuration options and optimize various performance parameters. The topology of current communication systems is mainly characterized as "star topology", while future communication systems will often use relay stations (RS) with intelligent resource scheduling and cooperative transmission (i.e. not analog transmitters). Relay stations will be used in order to serve the needs of the volatile environment of future Internet wireless networks, because of user equipments' high mobility and various traffic demands. Relaying is considered as the technique to improve the coverage of high data rates, to group mobility, to deploy temporary network infrastructures, and/or to provide coverage in new areas.

Relay technologies have been recently introduced in the standardization process of both WiMAX (IEEE 801.16j [17]) and 3GPP LTE-advanced mobile systems [18]. In both cases, there are various types of relay technologies according to their implementation features. For instance, the relay transmission scheme: a) amplify and forward, b) selective decode and forward, or c) demodulation and forward that is selected affects the delay, which is introduced in the transmission and whether error propagations through the RS is avoided or not. Furthermore, with respect to the knowledge in the mobile device (MD), relays can be classified into transparent or non-transparent. It should be noted that the type of the established relay affects in many cases the performance improvement that is achieved through the activated relay station.

The minimization of the energy consumption on the MD side is another key problem that could be addressed though relay stations and which is studied in this paper. The energy consumption is a very important requirement for the end user and for the network operators in general. The distributed Cognitive Cycle for Network Systems Management vision, which has been presented in section 3, is used in order to solve locally and in a distributed way (through the involved network devices) the optimization problem of energy consumption. More specifically the M-D-E cycle is placed per base station (BS) and undertakes in collaboration with other neighboring M-D-Es that exist in the same area, to solve the energy consumption problem, which is presented and discussed below.

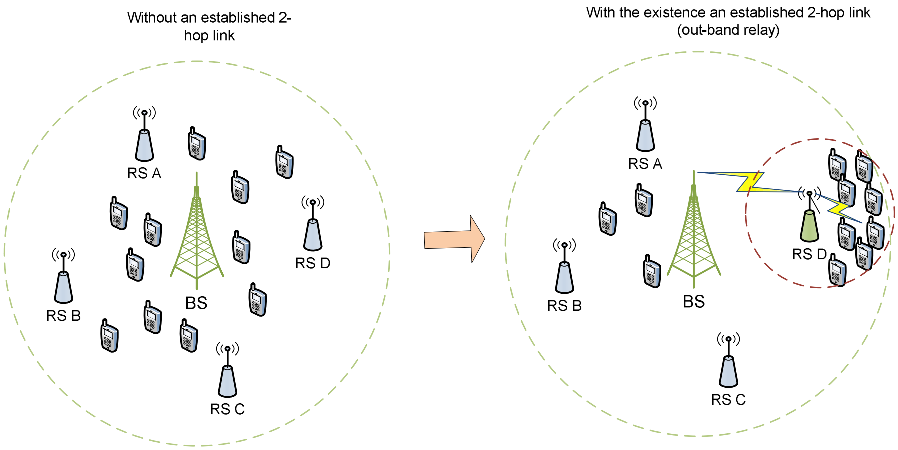

Fig. 3. Sample wireless network topology

The base station deduces whether it is efficient to activate a relay station of a specific geographic area, as it is depicted in Figure 3, where a group of mobile devices will be transferred so as to reduce energy consumption of the latter, without on the other hand increasing the total energy consumption (including the base stations) over a specified threshold. We suppose that the RS uses an out-of-band relaying, which means that for the communication between the base station and the relay station, a different frequency is used compared to the relay station and mobile stations link. For the calculation of the energy consumption (EC) two parameters are taken into account for this use case: a) the distance between two nodes (MD, RS, BS), and b) the packet error rate (PER). The threshold is defined by the network operator, while the total energy consumption includes:

- Uplink (UL) transmissions: from the user equipment to the relay station and from the relay station to the user equipment
- Downlink (DL) transmissions: from the base station to the relay station and from the last to the user equipment.

The goal of the base station is to identify the specific opportunity to minimize the energy consumption of the user equipment (Uplink). The existence of a RS will provide to the user equipment the capability to transmit its data packet to a shorter distance, thus consuming less energy resources ($EC(UL_{MD\rightarrow RS})$). On the other hand, the existence of the relay (2 hops) will increase the consumed energy consumption (EC) of the network operator (BS, RS) for both the UL ($EC_{Relay-enabled}(UL)$) and the DL ($EC_{Relay-enabled}(DL)$). The increase of the DL energy consumption is proportional to the selected transmission range of the RS ($EC(DL_{RS})$). While, the increase of the energy consumption of the UL ($EC_{Relay-enabled}(UL)$ - $EC_{one-hop}(UL)$) is proportional to the increase of the MD-BS distance (2 hops) after the establishment of the relay. $EC_{one-hop}(UL)$

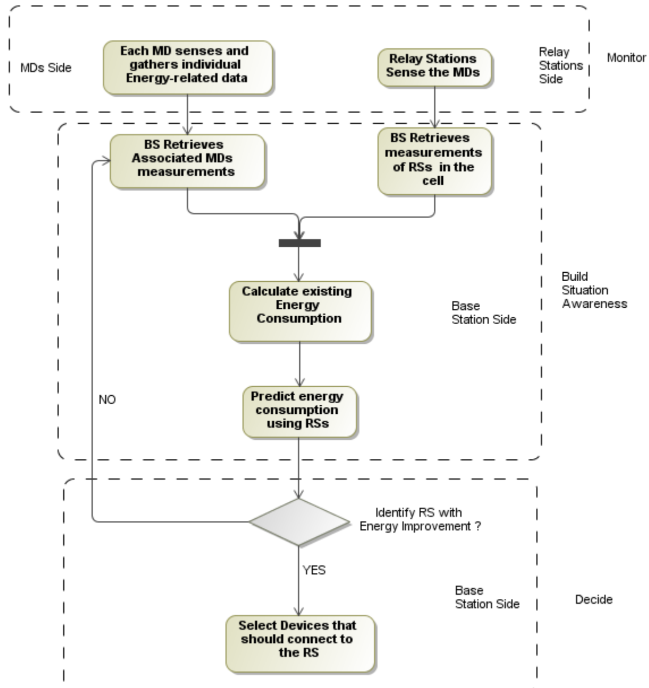

Fig. 4. Activity Diagram for the Local Topology Control

denotes the energy consumption of the UL between the MD and the BS without the usage of the relay.

Thus, the base station attempts periodically to identify if the usage of a relay station in the cell that the respective BS exists, and consequently the creation of a hop at (2-least) structure, will solve the following problem:

$$\left(\sum_{i=1}^{n}(\mathrm{EC}_{Relay-enabled}(\mathrm{UL})\ \text{-}\ \mathrm{EC}_{one-hop}(\mathrm{UL}))+\mathrm{EC}(\mathrm{DL}_{RS})\right)<\left(\sum_{i=1}^{n}(\mathrm{EC}_{one-hop}(\mathrm{UL})-\mathrm{EC}(\mathrm{UL}_{MD\to RS}))+k\right) \quad (1)$$

where n is the number of MDs that are in the transmission range of the RS and k is the energy consumption threshold specified by the operator. This threshold is defined, by taking into consideration other benefits that the network operator will have through the activation of the relay e.g., interference reduction especially in the case of an out-of-band relaying scheme. Consequently, n is a parameter that will allow the base station that is solving the above problem, to identify the optimal solution, considering the parameter k, which is provided by the network operator.

Figure 4 presents briefly the process for the solution of the topology control for the sake of energy consumption minimization, based on the distributed M-D-E cycle. The monitoring phase takes places at the MDs (distance, PER) and RSs (sensed MDs) side, using mainly the data link layer sensing capabilities. The data are periodically transmitted to the BS (UL/DL utilization, PER), which undertakes the gathering of the measurements and proceeds to the development of its situation awareness through the calculation of the existing energy consumption levels. The BS having built the topology graph, attempts to predict using inequation (1) whether the activation of a RS (e.g., RS D, Figure 3) will decrease the energy consumption of a group of mobile devices, without increasing excessively the network side energy consumption. In the network side there is a continuous energy supply juxtaposed to the restricted energy sources (i.e. battery) of a mobile device. After the identification of the RS that satisfies inequation (1), the BS undertakes to inform the set of mobile devices that will form the 2 hops link to associate to the respective RS. The above-mentioned continuous process helps the network operators to identify optimization opportunities for their network elements (BSs, MDs), in a localized and self-organized manner.

5 Conclusions

In this paper, we proposed the exploitation of the self-management concepts through an architectural framework in order to support cognitive adaptive behavior of next generation communication system. This framework enables the development of nodes intelligence, as well as the balance between proactive and reactive adaptive behavior on the management tasks. The orchestration of the cognitive cycles as well as the distribution of their phases (e.g., monitoring) is an essential feature for realistic implementation of self-managing network systems. A network optimization use case is discussed for the energy consumption, where the available relay stations are used, and the relative signaling for the adaptation of the network topology is presented. Our ongoing work includes performance evaluation of the proposed architecture and algorithmic scheme, using specific scenarios and use cases.

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