Routing in Cognitive Wireless Mesh Networks
An Intelligent Framework

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Abstract: Wireless Networks are limited in energy and resources, are subject to development constraints. The difficulties are such as the increasing RF spectrum saturation and efficient path discovery. The Cognitive Wireless Networks, leaning on a form communication model, develop new strategies to mitigate the inefficient use of the spectrum. The first application of the concept of *cognitivity* to communications was focused on exploiting the dynamics in spectrum utilization (cognitive radio), nevertheless network-wide deployment of such concepts is foreseen in the framework of the "cognitive networks", where the cognitive process will be employed to support end-to-end network-wide goals such as QoS. This paper presents a state-of-art of cognitive networks and proposes a framework, architecture for cognitive networks. This paper will also discuss mechanisms for self-adaptation, learning and evolutionary functionalities to support users/applications end-to-end goals.

1 INTRODUCTION

All the wireless networks use radio waves to connect devices like laptops, sensors. Nowadays we can see that these devices have become ubiquitous in nature. There is a seamless integration with the existing infrastructure.

The ubiquitous computing is one of the most important trends in networks with a 40-fold increase between 2010 and 2015(CISCO Inc, 2011). The applications include security, surveillance, monitoring, health, vehicular networks are few to name. The increased demand for wireless communication has a big challenge for efficient spectrum utilization. We also understand that due to increased demand of devices in 2.4 GHz range, the unlicensed spectrum bands are becoming overcrowded (Akyildiz et al., 2006, CISCO, 2011). To address these challenges in wireless networks a new technique called 'Cognitive Radio' (CR) (Mitola III, 2000, Akyildiz et al., 2006, Thomas et al., 2005). CR provides an opportunistic access mechanism to the spectrum using the concept of cooperation and context awareness. The spectrum sensing and cooperation between devices allow for better utilization of spectrums. The CR has three main components as shown in figure 1.

Cognitive	Collaboration	Learning

Figure 1: Components of Cognitive Radio.

The first component cognitive devices has capacity in hardware or Software Defined Radio (SDR).The collaboration component interacts among terminals while as learning component has the ability to learn about the pattern and behaviour of spectrum utilization.

Indeed, many scenarios were proposed, focused on accessing the spectrum using opportunistic techniques (Akyildiz et al., 2006, Wang et al., 2011). However, the possibilities offered by implementing the cognitive process within a communication network go far beyond improved spectrum utilization, as cognitive network (CN) technology can represent a suitable technology to support user and application QoS requirements. Thomas et al., (Akyildiz et al., 2006, Gunawardena and Zhuang, 2011) defines a cognitive network as a network with a cognitive process that can perceive current network conditions, and then plan, decide and act on the basis of such conditions.

The CN is not a radio network but data network that makes use of various disciplines of computer science like knowledge representation, machine

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learning and network management to solve some problems current networks are faced with. The CN covers all the layers of the OSI model while CR covers layer 1 and 2 only (Mitola, 2000).

The network can learn from these adaptations and use them to make future decisions, while taking into account end-to-end goals. The end-to-end scope is extremely important and distinguishes cognitive communications from cognitive networks. Indeed, there are two levels of cognitivity: at the node level and at the network level. The end-to-end scope refers to the collective decision taken by the whole network to achieve the stated complex goals. Such end-to-end goals represent the desirable state and will be reached after a specific set of actions, which are far too complex to achieve using current networking solutions.

A CN should be able to decompose the overall goals into sub-goals and as necessary identify further dependencies between these sub-goals as the main benefit of the cognitive learning process.

Starting from the definition, the problem of designing cognitive networks can then be considered as a complex, multi-constraint and multi-criterion optimization problem where a multi-objective optimization approach should be implemented.

Guaranteeing quality of service (QoS) in communication networks, particularly in cognitive mesh networks, represents a typical multi-objective problem involving simultaneous optimization of the cost of the communications in the network and various performance criteria such as: throughput, average delay of the network, etc. The optimization of one or more of such metrics is the main objective of design in most cases, in order to make the network efficient and possibly adaptable to different operating conditions.

In this paper, we define a framework for the design of Cognitive Wireless Mesh Networks (CWMN), which implements and instantiates the concepts of CN in a specific scenario where self-adaptation is a key feature. The goal of such networks is to foster self-adaptation and to extend it beyond "simple" topology or resource management in order to support end-to-end goals by exploiting conceptual similarities with biological systems.

The structure of the paper is as such: Section 2 introduces the CWMN reference model and related work on the topic, while Section 3 discusses the proposed architecture in terms of main modules and functionalities required. Section 4 concludes the paper with final remarks.

2 CWMN REFERENCE MODEL

Wireless mesh networks are attracting a great amount of attention from networking researchers as a promising technology for the next generation access infrastructure, especially due to their scalability and self-organizing features (Akyildiz et al., 2005).

A wireless mesh network (WMN) is a mesh network that is built using wireless access points (AP) installed at each network user's location. Every node in the network also acts as a provider to forward data to the next node. The networking infrastructure is decentralized and simplified. Each node needs in WMN only to transmit the data to the next node as shown in figure 2.

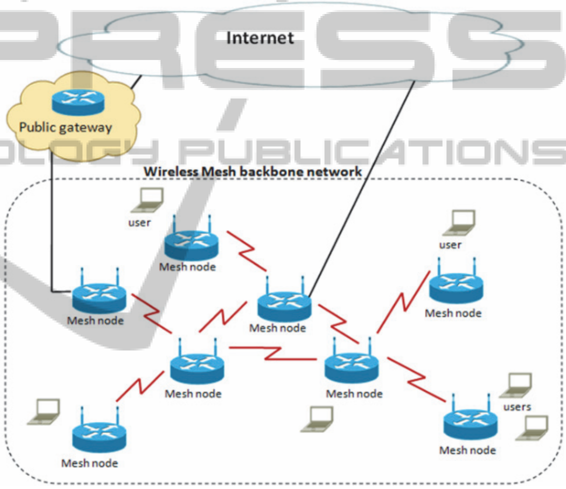

Figure 2: Wireless Mesh Network.

However, due to their distributed nature and heterogeneity of access technologies, QoS provisioning, and in general traffic engineering, represents a challenging issue, involving several functionalities at different layers of the protocols stack: routing at layer 3, resource allocation and reservation at layers 2&3, etc. In a cognitive network approach, QoS should be granted by self-adaptation, flexibility and situation-awareness of network elements.

As a consequence, the characteristics of CNs clearly represent desirable features on which to implement completely autonomous and self-adaptable wireless mesh networks.

The following paragraphs introduce the concept of Cognitive Wireless Mesh Network as a Wireless Mesh Network gaining biologically-inspired features from the Cognitive Network paradigm, with the aim of bringing the capability of the former to the next level by introducing the possibility of autonomously addressing end-to-end requirements and constraints.

In such a dynamic environment, two requirements should be taken into consideration for network control: scalability and mobility, as the network should be aware of nodes joining and leaving the system at any time and of their impact on the performance and other operating parameters of the network.

Such a lively scenario has significant similarities with biological systems or colonies, and as a consequence biologically-inspired approaches can be considered as promising references due to the fact that they are highly capable of self-adaptation and especially evolution, even though relatively slow at adapting to the changes in the environment.

Adding cognition to the existing WMN infrastructure will bring about many benefits. In order to pursue this idea, the paper proposes a framework to support the design, implementation of CWMN based on ideas such as evolutionary programming in bio-nets and multi-agents and actually starts to bridge the gap between conceptual similarity and actual design.

The biologically inspired techniques in information technology is not a new, many attempts have been concentrated in the area of optimization (Yu et al., 2010). However we can learn considerable lessons from biological systems and we have mainly to concentrate on the adaptability, scalability, self-organizational and robustness properties of such systems. Studying the symbiotic nature of bio-systems can result in obtaining a beneficial understanding on the behaviour of distributed systems. Many key factors may be observed in bio-systems like self-organizational behaviour which can be considered as the most important property describing systems consisting of autonomous entities (ants, bees, etc.). These systems tend to group together into certain structures very similar to biological systems where overall state of the system depends on individual behaviours and its collection. In general, four basic principles can be seen in the self-organizational property of bio-systems which have to be introduced in our proposed architecture.

First, positive feedback involves reinforcement to enable the system to evolve, and to promote the creation. Also, positive feedback behaves as amplifier for a desired outcome, whereby negative feedback is to influence from previous adaptations which were not successful.

Second, bio-inspired systems, in general, do not rely on any global control unit, but operate in an entirely autonomous and distributed way. Whereby the individual units acquires the information, processes and stores locally. However, in order to generate a self-organized structure, entities need to interchange knowledge with each other; either by direct or indirect interactions among them. Also, self-organized structures relies on randomness and fluctuation to enable the discovery of new solutions and to boost the resilience and the stability of the system.

Third, self-organization is also seen in swarm cognition. In biological systems, the intelligent and well-organized behaviour of insects can often be observed. For instance, ants solve complex tasks, like nest-building or food-collection, by delegating simple tasks to each other. In such emergent systems, it is the collective work of all single activities that determines the outcome and not the individual work. Such a behaviour is usually referred to as swarm cognition (Yu et al., 2010).The collaboration of insect societies is based on a process in which a group of workers is assigned specialized tasks in parallel in order to increase the efficiency of the swarm(Yu et al., 2010). All insect types have a division of labour which can be seen in its 'organizational structure' that consists of workers of different reproductive castes and layers. In Ants colony, the insect is not aware of the global conditions but gains the input only by interactions with other members of the species that are locally close within the rank in the 'structure'. This process may occur either by direct contact or indirect interaction. Direct contact can be chemical or visual while in the indirect interaction, one entity influences the environment while another responds to that change later on. For instance, Ants communicate with each other using pheromones that other ants follow, thus, reinforcing changed pattern. This mechanism of indirect coordination is called stigmergy.

Summarizing, we propose to build a framework for self-organizing cognitive wireless mesh networks inspired by the above observations.

3 PROPOSED ARCHITECTURE

The network consists of mesh routers, mesh clients, WiFi, Sensors, cellular network, conventional clients and internet as shown in figure 1. This presents the typical topology of a hierarchical Wireless Mesh Network.

The proposed architecture aims at providing global control of the topology using a distributed control scheme, where nodes are hierarchically organized in groups or clusters. In our proposed framework, the group formation and cluster interconnection is performed in a distributed and dynamic way. Assuming that at boot time, each node receives a unique identifier, the election of the head (H) of the cluster is performed. This process could be performed by exploiting group formation algorithms available in the literature for ad hoc networks, such as (Lin and Gerla, 1997) or by identifying specific algorithms for mesh networks (i.e. to exploit higher capacity of mesh routers). The choice of a specific clustering algorithm is out of the scope of the paper.

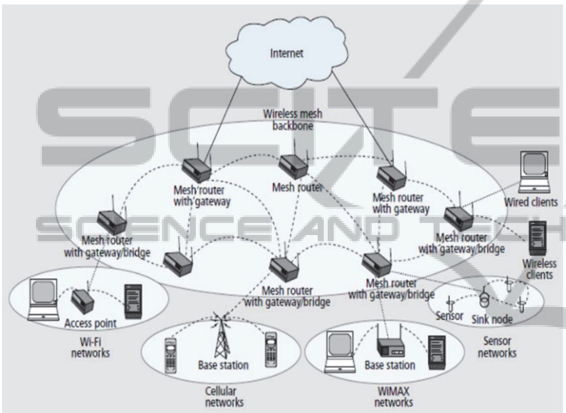

Figure 3: Hierarchical WSN (Akyildiz et al., 2005).

In this framework, cognitive nodes perform local adaptation, and such behaviour should be coordinated and optimized to better maintain a desired global state and achieve end-to-end QoS guarantees.

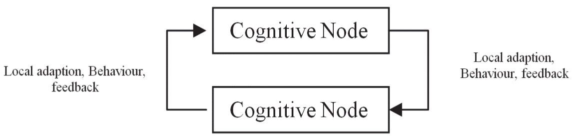

Figure 4: Cognitive Node.

Each node receives local input from the surrounding nodes and provides information about its current capabilities. By using such information, the nodes should organize themselves into a cooperative system.

The proposed approach involves a reformulation of the end-to-end QoS provisioning problem into a distributed artificial intelligence problem, in which cognitive mesh nodes coordinate parameters settings to maintain the desired goals.

3.1 Problem Statement

The nodes are cognitive, i.e. able to sense their environment and act intelligently and cooperatively to achieve a desired global behaviour. More specifically, nodes can learn to organize themselves in clusters to increase overall throughput and reduce the signalling overhead.

In this framework, the end-to-end QoS provisioning problem can be translated into a distributed artificial intelligence problem, where each cognitive node is an agent in a multi-agent system. Nodes interact with each other by competing for resources and also by coordinating the access to the resources to reach a satisfactory state, which is continually updated. This behaviour represents the design objective of cognitive networks, i.e. cognitive nodes are always coordinating and optimizing towards an ‘unknown’ global optimal state which does not exist in reality since it is nothing but an optimal state in a time *t* and for a given topology due to the dynamicity of the topology. Each action taken by a node is local in nature, and may not produce any noticeable benefit to the node itself. Collectively, however, the local actions can improve the global performance of the system.

For example, yielding a resource to a node which has to deliver urgent (high priority) traffic does not produce any local benefit to a node, but it does increase the overall throughput.

Ensuring global QoS provisioning can be seen from different points of views: at the node level and network-wide. The network aims at providing QoS while maximizing the resource utilization, whereas nodes’ goal is to maintain high throughput for packets waiting in its queues.

Indeed, the global performance of the network that should be maximized can be defined as a function of several parameters:

$$P_{global}= f\,(P_1, P_2, \ldots Pi) \qquad (1)$$

Approaches available in the literature aim mainly at providing the optimal (static) solution given specific constraints on network setup and complete “a-priori” knowledge of traffic characteristics and requirements, or at decomposing the problem within uniform independent domains (e.g. DiffServ domains). On the contrary, the main goal of the proposed Cognitive Wireless Mesh Network is to perform distributed optimization of the performance functional while continuously adapting to changing characteristics of the network and traffic.

3.2 The Proposed Approach

On the basis of the above discussion, the CWMN can be considered as an evolving autonomous system that aims at reaching the optimal status, which is represented by maximization of function P_{global}. The network will be dynamically partitioned into clusters, whose heads (H) will be able to interact to exchange and build global knowledge.

As a consequence, awareness of global end-to-end goals will be provided by cluster head nodes through inter-cluster signalling, while local optimization actions will be performed through intra-cluster interaction.

3.3 Modules and Functionalities

- *Input Goals :* Parameter to optimize
- *Routing Engine :* distributed optimization algorithm
- *QoS Engine :* To guarantee QoS Parameters
- *Reasoning and Learning Engine : For best actions*
- *Knowledgebase: For Best decisions*

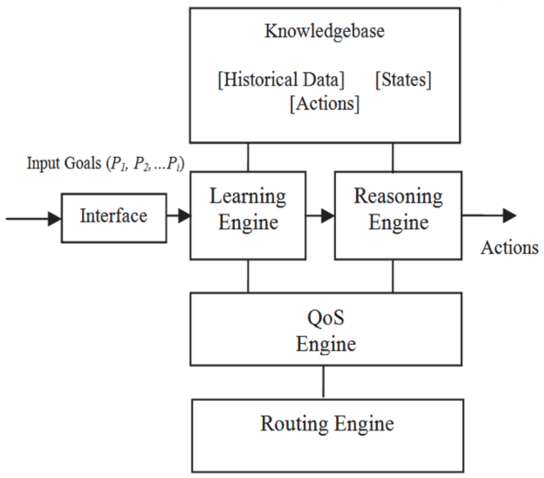

Figure 5: Proposed framework.

The proposed framework has input a goal that is described using a set of input parameters (P_1, P_2, P_3...P_i). This is the global parameters. The architecture has learning and reasoning engine to deduce best decisions about the routing.

The knowledge based is the collection of historical data, states and actions that has been taken in the past. The historical data, states and action help in taking right decisions. In order to guarantee the quality we have a QoS engine that ensures quality during end-to-end transmission.

The routing decisions and path are collectively computed based on the input parameters from different components of the proposed architecture like knowledge base, learning engine, reasoning engine etc.

4 CONCLUSIONS

In this paper we have discussed that increased demand for wireless communication which has a big challenge for efficient spectrum utilization. To address these challenges in wireless network a new technique called Cognitive Radio (CR) (Mitola III, 2000, Akyildiz et al., 2006, Thomas et al., 2005) has been discussed in many literatures. We also understand that CR provides an opportunistic access mechanism to the spectrum using concept of cooperation and context awareness. Since Wireless Networks are limited in energy and resources, this makes them subject to development constraints. We have presented an exhaustive state-of-art of cognitive networks and proposed a framework, architecture for cognitive networks. The proposed architecture has learning and reasoning engine to deduce best decisions about the routing. We also proposed a QoS engine to ensure quality during end-to-end transmission. As a future work, we will simulate the proposed architecture to demonstrate the effectiveness.

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