Cognitive Optical Networks Architectures

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***Abstract*—This paper presents a definition proposal for cognitive optical network, the main features of two cognitive optical network architectures that are currently ongoing, some considerations about them and the standardization process. Moreover, it presents a new cognitive optical network architecture proposal, based on the concept suggested, and its main features. This new proposal includes interactions between IP layer, MAC layer, optical physical layer and the control plane, aiming the establishment/release of new optical connections, resource optimization, self-healing, self-protection and learning, based on the events occurred at these layers.**

***Index Terms*— Cognitive Optical Network Architectures, Self-Configuration, Self-Healing, GMPLS, WDM.**

I. Introduction

The current optical networks are becoming increasingly complex due to its broad scope, the use of multiple bit rates and modulation formats, different types of equipment and the large number of interactions between the management, control plane and the network equipment. However, there is now a considerable consensus that these networks are not enough flexible and adaptable to deal with the environment of dynamically establish/release services with different QoS (Quality of Service) requirements, resulting in low efficiency in terms of resources utilization [1]. Additionally, these networks are currently managed by systems that rely heavily on human knowledge and skill of its managers to plan and maintain them. The current operating model results in high operating costs, low flexibility in deployment of services, low network availability, resource blocking and large intervals of recovery from failures, among others. In addition, typically the changes in the network are made in a reactive way, i.e., after the occurrence of problems. This happens because the network does not have features that allow it to be conscious of its own status, neither of the goals that it must pursue. Aiming to remove these limitations and allow the networks to become more dynamic, autonomous and proactive, the concept of cognitive optical networks has emerged. The main idea of this concept is to incorporate intelligence (cognition) to systems management and network control in order to make them dynamically adaptive, autonomic and have ability to learn from past events. In general, the cognitive network architectures aim to reproduce the human nervous system and to implement these features at the computational level [2]. Thus, the current optical networks need to be aware of the transmission medium, of the requirements of services, policies of the operators, etc. to provide the services and applications with proper QoS, reliability and to optimize the network resources. Such networks must perform actions based on reasoning, be adaptive and have autonomic features. In this kind of network, a cognitive system plans, decides, works and learns based on information collected from the network.

Currently, there are several worldwide projects in cognitive optical networks [3]-[4], but each one has its own architecture, employing different cognitive systems and having different goals to achieve, without standardization.

The main objectives of this paper is to propose a definition for cognitive optical network, to describe two cognitive optical network architectures that are currently ongoing, make some considerations about them and the standardization process and, finally, propose a new cognitive optical network architecture.

The paper is organized as follows. In section II, we present the definition of cognitive optical network proposed. Next, in section III, we present the main features of two cognitive network architectures: Cognition and CHRON, some considerations about them and the standardization process. In section IV, the new cognitive optical network architecture proposal is presented and finally, in section V the final comments are highlighted.

II. Cognitive Optical Network Concept

The term "cognitive" applied to the communications networks was first employed by Mitola [5], the inventor of cognitive radio (Cognitive Radio - CR). Mitola defined cognitive radio as *a system in which the radio, autonomously observes its environment, infers its context, evaluates possibilities, creates plans, supervises the services and learns from their mistake*s.

The CR defined by Mitola supports a cognition loop that consists of six steps, as shown in Fig. 1: (1) Observe, where the radio interacts with its environment, (2) Learning, where it learns, (3) Orient, which establish priorities, (4) Plan, which generates alternatives, (5) Decide, which allocates resources, and Action, which sets functionalities in the equipment.

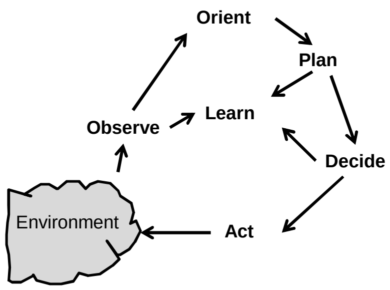


Fig. 1. Cognition Loop (based on [5])

Moreover, the CR definition of Mitola has a local scope of operation, at the network element, and only considers the physical layer and MAC layer of the OSI model as a basis.

The first cognitive network definition (Cognitive Network - CN) was presented by Thomas et al. in [6]. The authors was inspired by the knowledge plan (KP) defined by Clark et al. [7]. The main objective of the KP was to add the self-healing capability to the network, i.e., the capacity of auto-repair from failures automatically. Motivated by the fact that an incremental approach, built from the addition of new algorithms or protocols to the network, would not be enough to achieve this capability, the authors suggested an extra plan (KP) to add knowledge to the network. The KP is basically a distributed cognitive system that can learn and reason, designed as a closed loop control. This system spreads vertically in the protocol stack of each network element and horizontally between network elements, as shown in Fig. 2.

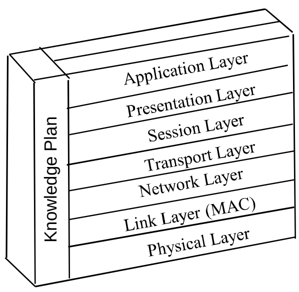


Fig. 2. Knowledge Plane (based on [7])

The KP has the ability of observe from different viewpoints in the network and employs a unified approach to solving problems, avoiding particular solutions that could lead to sub-optimization of the network. Moreover, it is capable of operating in a dynamic environment and following high-level goals.

Based on KP, Thomas et al. [6] defined cognitive network as *a network that contains a cognitive process that can observe the current situation, plan, decide and act under these conditions. This network can learn based on the events that occurred in the past and use this knowledge to make future decisions, taking into account the goals end-to-end*.

This definition is wider than previous ones because it has a global scope and a vision of the end-to-end requirements.

Hereafter, Fortune and Mohorcic [8] concluded that the current cognitive network terminology is not uniform. Some authors refer to it as having "autonomic" capabilites (instead of cognitive), as a network that can operate with little human intervention, i.e., self-manageable. Others call it "cognitive", referring to reasoning ability, learning and self-knowledge network. According to Fortune and Mohorcic, this confusion occurs because is not clear the distinction between these two terms. The term autonomic was inspired by the human autonomic nervous system that performs basic tasks such as: breathing, blood pressure and temperature control, in reaction to the environment changes. The existence of this system enables our brains to be "free" to perform tasks that require thinking and learning (cognitive). Thus, the authors concluded that the term autonomic has a narrower scope than the term cognitive, being applied to repetitive and predictable tasks, which are not performed through the use of learning. On the other hand, a cognitive approach is applied to new situations that require reasoning and learning. Despite of this distinction, what happens, in practice, is that some network architectures called autonomic may have some learning and reasoning ability to self-manage and others, called cognitive, in general, also have the ability to operate with minimal human intervention, i.e., have autonomic functionalities, such as:

- Self-configuration: means that the system automatically detects and configures new equipments, components and network connections, promoting the necessary adjustments to their incorporation into the network;
- Self-healing: means that the system detects failures and repairs problems that occur during the network operation, keeping it normal;
- Self-optimization: the system continuously monitors the network and performs rearrangements for resource optimization and performance.
- Self-protection: the system quickly identifies attacks and vulnerabilities, running appropriate protective actions.

In this work, we consider the autonomic functionalities (self-*) as part of the cognition concept, since they are essential to provide scalability to the architecture of the cognitive network.

Then, we propose a definition to cognitive optical network as: *a network that should have the following capabilities, as essential:*

1. *Environment monitoring and context inference;*
2. *Learning, retaining knowledge (memory) from interactions with the environment and storing this knowledge in a "knowledge base";*
3. *Decision, operation and planning: to make decisions, act on the system and plan future actions, based on:*
    a. *Data collected from the environment;*
    b. *Services requirements;*
    c. *Profiles of network customers;*
    d. *Policies provided by network operators;*
    e. *Knowledge stored in the knowledge base.*
4. *Auto-adaptation to the environment changes in a*

reactive and proactive mode (as minimum);

5. *Self-configuration;*
6. *Self-healing;*
7. *Self-optimization;*
8. *Self-Protection;*
9. *Cooperation between network elements and between different network domains;*
10. *Interaction between different network layers (also named cross-layer design) and*
11. *Distribution of cognitive properties between different network elements, aiming scalability, modularity and stability to the architecture.*

Based on this concept, below, we give a view of some cognitive optical network architectures that are currently been developed.

III. Architectures of Cognitive Optical Networks

Nowadays, two main cognitive optical networks architectures stand out worldwide: (1) Cognition (Cognitive Optical Network Architecture) [3] and (2) CHRON (Cognitive Heterogeneous Reconfigurable Optical Network) [4], briefly described below.

A. *Cognition*

Cognition was proposed by Georgios S. Zervas and Dimitra Simeonidou from High-Performance Networking group at the University of Essex in England. This architecture is composed of five layers, as shown in Fig. 3: (1) Application (Application Layer, AL), (2) Service Provider (Service Provider, SP), (3) Control Plan (Control Plane, CP), (4) Medium Access Control (Medium Access Control, MAC) and Physical (Physical Layer, PL).

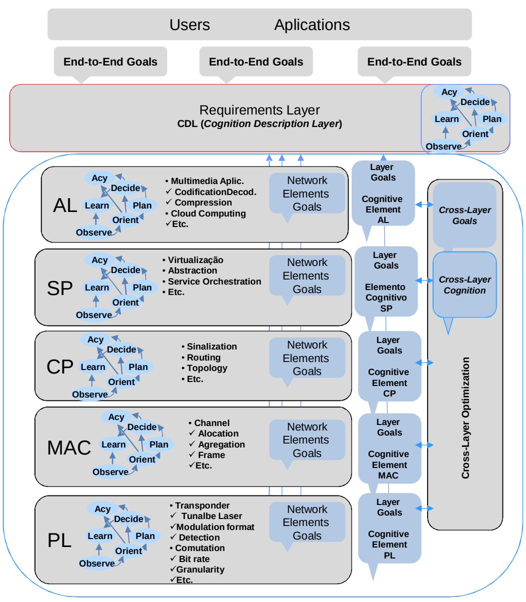


Fig. 3. Cognition Architecture (based on [4])

In Cognition, the network layers are reinforced with cognitive mechanisms. In this architecture, the end-to-end requirements, related to the users requirements are sent to the requirements layer. This layer performs the translation of these requirements into a CDL (Cognition Description Language) and determines the requirements for each layer of the architecture, including the requirements for optimization between layers (cross-layer). The CDL employs semantics and ontologies to describe the structure of network resources and protocols required to achieve the user requirements for each service/application requested. In the application layer, the cognitive elements adapt the application encoding and compression rates and distributes the tasks, in case of distributed applications (cloud computing - Cloud). In the service layer, the virtualization, abstraction, orchestration elements self-configure, self-optimize and self-organize themselves according to these requirements.

The control plane consists of signaling and routing protocols, algorithms for calculating routes and network topology. In this plan, there is the self-configuration and self-optimization of routes, according to the application requirements and the network infrastructure conditions. In the MAC layer, allocation and aggregation of sub- wavelengths optical channels are performed according to the user requirements and network conditions. Finally, in the physical layer, the network elements self-configure and self-optimize themselves in terms of modulation formats, bit rate, number of wavelengths, optical power amplification gain, offset, etc. in order to provide the end-to-end QoS required. In Cognition, all layers above mentioned follow a cognitive cycle: Observe Orient, Plan-Decide-Acts and Learn and the cross-layer optimization ensures a holistic approach, making the interaction between the different layers of the cognitive cycles.

Cognition also ensures the interaction between different areas and regions (access networks, metropolitan area networks and core networks). In this case, the network elements, from different domains, interact before making decisions and actions. This interaction is limited to ensure a proper convergence time, and agreements between different providers.

B. *CHRON*

CHRON is an European project which began in July 2010 and its completion is scheduled for June 2013. Its main objective is to provide a more intelligent optical layer through the use of cognitive processes, to solve some questions, such as:

• How to route new traffic demands on existing or new optical connections?

• How to configure network elements in terms of wavelengths, spectrum grade, modulation format, bit rate, etc.?

• How to ensure efficiency in the operation of the network?

The solution to these questions should also consider the QoS required for each demand, the QoT(Quality of transmission), the current status of the network and the knowledge acquired through previous experiences. The core of this architecture is a Cognitive Decision System (CDS), complemented by a network monitoring system and a management and control system. The interaction between these components is illustrated in Fig. 4.

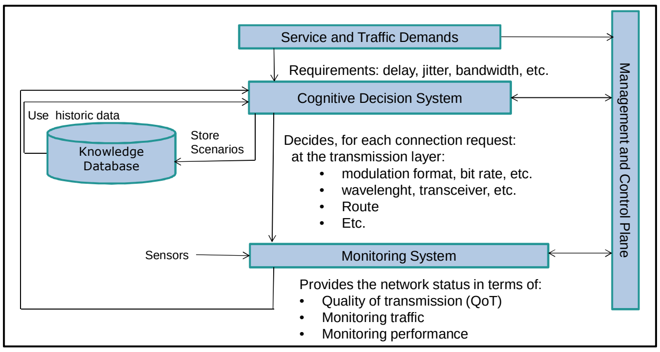


Fig. 4. CHRON Architecture (based on [9])

CDS is divided into five modules:

(1) RWA/RWSA: (Routing and Wavelength Assignment) / (Routing, Wavelength and Spectrum Assignment) module, to process optical connections requests;
(2) QoT estimator module, to predict the QoT before to establish connections;
(3) A virtual topology module, to determine the optimal set of optical paths on the infrastructure of the physical layer;
(4) Multiplexing traffic (grooming) module, to multiplex sub-wavelengths connections and
(5) Planning and decision module, to coordinate the operation of the other modules and communication with the network elements.

CHRON provides two types of architecture:

1. Centralized, where the decision system is centralized in a network element (called control node) and the cognitive control plane is distributed;
2. Distributed, where the decision-making system and cognitive control plane are distributed.

In centralized architecture, CHRON provides five types of use cases (Use Case - UC) to CDS (Cognitive Decision System):

UC#1: Estimation of the QoT in heterogeneous optical networks: in this use case, the CDS is employed to predict the QoT in optical connections before establish a new connection. For this, the physical layer impairments are analyzed;

UC#2: Establishment of optical connections: in this case, the CDS is used to determine the route, the wavelength and the spectrum allocation, taking into account the choice of the modulation format, the range of available spectrum, the physical layer impairments, the resources usage, the energy consumption and the end-to-end delay. This use case aims to perform a multi-objective optimization, considering all the parameters above mentioned to minimize the blocking probability and/or the delay in establishing of connections, while guaranteeing the QoS requirements

UC#3: Aggregation of traffic from multiple layers dynamically: in this case, the CDS is used to: (1) select an optical path, (2) modify the parameters of an existing optical path or (3) establishing a new lightpath on virtual network topology to accommodate new demands of sub-wavelength.

UC#4: Network optimization: in this case, the CDS is used to determine when and how to perform network optimization procedures aimed to improve the signal quality and/or a better use of the network resources. The actions in this case are: (1) re-arrange the routes, (2) modify the parameters of existing optical connections, (3) reallocate spectrum or (4) reallocate wavelengths. This is a pro-active action to accommodate future demands of new connections or to modify existing routes.

UC # 5: Traffic optimization: in this case, the CDS is used to optimize the traffic aggregation of sub-wavelengths (TDM, Ethernet, etc.). The actions in this case include: (1) rearranging and modifying the parameters (bit rate, modulation format, etc.) the existing connections or (3) reconfigure the virtual topology. For this it is necessary to make the prediction of new traffic demands, based on the history of the demands and monitoring data.

C. Considerations about the Current Cognitive Optical Architectures

Based on the public documents available on the websites [4]-[9]-[10], we could concluded that none of the cognitive optical network architectures presented, actually meets completely the concept of cognitive optical networks, as defined in section II. For example, the self-configuration of routes is common feature to both architectures, but none of them presents (explicitly) the self-protection functionality; the self-healing, the proactivity and the capacity to operate in multiple network domains are not present (explicitly) in some of them; to pursue goals given by network operators aren´t common features to both; lack of interaction with any of the network layers, appears in both; there is no metrics explicitly defined to evaluate the performance of the architecture and, the choice of learning and reasoning techniques, aren´t explicitly justified.

D. Standardization

Various standards bodies have recognized the need and the potential to introduce the concepts of cognition in the process of standardization and some standards are being updated and/or new ones have being created. At the moment, most of the standardization work focuses on wireless networks and cognitive radios. As an example, the IEEE Technical Sub-Commitee on Cognitive Networks [11], aims develop standards for dynamic spectrum allocation in cognitive radios.

The IEEE 802.21 [12] aims provide handover and interoperability in heterogeneous networks and, the IEEE 802.22 [13] is related to the operation of cognitive radios in a spectrum band allocated prior to terrestrial TV. The IEEE 802.16m [14] defines requirements for fourth-generation mobile networks (4G) and one of these requirements is the ability of self-organization. Another representative initiative toward standardization is the COST Action IC0902 [15], that aims to study, at medium and long term, the standardization of cognitive networks. Related to the optical networks, the ITU-T G.694.1 standard [16] defines a flexible grid of spectrum for WDM equipment. In addition, there are three drafts of the IETF regarding: (1) Extensions to OSPF supports allocation of wavelengths in flexible grid [17], (2) extensions to RSVP-TE flexible grid [18] and (3) superchannel allocation in flexible grid [19]. Then, we concluded that there is a big opportunity to create new standards related to cognitive optical networks.

IV. New Cognitive Optical Network Architecture Proposal

Based on the definition of cognitive optical network shown in section II, we design a new cognitive optical network architecture proposal, as shown in Fig.5.

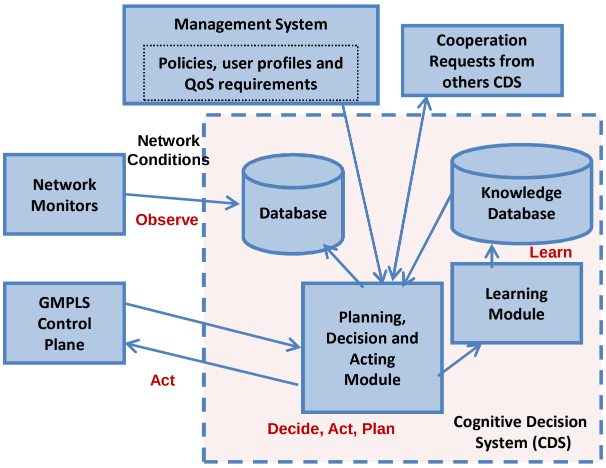


Fig. 5. New Cognitive Optical Network Architecture

We consider the context, the profiles of network clients, the services and applications requirements and some policies determined by the network operators, as inputs to our system. We also consider network monitors and a distributed architecture, using intelligent agents in each network element, cooperating.

We propose to aggregate this cognitive system as a GMPLS control plane extension, as shown in Fig.6.

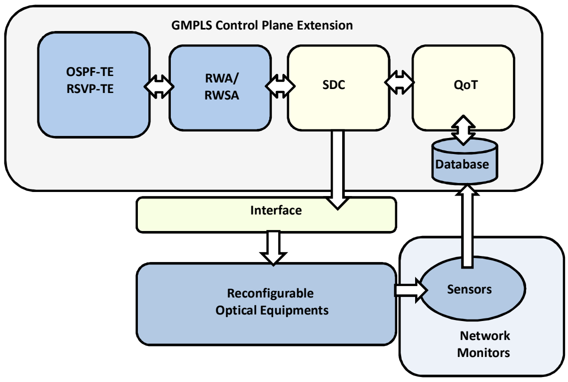
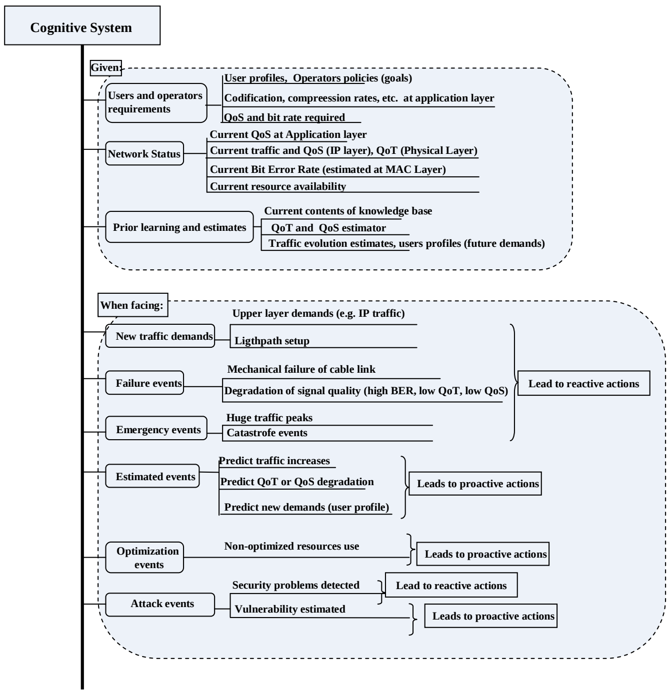


Fig. 6. GMPLS Control Plane Extension

The GMPLS is an IETF standard [20] control plane which has been consolidated in optical networks and consists basically of a routing protocol with traffic engineering, in general OSPF-TE (Open Shortest Path First - Traffic Engineering), a signaling protocol called RSVP-TE (Reservation Protocol - Traffic Engineering), and a protocol for managing the connections, called LMP (Link Management Protocol). After calculating the route by OSPF-TE, the signaling protocol RSVP-TE provides the path on all nodes belonging to the route. The selection of a route in the optical network involves the selection of nodes and links and also the wavelength to be used for transmission. The algorithm which makes the route selection and wavelength assignment is known as RWA (Routing and Wavelength Assignment).

Additionally, the following functionalities are envisaged, as shown in Fig.7.



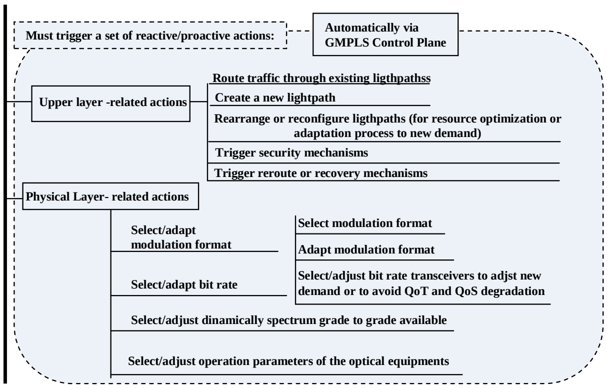


Fig. 7. Functionalities Proposed for the New Cognitive Architecture

Thereby, this architecture encompasses interactions between Service/Applications layer, IP layer, MAC layer, optical physical layer and the management and control plane, aiming the establishment/release of new optical connections (self-configuration), to optimize resources (self-optimization), self-healing, self-protection and learning, based on the events occurred at these layers. These features aims to complete the features required in our cognitive optical network definition.

V. Final Comments

Through our study in terms of the state of art in cognitive optical network, we found that this area is currently in an embryonic stage, without a standard (reference model) defined. Then, we propose a definition for cognitive optical network and a new cognitive optical architecture proposal based on it. The next steps consist in to implement this architecture, to define comparison metrics and learning techniques, to justify them, and compare its results with a non-cognitive optical architecture.

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