Cognitive Dynamic Optical Networks [Invited]

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***Abstract*—The use of cognition is a promising element for the control of heterogeneous optical networks. Not only are cognitive networks able to sense current network conditions and act according to them, but they also take into account the knowledge acquired through past experiences; that is, they include learning with the aim of improving performance. In this paper, we review the fundamentals of cognitive networks and focus on their application to the optical networking area. In particular, a number of cognitive network architectures proposed so far, as well as their associated supporting technologies, are reviewed. Moreover, several applications, mainly developed in the framework of the EU FP7 Cognitive Heterogeneous Reconfigurable Optical Network (CHRON) project, are also described.**

***Index Terms*—Cognition; Heterogeneity; Monitoring; Optical networks; Software-adaptable elements.**

I. Introduction

Optical networks are facing increased levels of heterogeneity, from types of services to transmission technologies. Hence, a key issue of highly heterogeneous networks is how to efficiently control and manage network resources while fulfilling user demands and complying with quality of service (QoS) requirements. A solution for such a scenario may come from cognitive networks. A cognitive network is defined as "a network with a process that can perceive current network conditions, and then plan, decide, and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals" [1]; that is, the network implements the so-called cognitive loop (Fig. 1). Hence, there are three main ingredients in such a network:

- *Monitoring elements*, which provide the network with the perception of the current conditions, and thus enable an *aware network*.
- *Software adaptable elements*, which provide the network with the capacity to modify its current configuration, thus enabling an *adaptive network*.
- *Cognitive processes*, which learn or make use of past history, so that even when facing two equivalent scenarios, the network (or the entity containing those cognitive processes) may act in a different way if its previous history is different. This third element is the main feature that enables a *cognitive network*.

Therefore, a cognitive network is a network that is able to adapt itself to current or forecasted conditions by taking into account previous history and that is able to act proactively, rather than reactively, in order to avoid problems before they arise. Moreover, those tasks should be performed autonomously, with little or no intervention of the network operator. Cognitive networks are thus closely related to autonomic networks [2]. An autonomic network relies on self-configuration, self-healing, self-optimization, and self-protection functionalities, so that it may make decisions without manual intervention, i.e., without having to consult with a human administrator [3]. In this way, an autonomic network is not only aware and adaptive, but also automatic. Therefore, a cognitive network can be considered as a variant of an autonomic network [2], but it emphasizes the self-optimization functionality as well as the use of learning mechanisms, in contrast with other types of autonomic networks, which generally rely on policy-based methods rather than on learning techniques to support the adaptations ([2], Table VIII). Cognitive networks have already shown their advantages in wireless environments [4], but they are also applicable to wired communication architectures and are especially appealing for optimizing performance in heterogeneous networks.

In this paper, which extends [5], we describe (following a tutorial approach) how cognition can be applied in the

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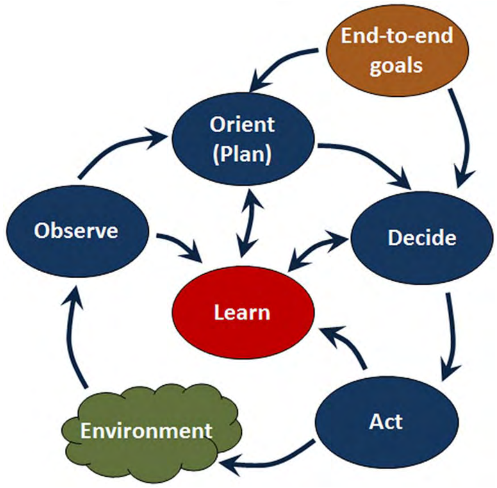

Fig. 1. Cognitive loop.

framework of optical networking. First of all, we review a number of architectures recently proposed for cognitive optical networking. Then, the enabling technologies supporting those cognitive architectures are reviewed, which include software adaptable elements, monitoring solutions, and control and management mechanisms. Once the fundamentals have been presented, a number of applications where cognition brings advantages in optical networks are described. Finally, we provide a set of concluding remarks.

II. Architectures for Cognitive Optical Networks

The design of a cognitive optical network involves determining how the three aforementioned key ingredients—monitoring elements, software adaptable elements, and cognitive processes—are implemented (and where) and how they are glued together, as well as determining which tasks are going to be solved with the help of cognition. An initial answer to some of these issues is provided by a set of cognitive architectures or frameworks proposed in the literature, such as the work by Thomas *et al.* [1] and Kliazovich *et al.* [6], targeted to generic cognitive networks, or the proposals by Zervas and Simeonidou [7] and Wei *et al.* [8] and the Cognitive Heterogeneous Reconfigurable Optical Network (CHRON) project approach [9,10], targeted at cognitive optical networks.

These architectures show that cognition can be implemented in different dimensions, in terms of devices and protocol layers. For instance, in a cognitive network implementation, software-defined transceivers may include monitoring functionalities together with internal intelligence to modify their configuration autonomously, i.e., being truly cognitive transceivers. However, another implementation may opt for shifting the intelligence in charge of configuring those transceivers to the upper layers of the nodes where the transceivers are located, thus making the network nodes the cognitive elements rather than the transceivers themselves. That example may find its way in a network with distributed cognition, where all network nodes are equipped with cognitive capabilities and collaborate in sharing acquired knowledge. Nevertheless, another possibility is a network with centralized cognition, where a single node (the control node) contains the intelligence and makes decisions, which are then communicated to the remaining network nodes by means of control and management plane protocols with suitable extensions.

On the other hand, the level and type of cognition to be added to a network is dependent not only on the adopted approach, as we have just described, but also on the capabilities of the network monitors and software-adaptable elements employed: the higher the flexibility of the available software-adaptable elements, the higher the potential of cognition. However, although the utilization of software-defined networks [11,12], as well as software-defined transceivers [13] and flexible (or elastic) networks [14–16], is usually associated with cognitive optical networks, it should be noted that these technologies are not strictly necessary for adopting a cognitive networking approach.

For instance, Zervas and Simeonidou have presented a cognitive architecture for optical networks called COGNITION [7]. It represents a holistic framework, where all network layers—the application layer, service plane, control plane (CP), medium access control (MAC), and physical layer—are enhanced with cognition, and it also includes cognitive cross-layer optimization where required. Optical nodes, besides having the usual transport and switching modules as in any legacy network, also contain additional modules to incorporate cognition, allowing for the dynamic adaptation of physical layer parameters, such as the modulation format or the bit rate, for adaptive bandwidth allocation in the MAC layer, and so on.

On the other hand, Wei *et al.* [8] have proposed a framework for software-defined cognitive optical networks (CONs). Regarding the transport plane, these networks are envisioned to employ optical transceivers with programmable modulation formats as well as an adjustable optical grid for each channel, and they are enhanced with automatic impairment compensation and performance monitoring capabilities. Regarding the CP, CONs rely on cross-layer traffic management, physical-impairment-aware routing and wavelength assignment (RWA), and dynamic adaptation of transmission pipes. Finally, regarding services, CONs adopt a client-service-aware approach and are targeted to support bandwidth on demand with rate-adaptive optical reach and flexible subwavelength services.

Another example is provided by the CHRON project [9,10]. It has proposed a distributed and a centralized architecture for cognitive optical networks but has mainly focused on the latter one, shown in Fig. 2. The core element of the CHRON architecture is the cognitive decision system (CDS) [17]. The CDS receives traffic demands and determines how to handle them by taking into account both the current status of the network and past history and instructs the CP to configure network elements accordingly. Therefore, the CDS is complemented with a network monitoring system, which provides traffic status and optical performance measurements, and with a set of generalized multiprotocol label switching (GMPLS)-based control and

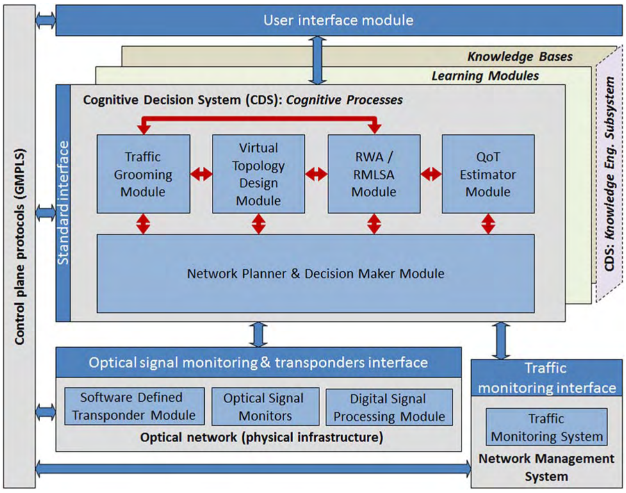

Fig. 2. CHRON schematic architecture (for a network with centralized cognition).

management mechanisms to implement the decisions that are made by the CDS and to disseminate the monitored information. The CDS is involved in very diverse tasks related to network control and optimization. Hence, rather than implementing the whole CDS as a monolithic module, it is divided into different modules, each offering a functionality (or a set of related functionalities), and all of them exploiting cognition, as shown in Fig. 2.

Thus, the traffic grooming module is in charge of routing nonoptical traffic demands (e.g., time division multiplexing label-switched paths through existing optical connections—lightpaths—composing the virtual topology). The virtual topology design (VTD) module is in charge of (re)designing the virtual topology (i.e., the set of lightpaths) to be established in the network. In networks following the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) grid, the RWA/routing, modulation level, and spectrum allocation (RMLSA) module solves the RWA problem (as well as determining the modulation level), while in elastic networks, where channels do not necessarily comply with the ITU-T grid, it solves the RMLSA problem. The quality of transmission (QoT) estimator module makes a prediction of the QoT of new lightpaths to be established in the network (as well as the impact on existing connections when undertaking a new one). Thus, the establishment of impairment-aware optical connections relies on this module. Finally, the network planner and decision maker (NPDM) module coordinates the operation of the other modules, relying on their results, and provides additional functionalities like forecasting. The NPDM communicates the actions to be performed to the network nodes through CP protocols and handles the information received from the network monitoring system.

III. Enabling Technologies for Cognitive Optical Networks

As we have just mentioned, cognitive architectures rely on the utilization of software adaptable elements, together with monitoring techniques and control and management protocols. Thus, in this section we review these enabling technologies.

A. *Software Adaptable Elements in Cognitive Heterogeneous Optical Networks*

Software-defined adaptable elements are essential for the realization of the cognition concept in networks, since they allow the optimum and on-demand use of resources, according to the intelligent (i.e., cognitive) processing of connection demands [8]. Although a cognitive network could rely on a set of fixed transceivers in the nodes, the higher degree of flexibility provided by software-defined transmitter and receiver subsystems is turning them into key network elements to perform the adaptable allocation of traffic demands.

In practice, the transmitted bandwidth adaptability in optical transceivers is realized by (1) altering the modulation level or format (i.e., the bits per symbol) per optical carrier and (2) varying the number of electronic or optical carriers in multicarrier formats [14]. The general purpose of these adaptable schemes is to apply the optimum format over the minimum number of carriers, thus maximizing the spectral efficiency (i.e., the number of bits per second per Hertz) for a certain traffic demand over an optical path with certain end-to-end performance requirements [18,19].

Format adaptability can be performed either in the optical domain, by simply enabling or disabling the different arms of nested Mach–Zehnder modulator structures at the transmitter and the related output port of 90° hybrid at the receiver or directly in the electronic domain by appropriately defining the signal levels of the modulation signals [20]. Moreover, for multicarrier schemes based on electronic generation of subcarriers, the subcarrier number is defined in the electronic domain by the length of the digital signal processing (DSP) function prior to the optical modulation, while for optically generated subcarriers, their number is defined either by filtering the appropriate number of carriers or by gating the appropriate number of subcarrier transmitter outputs directly in the optical domain [21,22].

The bandwidth adaptable data transmission schemes mentioned above can realize the optimum use of network resources according to the traffic demands, but they result in added complexity in terms of control. This is attributed to the fact that any decision mechanism must account for a large number of possible combinations (i.e., central wavelength allocation, format, and number of subcarriers) to optimally serve a demand for a given optical path. The role of cognitive optical networking is particularly beneficial for the practical implementation of these schemes, since it can significantly relax the decision mechanism by exploiting past history. It is noted that cognition can apply in combination with any adaptable (flexible) transmission technique, since all of them are intrinsically software-defined schemes.

B. Monitoring Elements for Cognitive Heterogeneous Optical Networks

Both traffic and optical performance monitoring (OPM) techniques are required to know the current state of the network. That information can be used not only for making immediate decisions but also as an input for forecasting procedures facilitating the execution of proactive actions. While existing techniques for traffic monitoring can also be exploited in cognitive optical networks, the introduction of new optical transmission systems, and their coexistence, triggers the need for the development of novel OPM techniques.

Thus, to guarantee that the QoS and resiliency are achieved along the lightpaths, a sophisticated monitoring of the physical properties of the signal is required. OPM analyzes the accumulation of the so-called "noncatastrophic" transmission impairments, such as chromatic dispersion (CD), polarization mode dispersion (PMD), and nonlinear effects [23]. These effects, combined with the accumulation of network element impairments, like crosstalk, amplified spontaneous emission noise, polarization-dependent loss (PDL), and filter/reconfigurable optical add and drop multiplexer (ROADM) concatenation, make the information data unrecoverable even though the received optical signal power is at an acceptable level. Furthermore, the so called "catastrophic" impairments such as accidental fiber cuts and damaged or improperly installed network elements can cause critical network performance degradations [23]. Meanwhile, other channels copropagating in the same link can be affected as well due to transients in the amplifiers caused by the rapid change of the total optical power (several decibels) [24]. Despite the nature of the failure, it becomes clear that accurate and fast parameter monitoring would allow an early fault analysis with fast switching to a protection path. The efficiency and reactivity to different problematic events also depends on the critical interaction between OPM and higher-level control and management plane systems [24]. Therefore, monitoring devices must be placed in strategic places during the planning stage of an optical network.

In 10 and 40 Gb/s optical networks, various OPM techniques have been developed relying on external devices, such as optical spectrum analyzers, RF devices, and frequency-selective polarimeters. On the other hand, modern transmission technologies for 100 and 400 Gb/s and 1 Tb/s and beyond are based on coherent technologies by taking advantage of powerful and cost-effective silicon DSP capabilities. OPM techniques based on DSP, where expensive external devices are not required, are adaptable to varying data rates and modulation formats and are capable of realizing joint monitoring of key physical layer parameters like CD, PMD, PDL, optical signal-to-noise ratio (OSNR), bit error rate (BER), etc. The DSP has already been integrated into the receiver side, so it will provide network information at the end points. Furthermore, in the future, DSP could also be integrated into optical amplifiers or ROADMs, thus allowing the derivation of relevant information at these midpoints [24].

In DSP-based OPM techniques, frequency-domain equalization combined with data-aided (DA) channel estimation can be considered as a promising technology [25]. Compared with non-DA methods based on gradient algorithms for time-domain filters, which are strongly dependent on the modulation format and suffer from a relatively slow convergence with potential suboptimum acquisition and even failures, DA channel estimation, based on periodically transmitted training sequences (TSs) [26], allows instantaneous filter acquisition and immediate OPM, and the modulation format can be altered arbitrarily in between the fixed training patterns. All these benefits come at the cost of slight bandwidth efficiency degradation due to the insertion of TSs, and the required overhead can be below 5% [27]. Moreover, in a coherent burst-mode receiver, each burst must be instantaneously equalized, and only DA channel estimation is suitable.

These DSP-based OPM techniques can be implemented in hardware, and therefore real time physical impairment information will be available for the control and management plane. However, if offline DSP processing is used instead, then the control and management databases can be periodically updated by the OPM with the physical impairment information, and thus the control and management plane does not need to wait for the DSP processing.

C. Control and Management Mechanisms for Cognitive Heterogeneous Optical Networks

In a cognition-driven optical network architecture, the coordination between the "brain" that makes decisions and establishes network operations and the data plane (photonic layer) is provided by a control system, which supports the cognitive intelligence in an automated and reconfigurable manner. We distinguish between two different approaches to implementing the cognitive architecture: (1) *centralized*, in which the network and all components are under the control of a single cognitive entity, which receives all the information related to network configuration, availability, monitored parameters, etc. and (2) *distributed*, in which there is not a specific node with a prominent role, and where the cognition is distributed among all the network nodes (or a large part of them), which exchange the information mentioned above. Both the centralized and the distributed cognitive architectures need a system delivering updates related to network status, reserving the resources, and configuring the optical devices. These tasks are carried out by the CP.

A cognitive optical architecture is expected to make effective decisions by leveraging on a knowledge base (KB), built with the support of the CP. Decisions are made for different activities, such as lightpath activation in response to a user request or rearrangement of active network connections. In such a context, and in particular for the latter activity, knowledge of the status of currently active lightpaths is required. While it is evident that this information can be disseminated by adapting already existing protocols, it is also clear that it would demand the exchange of a nonnegligible amount of data between distributed control nodes (including the path of each active connection, physical layer impairments, etc.). Hence, from the operational point of view, a solution with distributed control entities may not be cost-effective. In addition, distributed decisions may conflict. Finally, cognitive decisions are also grounded on the values collected by the monitoring system of the network. Also in this case, a distributed solution is harder to keep updated. On the other side, a centralized approach may suffer from scalability issues, and the cognitive entity is potentially a single point of failure of the network. While the latter issue may be lessened by enhancing the protection/robustness of the cognitive entity and by introducing backup entities, the former is a matter of network scenarios. In the context of optical networks and with a limited amount of managed nodes, a centralized approach could still scale sufficiently, while ensuring a high level of reliability and providing more effective path computations.

Let us now focus on the CP. Whatever the chosen architectural approach, current CP solutions need to be enhanced to realize the full potential of the cognitive processes. In order to achieve such a result, the CP, eventually assisted by other systems, has to be able to perform the following tasks:

1. *Disseminate network configuration information to the cognitive entities*: The CP should control the network configuration, providing a description of the network in terms of physical components, topology, resource availability, and configuration of the used resources. This description has to be continuously kept updated by the CP by notifying the cognitive entities of any change occurring in the network configuration. In both centralized and distributed cognitive architectures this task can be performed by the open shortest path first with traffic engineering extensions (OSPF-TE) protocol [28] of the GMPLS suite. The OSPF-TE protocol has to be extended to describe the status of the fixed and configurable parameters of the devices inside a node or associated with a link (e.g., amplifiers, filters). Regarding the configuration of the devices and the physical components, the CP has different ways to collect this information before disseminating it; indeed, it can be statically provided by the network operator, or it can be dynamically discovered by means of the link management protocol (LMP) [29], as is shown in [30]. With respect to the disseminated information, network scalability can potentially be an issue, since OSPF-TE may have a lot of data to advertise; however, it can be mitigated by an appropriate choice of the number and the encoding of the parameters needed by the cognitive system. In addition, if a centralized approach is considered, it could be noted that the central cognitive entity should be aware of resource availability, since it is this element itself that makes the decisions on the devices to configure. Nevertheless, OSPF-TE utilization remains paramount to providing the initial configuration of the devices and to updating the database of the cognitive entity when links are not available anymore. Moreover, OSPF-TE is a widely used, standardized, and stable protocol; extending it to support the cognitive features is a safer solution than implementing these features as new in a nonstandard solution. However, the centralized knowledge of the cognitive element may be exploited to enhance the resource availability information in order to avoid potential problems incurred by the misalignment between the information carried by the OSPF-TE protocol and the real network status due to the latency in the updating process [31].
2. *Feed the cognitive entities with information regarding monitored QoT and traffic, check the correct behavior of the components, and signal anomalies or failures*: Cognitive processes can exploit traffic status information and optical QoT measurements in order to perform effective decision making during lightpath setup and to foresee potentially service disrupting situations. There are different techniques to retrieve the aforementioned information, and different protocols are available to manage this task [i.e., simple network management protocol (SNMP) [32], remote network monitoring (RMON) [33]]. The approach proposed in [34] leverages on a monitoring agent located on each node that collects information about monitored parameters (e.g., power, BER, OSNR, traffic) by querying the physical nodes. This information is sent to a monitoring server located in the cognitive node that collects the information and stores it in a database, which the cognitive processes can access. Moreover, the cognitive entity can also receive alarms from monitoring agents when a critical (or potentially critical) situation at the physical layer occurs.
3. *Implement the decisions of the cognitive entities on the devices*: The CP has to reserve the resources on the basis of the decisions made by the cognitive entities. Also in this case, in both centralized and distributed cognitive architectures, this task can be performed by a GMPLS protocol, namely, the resource reservation protocol with extensions for traffic engineering (RSVP-TE) [35]. If this happens, the RSVP-TE protocol must be extended to carry the instructions that the cognitive entities have produced for each device throughout the path. In particular, the PATH message requires an extension to encode the configuration parameters of each device on the path [e.g., the modulation format for the transmitters, the port and connectivity parameters of the optical cross-connect (OXC) switching matrices]. At the end of this process, via nonstandard communications, the CP may also be able to notify the CDS if the required operation has been successfully performed and, in case of failure, report the issue that caused such a failure. The implementation of the decisions can also be performed according to an alternative approach, called software-defined networking (SDN) [11]. In such a case, a controller opportunely programmed to manage optical devices could directly configure the OXCs involved in the setup of a lightpath [36].
4. *Support the cognitive elements in case of network reoptimization*: As previously discussed, the cognitive entities can directly manage network operations and thus perform the reoptimization of the resources in

order to achieve better efficiency in terms of utilization, energy efficiency, etc. Complete information about network status is needed to perform this task. In this case, a distributed approach cannot be easily adopted for such a reoptimization, since the information disseminated by OSPF-TE does not allow the construction of a stateful database. Regarding the centralized approaches, a standard path computation element (PCE)-based solution [37] would not be suitable to carry out this task, because the PCE is a computation element used to answer requests forwarded by source nodes by means of the path computation element communication protocol (PCEP) [38]. Although the current PCE architecture is not fully standardized to autonomously trigger lightpath activation, some recent standardization efforts are addressing this issue by means of extensions to PCEP [39] that should allow a stateful PCE to remotely initiate lightpath setup. However, for the time being, the discussion within the Internet Engineering Task Force is still at an early stage. A feasible centralized implementation based on GMPLS is the one proposed in [34], in which the cognitive element can initiate a lightpath setup and trigger the RSVP-TE reservation. Once the reservation has been completed, the CP sends a response to the cognitive entity notifying it of whether the required operation has been successfully performed and, in case of failure, reporting the issue that caused such a failure.

The process of evolution of the CP may be directed to a joint control of the optical and the packet domains [40]. In this perspective, an SDN-based controller may cooperate with the cognitive entities and the CP of an optical network. The cognitive entities could relieve the SDN controller from the high overhead due to the complexities at the photonic layer. In particular, they could provide the controller with already signaled and optically feasible lightpaths, whose computations are optimized in a multilayer fashion and tailored on the basis of the needs of the packet layer.

IV. Cognitive Processes for Optical Networks

Cognition may find many diverse applications in optical networks. In this section, we review a number of applications of cognition proposed within the CHRON context as well as in other approaches.

One of the modules of the CDS in CHRON (Fig. 2) is the QoT estimator. This module makes a prediction of the signal quality of new lightpaths to be established in the network (as well as of the impact on existing connections) by using past history. Thus, the establishment of impairment-aware optical connections relies on this module. It should be noted that this module provides estimates (which are useful for discarding connections where a low QoT is expected or that would disrupt existing ones), but once a new lightpath is established, the QoT is verified by means of network monitors, and the result of this verification may be used to improve the behavior of the module for future QoT estimations.

The cognitive operation of this module relies on the utilization of data mining techniques [41]. For instance, in [42], we proposed a cognitive QoT estimator based on case-based reasoning (CBR) [43]. The key idea in CBR is to solve a new problem by relying on previous experiences (or cases), which are stored in a KB. Thus, when facing a new problem, the most similar cases stored in the KB are retrieved, and by reusing those cases, either directly or after adapting them, a solution to the new problem is provided. Moreover, the KB can be updated to include new experiences, which can lead to improving the performance of the system.

For the purposes of cognitive QoT assessment, the KB is composed of a number of cases, each consisting of a description of a lightpath (i.e., its attributes, including elements like its route, wavelength, and number of copropagating lightpaths) together with its associated QoT value. The initial KB can be built by running a set of offline physical layer simulations (emulating different configurations of the network and recording the QoT evaluation of the different lightpaths) or by gathering experimental data from the optical network prior to its dynamic operation [42].

When the CBR system is used to classify a lightpath in terms of its QoT, the most similar lightpath from the KB is retrieved, and the QoT value of the lightpath to assess is assumed to be the same as that of the retrieved case. That value is then used to decide whether the lightpath fulfills the QoT requirements or not, by comparing with a threshold value.

It should be noted that the CBR technique does not really build a model *a priori* from existing data in the KB, but that KB is searched in real time each time a request for QoT assessment arrives. However, other data mining techniques (like the naive Bayes classifier or decision trees) [41] build a relatively simple model *a priori* (i.e., before online operation) by using existing data in the KB. That means that they may require a relatively large period of time for building such a model, but once the model is built, the computing time to use it and provide a decision is not really significant, and it is much faster than the CBR approach.

Figure 3 shows the percentage of successful classifications of lightpaths into high or low QoT categories when using different techniques, such as a naive Bayes classifier [41], different types of decision trees [41], and the CBR approach previously mentioned [42] for the 34-node GÉANT2 dispersion-compensated network, equipped with 64 wavelengths. Since solid work exists on 10 Gb/s OOK networks, we have focused on this technology for the sake of comparison with a validated method for QoT assessment (in particular, the Q-Tool [44]).

As shown in Fig. 3, and as demonstrated in [42], the CBR approach achieves more than 99% successful classifications of optical connections and is much faster for online operation than an existing noncognitive approach (the Q-Tool), thus demonstrating the advantages of cognition.

The CBR technique provides the best results in terms of the percentage of successful classifications of lightpaths in QoT categories, but, as shown in Fig. 3, the results obtained when using the J4.8 decision tree method [41] are

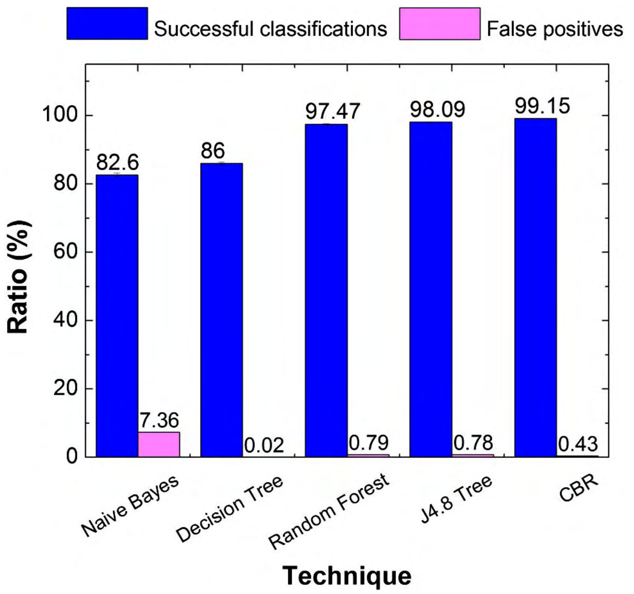

Fig. 3. Percentage of successful classifications and false positives obtained by different data mining techniques when used for QoT assessment in the GÉANT2 network [5].

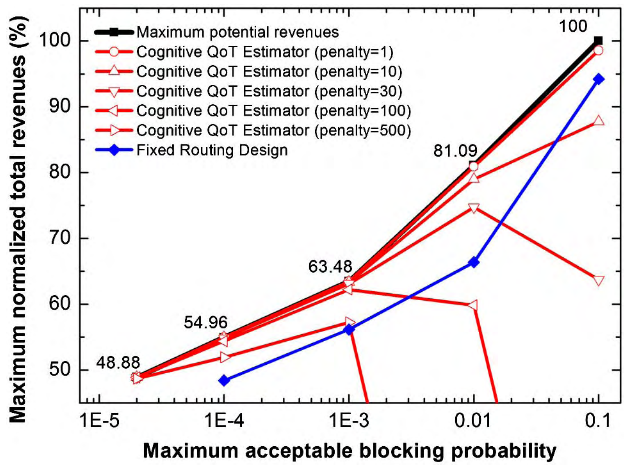

Fig. 4. Maximum normalized total revenues that a network operator can obtain as a function of the maximum acceptable blocking probability in the Deutsche Telekom network with 64 wavelengths per link [46].

relatively close. Therefore, that technique offers a suitable alternative in the case where an even higher computing speed (when operating online) than that provided by the CBR method is required, for instance, when considering networks of a very big size leading to big sized KBs.

Unsuccessful classifications of optical connections by the QoT estimator module lead to two types of penalties. First of all, the cognitive QoT estimator may decide that a new lightpath has enough quality, but once it is established the monitors measure that it does not have enough QoT, so it has to be dropped. More importantly, existing lightpaths in the network could be disrupted in some cases where the cognitive QoT estimator makes an erroneous decision. However, in our simulation studies the second type of penalty is virtually nonexistent. On the other hand, conservative estimations provided by the cognitive QoT estimator may lead to not establishing connections that would have been otherwise completely valid, and thus to not earning its associated revenues. These events have been considered in a techno-economic study, which compares the joint use of the cognitive approach (based on CBR) and adaptive routing [45] with traditional dynamic optical networks (based on fixed routing designs, engineered *a priori*, so that all connections are ensured to comply with QoT requirements). As shown in Fig. 4 (where the 14-node Deutsche Telekom network with 64 wavelengths per link is analyzed), the revenues obtained when the cognitive QoT estimator is used significantly depend on the value of the monetary penalties. If the monetary penalty per affected Erlang is equal to the revenues provided by one carried Erlang (penalty = 1), then the revenues of the cognitive QoT estimator are extremely close to those that would be obtained if an ideal QoT estimator were used (which provides an upper bound on the potential revenues). As this monetary penalty increases, the revenues decrease when compared with the ideal case, especially as the maximum acceptable blocking probability is increased. Nevertheless, for realistic blocking probabilities ($<10^{-3}$) and up to a penalty of around 100, the revenues are very close to those of the upper bound and higher than those obtained with the fixed routing design solution [46].

A second example of the potential of cognition in optical networks is related to the VTD module. In [47] we have proposed a multiobjective genetic algorithm to design impairment-aware and survivable virtual topologies with the aim of reducing both the energy consumption and the network congestion. In a single execution, the algorithm provides several solutions with different trade-offs in terms of the two optimization objectives just mentioned [i.e., a collection of virtual topologies that constitute a good estimate of the so-called Pareto optimal set (POS)[1]]. That method has been further enhanced with two cognitive techniques based on the utilization of memory to remember solutions successfully used in the past and a Tabu list to remember connections with low QoT. We have studied the performance of this method in the transparent Deutsche Telekom network and assumed a traffic-varying environment where the virtual topology is reconfigured every hour. By means of simulation, we have demonstrated that the inclusion of cognition leads to finding more and better solutions, as shown in Figs. 5 and 6, respectively, and moreover, that the network learns as time passes, since results improve with time. First of all, Fig. 5 shows that the genetic algorithm alone is usually unable to find even a single feasible solution (the problem we are facing is very hard, since not only the primary virtual topology but also all the backup solutions—i.e., for all potential failures—must comply with QoT requirements, and we have assumed no regeneration along the lightpaths). In contrast, when complemented with cognition, a set of feasible solutions

[1]The POS is composed of those solutions that cannot be improved in any of the optimization objectives without worsening at least one other one.

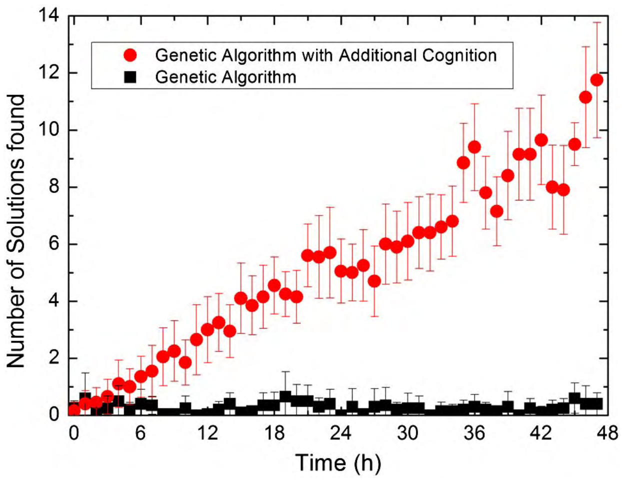

Fig. 5. Number of solutions found depending on the time in which the request to design the virtual topology is created [47].

are found. Moreover, at the beginning (i.e., at time = 0 h) both the memory and the Tabu list of the cognitive method are empty, so that both algorithms obtain a similar number of solutions, and with similar features. However, as time evolves the cognitive method learns from the past and uses this learning to improve its results. In this way, in each new request to design a survivable virtual topology (i.e., each hour), the number of solutions found by the cognitive method grows, and if the solutions provided by both methods are considered together, and the common POS is obtained, most of the solutions of the common POS are provided by the genetic algorithm enhanced with additional cognition (Fig. 6).

Moreover, as demonstrated in [48,49], the introduction of cognitive techniques in VTD and reconfiguration leads to significant savings in terms of the total cost of ownership compared to conventional methods. For instance, the case study in [48] shows that capital and operational expenditures can be, respectively, reduced by up to 20% and 25%.

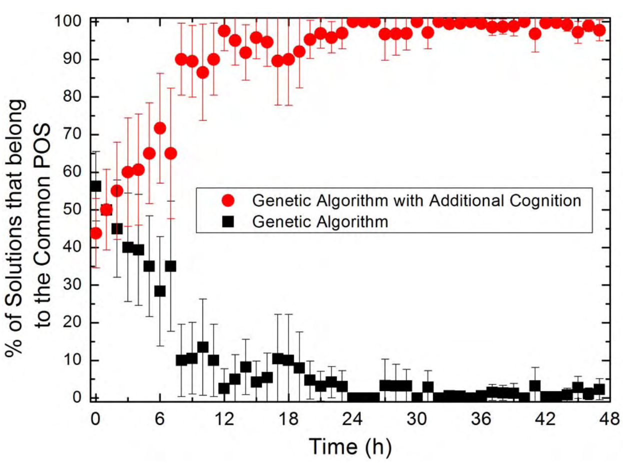

Fig. 6. Percentage of solutions that belong to the common POS depending on the time in which the request to design the virtual topology is created [47].

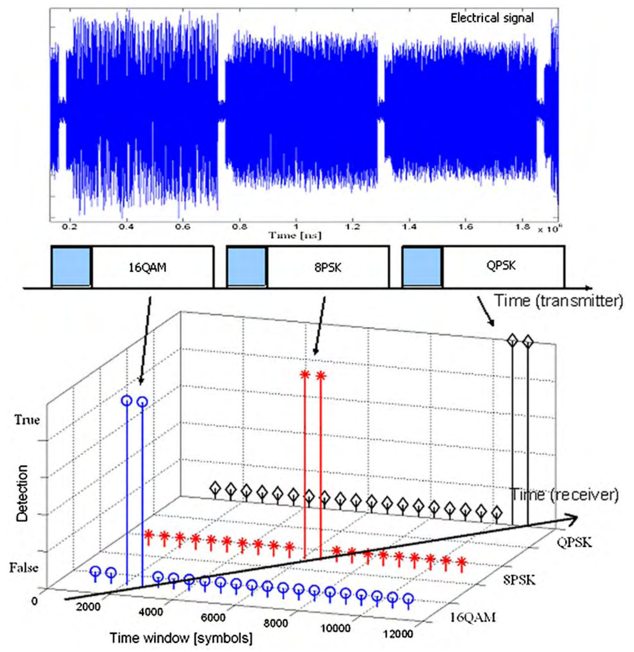

Fig. 7. Cognitive signal modulation format recognition for three data payloads with alternating QPSK, 8PSK, and 16QAM modulation formats [50].

The third and last example of the use of cognition within CHRON is a step forward toward more autonomous networks, where cognition resides in transceivers rather than in a control node. Thus, in [50] we have proposed a cognitive digital receiver that, by means of clustering algorithms, is able to identify the incoming signal format [quadrature phase-shift keying (QPSK)/8PSK/16 quadrature amplitude modulation (QAM)] without the need to receive a prior control message, thus opening the door to the autonomous modification of the modulation format, as shown in Fig. 7.

Finally, we will mention a few examples of the use of cognition in optical networks outside the CHRON project. These works do not propose general cognitive architectures (in contrast with the approaches described in Section II), but rather the application of cognitive techniques to specific aspects of the operation of an optical network. For instance, Zervas *et al.* [51] have proposed the concept of architecture on demand (AoD). AoD introduces additional flexibility in the configuration of optical networks by enabling the selective use of a set of building modules, with different capabilities, connected by means of an intelligent optical backplane. The role of cognition comes from the application of a reinforcement learning approach for resource allocation in such an architecture. Cognition has also been applied to optical burst-switched (OBS) networks. In particular, the group led by C. Siva Ram Murthy has proposed a novel OBS architecture, which takes advantage of machine-learning techniques to achieve self-awareness, self-protection, and self-optimization, leading to significant improvement on burst loss probability [52,53]. Finally, Valcarenghi has also proposed the use of cognition in passive optical networks with the aim of improving energy efficiency [54].

V. Summary

We have provided an overview of cognitive optical networks. By means of network monitors, the network becomes aware of current conditions and thus can adapt itself in order to optimize network performance with the help of software-adaptable elements. However, these networks also rely on cognitive processes, which make it possible to learn from the past and thus get an advantage from knowledge acquired through experience for further improvements. There are many different alternatives for the implementation of cognition, and we have briefly described a number of architectures, mainly focusing on the CHRON approach. We have also analyzed their enabling techniques in terms of monitoring elements, software-adaptable elements, and control and management plane solutions, taking into account the current trend toward the use of more flexible and heterogeneous optical technologies. Finally, we have shown how cognition can help in diverse optical networking tasks, such as assessing the QoT of optical connections, designing optimized virtual topologies in reconfigurable environments, or helping identify the incoming signal format at a receiver, thus facilitating the autonomous modification of the modulation format.

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