Cross-Layer Analysis in Cognitive Radio - Context Identification and Decision Making Aspects

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***Abstract*—Research on context-aware communications recently led to the introduction of features and algorithms relying on the presence and rich, accurate context information, requiring however the introduction of cross-layer information exchanges. Cognitive radio (CR), in particular, is expected to benefit from context awareness, as the cognitive engine (CE) relies on the availability of multiple information sources to operate efficiently. In this context, this work delivers a detailed, yet concise classification and description of the information exchanged in a CR network between the layers of a generic protocol stack, and between each layer and the CE. For each layer, the key services provided and delivered are presented, followed by a catalogue of exchanged parameters. The analysis, supported by a set of use cases providing a quantitative assessment of the impact of cross-layer information exchanges in a CR framework, is the basis for the for the discussion of key implementation challenges and the identification of the most promising partition of functions and tasks between layers and CE.**

I. Introduction

A communication system is typically represented in the form of a layered model, with each layer performing a very specific system functionality, such as physical transmission, data routing, user interfacing, etc. The protocol stack model that divides the different functionalities in a communication system in logical layers played a central role in the development of global telecommunications, as it allows for modular design and implementation, at the price however of limiting the interaction and exchange of information to neighboring layers. Cross-layer designs aiming at removing this limitation have raised a growing interest in recent years, but so far the protocol stack concept remained relatively unaltered in real world communication systems.

The most widely solution used to describe the communication system is the International Organization for Standardization (ISO) - Open Systems Interconnection (OSI) reference layer model, which consists of seven layers [1], [2]. Various modifications of this concept have been proposed in the literature during the last decades, adapting the layer concept to new applications. Specifically, for Internet Protocol (IP) networks the Transmission Control Protocol (TCP)/IP layer model was proposed [3], [4], while different types of layer models are considered for Broadband Integrated Services Digital Networks (B-ISDN) [5], or for the Asynchronous Transfer Mode (ATM) solutions [6], [7]. All the above models can be considered specific instances of the generic model adopted in this work, consisting of the physical, link and network layers, and of a set of higher layers with functionalities and boundaries depending on the specific application context.

In parallel, the paradigm of cognitive radio (CR) communication has been developed over the last 15 years [8]–[11]. It proposes to endow the terminals with cognitive abilities so that they can decide when and how to transmit, depending on the environment in which they are operating. In order to achieve this goal, CRs need to implement several new functionalities. Specifically, it is necessary for a CR to sense the environment and the context of operation, identify the relevant features of this context, make decisions based on them, and finally communicate appropriately. Furthermore, the concept of the Cognitive Engine (CE), i.e., the entity responsible for steering the process of data collection and delivery is widely considered in the literature [12]–[16]. According to [17] a CE acts as an agent that makes decisions based on its own observation and experience and also supervises its own performance. It may incorporate functionalities such as learning, reasoning, input memory, experimental databases and decision evaluation. This doesn't imply that the CE makes all decisions nor that it executes algorithms belonging to different layers. The CE monitors the overall situation (on longer time-scales), exploits information from different layers and -based on cognition cycle outcomes- it provides updated parameters, new guidelines and constraints that can then be used on each layer for executing the respective algorithms (on shorter time-scales).

A natural question in the case of CR networks is therefore how to integrate the CE with the protocol stack and the services provided by the different layers, an issue that is often neglected when designing CR radio network algorithms and protocols that rely on the presence of a CE. In [18], for example, a load balancing algorithm based on a CE is proposed, but no discussion is provided on how the cross-layer information required to implement it should be conveyed and exchanged. In [19] a CE that relies on statistical modeling of environment parameters and hypothesis testing is proposed: in this case a list of parameters that need to be taken into account is provided, but methods to collect, exchange and feed to the CE such information are not discussed. Conversely, our work focuses on the identification of the interactions and

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information flows between the CE and the protocol stack layers that are necessary to support this cognitive behavior. The analysis carried out in our paper focuses on the relation between the CE and a layered protocol stack, and holds independently of the actual implementation of the CE, i.e. the CE may reside in a centralized, dedicated entity or it may be the result of a distributed approach, sharing its functions across the network.

In [20] the authors studied the Cognitive (Radio) Engine design principles aiming at configuring the radio system parameters so to achieve the best performance with respect to a predefined sets of objectives and constraints, formulated into a complex optimization problem. They surveyed and categorized the related problem formulation for single- and multi- carrier systems and they further subdivided each category into single- and multi- objective optimization. The paper also provided a survey of evolutionary algorithms for solving the above mentioned optimization problems. Our paper complements and extends [20] by introducing a taxonomy of the information elements from different protocol stack layers that are required for employing these algorithms and for solving the related optimization problems, also highlighting those information elements that transcend multiple layers.

The work in [17] provides a detailed study of the incorporation of CEs within CR systems and extends the CE scope to also describe the design of meta-CEs, that learn which CE is more appropriate to provide the adaptation needed for specific operating conditions, assuming that a meta-CE combines several CE algorithms to form an entity that exploits the strengths of its parts, thus resulting in better and more predictable performance. Our paper builds on such concepts since it shows in detail how information from different communication stack layers can be used by appropriate CEs or meta-CEs that will act as intelligent agents to process this cross-layer information and provide thus the expected performance optimization. In [21] the authors proposed a universal CE functional architecture design by studying the cognitive loop OOPDAL (Observe, Orient, Plan, Decide, Act, and Learn) by also considering a Knowledge Base. They integrated a cognitive core, a scheduler, a user interface, a sensor interface and a network interface that could make the necessary reconfiguration of the different OSI layer techniques according to the specific parameters, requirements and constraints. They proposed a structure for the cognitive core consisting of a data base, a learner, a reasoner and an optimizer. Also, in this case, our paper complements [21] since we follow similar architectural principles for the CE (trying to keep it as generic as possible to allow its applicability in many different scenarios and use cases) and we further show a hierarchical view of the related information elements in each of the lower communication stack layers that can be used by the various sub-blocks of the CE.

Considering the aforementioned analysis, it is apparent that an effective and precise parameter exchange i.e. the access to rich and accurate context information, is paramount for the practical implementation of future CR communication systems. This has led to the development of various cross-layer algorithms and solutions, that mainly concentrated on the lower levels of the protocol stack. Further research in the area of wireless communications and particularly of inter-layer data exchange, including higher layers as well, led to the idea of redefinition of the original layer stack model [22]. The mechanism by which information is exchanged between non-adjacent layers can differ between implementations; possible solutions include the introduction of direct interfaces between a protocol layer and all the layers with which it exchanges information, as well as the introduction of a common repository for all cross-layer information, to be used as a blackboard by all layers; in [22] a good overview of the different approaches is provided.

In [23] the authors also focus on the issue of cross layer information exchange for distributed CR networks, and identify some necessary operating parameters to be collected at each node and exchanged among nodes to perform distributed optimization, based on specific objective functions and employing genetic algorithms. In our paper we extend this view to capture all the important information in each communication stack layer that could be useful for different optimization frameworks and assuming both centralized and distributed management schemes.

Moving from the above analysis, the main target of this work is to classify and discuss the need for information exchange between the generic layered model introduced earlier and the CE as shown in Figure 1. In each of the following sections

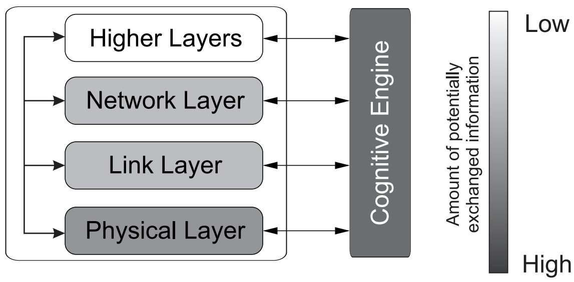


Fig. 1. The generic protocol stack with the cognitive engine entity; the amount of information that can be potentially exchanged to/from each layer/cognitive engine is illustrated using color coding

the services provided by each layer will be briefly presented, followed by the analysis of the information exchange between each layer and the other layers as well as the CE and by the individuation of information pieces, presented in a concise tabular form. Although it is not the goal of this paper to validate protocol modifications required to support the introduction of a CE, some examples of the potential impact of the introduction of a CE supporting and taking advantage of cross-layer exchanges will be provided in Section VII.

The paper novelties are summarized as follows. 1) It identifies and provides a detailed description of the information exchanges and the corresponding information elements in the protocol stack layers to be considered in the design of a CR system, providing a cross-layer information framework that can be applied to any existing or future CR system; 2) it discusses the corresponding implementation issues and optimal decision making sharing between the CE and the protocol layers.

The rest of the paper is organized as follows. Section II describes the role of the physical layer within the cognitive radio, discussing on the services that it provides and the information that it exchanges with the CE, as well as with the other layers of the protocol stack. Section III addresses the role and interactions of the link layer, while Section IV focuses on the network layer. Section V addresses the higher layers within CR. Next, Section VI summarizes the information exchanges between the layers and CE, discusses the challenges related to the implementation of CE and identifies future research directions. Section VII presents three use cases showing the potential impact of the CE on CR performance, and highlighting the required information exchanges. Finally, Section VIII concludes the paper.

II. The physical layer within cognitive radio

In this section we will focus on the services and functions involving the physical layer that are specific to CR: existing specifications of the physical layer include of course many services and functions that are not specific to CR, and therefore are out of the scope of this paper, but that are nevertheless necessary for the system operation. Furthermore, the section will address not only vertical interactions (i.e., with the link layer) but also horizontal ones (i.e. with the CE). Similar considerations hold for the other layers analyzed in Sections III-V.

A. Services provided

There are two basic services that the physical layer needs to implement in order to allow cognitive devices to operate, i.e., (cooperative) spectrum sensing and communication. The former is a new role of the physical layer, necessary in order to obtain information on the context of operation. In contrast, all current specifications of the physical layer already consider direct access to the communication medium. The difference is that, in the case of CR operation, it is required that the physical layer is able to adapt rapidly to the varying channel conditions. This brings new challenges to its specification and implementation.

Sensing services Spectrum awareness is a fundamental feature for identifying transmission opportunities in CR and other dynamic spectrum access (DSA) related technologies. Spectrum sensing is the primary asset of spectrum awareness, enabling devices and networks to detect spectrum characteristics, such as signal power or signal patterns, in order to identify the portions of vacant incumbent spectrum. Based on what the CR devices sense, the spectrum sensing techniques can be classified as either transmitter or receiver detection techniques. Interested readers are encouraged to search the rich literature on that still vivid research topic [24]–[29]. The physical layer has direct access to the hardware resources of the CR. It is therefore responsible of sensing in order to acquire information about the environment, for example to detect communication opportunities. Note that, however, the physical layer does neither take the initiative nor make any decision. It is the responsibility of the CE to determine what needs to be sensed, e.g., spectral bands, request this service from the physical layer, and to make a decision, e.g., the band is available or not, based on the data provided by the sensing service. This observation is of particular importance in the context of cooperative sensing, where final decision on the sub-band occupancy is made based on the information exchanged among or received from many users (nodes). Depending on the assumptions, e.g. on network topology (if it is centralized with dedicated steering node playing the role of fusion center, distributed or hybrid) different data can be exchanged between the nodes. And again, it is the role of CE, with the support of the link layer (see Section III) to control the sensing phase and manage the information exchange process.

Communication services. Generic descriptions of CR often assume devices to be fully reconfigurable. In practice, however, CR devices are limited by hardware and software constraints. This means that although several different paradigms have been envisioned, i.e., interweave, underlay, and overlay, and many different communication strategies have been defined, e.g., multi-carrier, spread spectrum, multi-antenna, etc., only a subset of them are available for a given device [30]–[32]. Some factors that limit the available operation modes are presented below.

- **Spectrum sharing modes.** Three different spectrum sharing modes with different degrees of sophistication can be envisioned: interference avoidance, interference control, or full coexistence with possible cooperation. Many CR devices will be restricted to only one or two of such modes. Moreover, not all primary systems are suitable for coexistence with all three modes.
- **Hardware constraints.** The technology used for realizing each CR device limits the available resources. For example, processing power, latency times, number of antennas, spectral characteristics of the filters, etc.
- **Software constraints.** Due to storage or processing limits devices may implement only a reduced set of software algorithms, hence limiting the modes of operation.
- **Regulatory constraints.** Regulatory bodies in different countries, e.g., the European Commission (EC) in Europe or the Federal Communications Commission (FCC) in the United States of America, are establishing legal frameworks for operation of CR systems for opportunistic spectrum access. These rules will restrict the operation modes and parameters, e.g., power allocation, tolerable interference by the primary users, etc.

B. Information exchange

In this subsection we focus on the signaling and information exchange between the physical layer and the CE. In addition, we identify the differences in the interaction of the physical layer with the neighboring layers due to the special requirements of cognitive operation.

1) To/From the CE: In general, the nature of the information exchanged between the physical layer and the CE depends on the spectrum paradigms implemented in the cognitive device. As an example, Figure 2 represents some of the distinguishing elements exchanged for each of the paradigms. In addition, there are also significant overlaps in the information required when operating under the different paradigms. For example, important pieces of information that are useful and necessary for interweave CR are also used in the underlay and overlay modes. Moreover, it is possible that a single CR device can operate under more than one paradigm. For this reason, the analysis of information exchanges in this section is does not refer to any specific paradigm. Firstly, we cover the information related to the services provided by the physical layer and listed in Section II-A and then other context information.

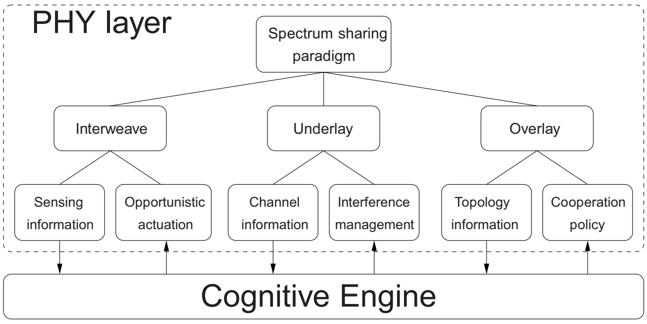


Fig. 2. Examples of information exchanged between the physical layer and the CE under different spectrum sharing paradigms.

Sensing information: The spectrum sensing services provide the necessary tools to assess the vacant incumbent spectrum. In order to operate with the required precision and reliability, spectrum sensing techniques must utilize the physical layer resources and the characteristics of the device in the most efficient manner.
However, different spectrum sensing techniques require different settings of the hardware parameters in order to perform the primary user detection, and correct settings and information exchange of the physical layer parameters are crucial for reliable spectrum sensing. Table I describes the information exchanged between the physical layer and the CE.

Communication information: Although the specific flow of information between the physical layer and the CE will heavily depend on the characteristics of the device and the modes of operation implemented, a general description of the information exchanged between the physical layer and the CE can be provided, and is shown in Table II.

Other context information: The information exchange between the physical layer and the CE is not only restricted to the services provided and required by the layer. Any information that might allow the CE to obtain information on the environment and making decisions should be exchanged with the physical layer. Table III summarizes other context features that do not fit in the previously described services but are useful for CR operation.

2) To/From the other layers in the protocol stack: This section focuses on the information exchanges between the physical layer and other layers in the protocol stack that are specific for CR operation, in particular for context identification and decision making.

To/From the link layer: In the protocol stack, link services are provided by layers above the physical layer, in particular by the link layer. Protocols that are not restricted to point-to-point communication require to some extent an exchange of information between the physical and link layers. We summarize the most common information exchanged in Table VII.

To/From the network layer: Recent advances in information and communication theory have assessed the benefits of a tighter interaction between the different layers of the protocol stack. The design of the network layer for a cognitive network may indeed benefit from the introduction of cross layer information from the physical layer. An example of this is the use of information on the presence and position of primary systems co-located with the secondary network, and of their emitted power in case they are transmitting. Integrating this information into the routing metric may significantly increase the coexistence capabilities of the cognitive network, and improve performance by guaranteeing higher path stability, e.g., by avoiding links subject to strong mutual interference with primary systems [33]. A second example is the combination of routing and network coding, as it is well known that network coding can yield significantly larger communication rates [34]. This increased throughput comes at the price of more sophisticated designs and an exchange of information between the physical, link, and network layers [35]. The amount and the nature of information to be exchanged depends heavily on the type of protocols used, which are currently in the initial stages of development.

III. The Link Layer within Cognitive Radio

A. Services provided

In CR networks, the link layer is responsible for accessing and efficiently utilizing the available spectrum opportunities. The following services can be identified.
Medium access. Besides the typical services provided to the network layer , e.g., fragmentation, framing, security, etc., the link layer also provides the key service of coordinating the access to the wireless medium by means of the Medium Access Control (MAC) sub-layer. In the case of CR networks this service differs from the one offered by link layer in traditional wireless networks as it pursues an optimal trade-off between the required application's QoS parameters, such as throughput and/or delay, and the sensing process. By managing the sensing operation of the physical layer and the spectrum access decisions obtained from the CE, the link layer controls the quality of the communication link [36].
Implementation and monitoring of sensing strategies. In CR systems, the spectrum access and sharing will be the result of decisions taken by the link layer on the basis of strategies set by the CE based on (i) the sensing information it receives from the physical layer, (ii) the targeted application, (iii) the supported operational mode by the network, (iv) the supported spectrum sharing modes (interweave/underlay/overlay) and (v) the protection constraints imposed by the incumbent system. In this context, the task of the link layer is twofold: 1) it has to feed the CE with the required information to define the optimal strategies and 2) it has to implement such strategies and

TABLE I
INFORMATION EXCHANGE BETWEEN THE PHYSICAL LAYER AND THE COGNITIVE ENGINE FOR SENSING SERVICES.

Parameter	Comments	Direction
Data from RSSI sampling	**Received Signal Strength Information (RSSI) sampling** is the simplest spectrum sensing approach. Due to its low signal processing complexity, it can be implemented in any sensing device. However, it offers limited options when manipulating the sensed data, thus it is only suitable for energy based detection.	PHY → CE
Data from IQ sampling	**In-phase Quadrature (IQ)** sampling requires higher computational and hardware complexity compared to RSSI sampling, but offers more options for manipulation of the sensed data. The IQ sampling is used in more complex and reliable detection techniques, e.g., Higher Order Statistics (HOS), cyclostationarity based detection, etc.	PHY → CE
Resolution bandwidth (Start and end frequency)	The **start frequency** defines the starting point of the sensed band, while the **end frequency** defines the ending point of the sensed band. They define the sensed bandwidth window as well as the frequency band that is being sensed. Both parameters can have impact on the sensing performance (higher resolution bandwidth can increase the accumulated noise level) and can vary for different scenarios and applications.	PHY ← CE
Number of sensed samples (Sampling rate / Sweep time / Sensing points)	The **sampling rate** defines how often samples are taken from the received signal. Increasing the sampling rate will increase the number of sensed samples. For example, in feature detection techniques higher sampling rate enables better performance of the detection method. The **sweep time** delineates the time needed to cover the whole sensing band. The ratio between the sweep time and the sampling rate gives the number of sensed samples per sweep, i.e., the number of **sensing points**. If multiple sweeps are performed, the number of sensed samples will be the product between the sensing point and the number of sweeps.	PHY ← CE
Sensing time (Number of sweeps / Dwell time / Sensing points)	The **number of sweeps** defines how many times the sensed band will be swept repeatedly. The **dwell time** shows how much time is dedicated per one **sampling point**. Hence, the total sensing time will be defined as the product between the number of sweeps, sampling points and dwell time. In general, a higher number of sweeps as well as a longer dwell time can increase the precision of the sensing technique, but will increase the sensing time as well.	PHY ← CE
Nodes' related information (Network topology / Number of nodes and their characteristics)	In the context of cooperative sensing the **network topology** determines the type of network of cooperating nodes (cooperative with leading node, distributed, hybrid); such information will be rather rarely distributed. The **number of nodes and their characteristics** indicates the presence and the type of cooperative nodes, i.e. the knowledge on the exact location of the neighboring nodes, on their velocity (if any) as well as on the level of nodes certainty in decision making process. Such information delivered to PHY and/or LINK layer allows for fine determination of e.g. the best sensing procedure, number of samples, creation of sensing nodes coalitions etc.	PHY/LINK ← CE

TABLE II
INFORMATION EXCHANGE BETWEEN THE PHYSICAL LAYER AND THE COGNITIVE ENGINE FOR COMMUNICATION SERVICES.

Parameter	Comments	Direction
Channel state information	**Channel state information (CSI)** is typically acquired by the physical and link layers. When provided to the CE, it can be used to make decisions to optimize the performance locally (e.g., selecting appropriate transmission rates, etc.) and globally (e.g., lowering unnecessary interference, routing traffic through higher capacity links, etc.).	PHY → CE
Propagation information	**Propagation information** can be either on the level of raw data or statistical models. The former is normally collected by a receiver, which can be a terminal or an access point, and used for short scale Radio Resource Management (RRM) and signal processing techniques such as fast power control and Adaptive Modulation and Coding (AMC). Therefore, it is normally stored in the receiver itself for short time. In addition, the information collected by the terminal is normally sent to the access point that may transform these raw data into statistical models. The raw data are deleted shortly after use (in the order of milliseconds) while the statistical models are stored for longer time and can be updated when significant changes occur in the system.	PHY → CE
External interference and SINR patterns	This information is normally collected by the receivers and stored for a short term. In addition, they are sent to the access point, where they are used to build interference Signal-to-Interference plus Noise Ratio (SINR) maps.	PHY → CE
Interference and leakage produced during operation	Co-existence of different users belonging to different systems requires strict control of the interference generated by CR equipment. In particular, it is important to measure the amount of energy transmitted not only in the nominal frequency band but also out of it. This is strongly related to the characteristics of the equipment used by the CR devices, which in turn may depend on the operating mode (e.g., spectrum paradigm, operation parameters, etc.). Metrics like the transmit power, or Equivalent Isotropic Radiated Power (EIRP), Peak-to-Average Power Ratio (PAPR), or Adjacent Channel Leakage Ratio (ACLR) are highly relevant. These parameters should be considered by the interference mitigation algorithms controlled by the CE.	PHY → CE
Operation mode	Based on the knowledge of the type of environment in which the CR is operating, its degree of sophistication, etc., the CE will choose among one of the different modes available for operation (i.e., spectrum sharing paradigms: overlay, underlay, or interweave). Information about the selected mode can be used for defining the transmit parameters, e.g., the maximum transmit power that will not cause violation of the interference limit induced to primary user, or the order of the applied, programmable reception filters.	PHY ← CE
Operation parameters	The CE, making use of all the available information, makes a decision on the desired mode of operation and specifies the different parameters that should be used for transmission/reception. For example, based on the availability of the spectrum, the knowledge about the surrounding primary system, the propagation characteristics, etc., the CE specifies the carrier frequency, bandwidth, transmission power, etc., to be used by the physical layer for communication.	PHY ← CE
Available operation modes	Not all the modes of operation implemented by a CR are available all the time (for example, due to low power, etc.). The physical layer should inform the CE about the available modes of operation. It will allow the CE to consider only available operation modes (please refer to "Operation mode" above). Finally, please note that an alternative to direct information collection by the PHY layer is the retrieval of information from external databases: most implementations are expected to rely on the combination of these two approaches.	PHY → CE

TABLE III
OTHER (POSSIBLY CROSS-LAYER) CONTEXT INFORMATION POTENTIALLY USED BY THE COGNITIVE ENGINE.

Parameter	Comments
Population and traffic distribution	This information can be collected by the access point by counting the different connecting identities (IDs) and the frequency of data transfer. This type of information has normally a repetitive pattern such as daytime and night periods where different patterns can be applied. This may be stored in the access point in order to be used for interference mitigation.
Static information	This includes information such as the characteristics of the building, the approximate position of the access points within the coverage area, etc. This type of information may be stored in a database and may be accessed by the access points that are within the coverage area.

enforce the resulting decisions regarding system parameters such as the transmit power, bandwidth, carrier frequency. The outcomes of the link layer's decisions taken on the basis of CE-set strategies will allow the link layer and the CE to improve the decision making process by utilizing learning mechanisms that harness historical spectrum data and past experiences.

Control channel. The CR link layer is provisioning the upper layers and the CE with adequate network resources for control signaling, such as dissemination of spectrum sensing outcomes, spectrum sharing decisions, access to radio environmental databases for retrieving radio context information, etc. This is typically achieved by means of a cognitive control channel [37], [38], selected on the basis of the input by the CE on best suitable primary user channels for control channel establishment, based on historical spectrum sensing decisions and exchanged data.

B. Services required

The link layer can make use of the two main services provided by the physical layer, namely the communication and sensing services.

Communication services. Moving from the traditional role of the physical as the interface between the link layer and the communication medium, recent advances in transmission protocols rely on a tight interaction between the physical and link layers and, in some cases, the network layer as well. It is indeed expected that in CRs the link layer will require new, flexible methods for accessing the communication medium, allowing for mixed physical-link layer communication strategies or even mixed physical-link-network ones. Indicative examples are:

- Relaying protocols that operate at physical and link layer level [39], [40].
- Overlay CR protocols that use mixed physical-link layer transmission strategies [41], [42].

Sensing services. The CE is the main user of the sensing services provided by the physical layer. However, some functions of the link layer may benefit from access to these services as well. In particular, this information is useful for some of the functionalities provided by the MAC, such as collision detection and avoidance mechanisms.

C. Information exchange

1) To/From the CE: The type and amount of information exchanged between the link layer and the CE largely depends on the operational scenario and the implemented optimization techniques. Table IV summarizes the types of information flows between the CE and the link layer.

2) To/From the other layers in the protocol stack: The link layer will have as well several information exchanges with other layers in the protocol stack, that are relevant to specific CR functions, such as decision making and context identification. While the interaction with the physical layer was described in Section II, Table V describes the most relevant information elements exchanged between the link layer and layers above it.

IV. The Network Layer within Cognitive Radio

This section tackles the problem of context information exchange and the decision making aspects from the perspective of the network layer. With the partial exception of the MAC sublayer, the network layer is the first layer within the protocol stack that carries on functions requiring end-to-end interaction among network devices [47], and traditionally interacts with the link and the transport layers. The deployment of network layer solutions for CR networks calls for additional interactions between network layer and other layers/modules, either pre-existing, e.g., with direct interaction between network layer and physical layer, as described later in this paper, or specific to the CR case, such as the CE.

A. Services provided

The network layer is in charge of providing two main services:

Routing. The main aim is the selection, maintenance and update of routes used for delivering packets from source to destination. It is expected that the definition of the routing metric and the selection of the routing algorithm will take place in the CE, based on information provided by multiple layers, including the network layer itself. Such elements will be used by the network layer to take routing decisions, possibly using information provided by the CE or by lower layers.

Flow/admission control. The main aim is to tune the rate of packets and the number of devices allowed in the network with the goal of adapting to congestion and network conditions in general; in this case as well coexistence requirements will be taken in to account by the CE in determining the admission control strategies later transferred to the network layer for implementation.

In addition, it is foreseeable that future specifications of the network layer will consider network coding services as well. Network coding aims at combining the packets at physical-network levels in order to increase the throughput of the network by exploiting the multiple routes existing in a network to reach a single destination.

B. Services required

The network layer traditionally requires services to be provided by the link layer. On one hand, the link layer is in charge of providing the information required for the network layer to take decisions; on the other hand the link layer is responsible for implementing at local scale the end-to-end decisions taken by the network layer. Among the main services required from the link layer, the following can be identified:

Provision of local information. The link layer provides the network layer information about the status of the node and of the surrounding nodes required to take routing and admission control decisions. Examples include the length of link layer packet queues and performance measurements of the MAC protocol.

Resource allocation. The link layer allocates the resources required to implement decisions taken at the network layer. Examples include the allocation of resources on a common

TABLE IV
INFORMATION EXCHANGE BETWEEN THE COGNITIVE ENGINE AND THE LINK LAYER

Parameter	Comments	Direction
Medium access-related decisions	This information can be regarded as the outcome of constrained optimization and/or learning-based mechanisms and it enables the essential strategy for secondary utilization of the available primary system spectrum. It comprises of spectrum access, sharing and resource allocation decisions. In particular, it includes the primary channels to be accessed by a particular secondary user and how the users share the available primary spectrum opportunities based on the employed spectrum sharing strategy (interweave/underlay/overlay). Additionally, it includes the bandwidth, power, modulation and coding allocated to the secondary users' scheduling strategy, as well as Automatic Repeat reQuest (ARQ) and buffer management information.	CE → LINK
Spectrum sensing-related parameters	This information is used by the link layer to control the sensing functionality of the physical layer and to provide an optimal tradeoff between the upper layers' QoS and the wasting of resources due to sensing. It comprises information on the primary channel sensing order and the duration of the sensing. Additionally, it contains information on the sensing metric, the cooperation strategy, if enabled, the sensing mechanism, etc.	CE → LINK
Additional radio context information	This information may include various types of radio environmental-related information that can be utilized by the link layer for improving certain functionalities, such as suggestions on primary channels adequate for control channel establishment in the case when the control channel management is performed by the link layer, etc.	CE → LINK
Medium Access feedback	Outcomes from the medium access process (such as intra-system or inter-system collisions, link reliability, length of packet queues etc.) are delivered to the CE for improving the medium access and the spectrum sensing. Also relevant for the network layer to adjust the cost of a link and evaluate routing performance	LINK → CE
Control channel-related information	It comprises information regarding the control channel management functionality of the link layer, such as the allocated band (licensed/unlicensed), establishment technique and parameters related to the establishment technique. For example, if the global dedicated control channel is established, the link layer feeds the CE with information about the frequency carrier, bandwidth and additional physical layer information.	LINK → CE

TABLE V
INFORMATION EXCHANGED BETWEEN THE LINK LAYER AND LAYERS ABOVE IT

Parameter	Comments	Direction
Network coding maps	Network coding spans across the physical, link, and network layers. In the cases where the network coding coefficients are defined by the network layer, this information has to be shared with the link layer as well for correct operation [43], [44].	LINK ← NET
Traffic demands	Awareness of the traffic demands of the secondary users is of significant importance as it allows to address the tradeoff between fulfilling the user demand and achieving increased spectrum utilization [36], [45].	LINK ← NET
Frame size	The TCP throughput can be maximized by employing cross-layer schemes that consider the link layer frame size [46].	LINK → TRAN
Medium Access feedback	MAC performance indicators, see Table IV.	LINK → NET

control channel to a new device accepted as a result of an admission control decision, or the management of data packets flowing as a result of a routing decision that includes the node in a route.

In addition, some of the services that are traditionally provided separately by the network and link layers might be provided jointly in the context of a cognitive network. As an example, combined routing and channel allocation in interweave CR has been proposed by several researchers as a solution to increment efficiency [48]–[50]. In particular, dynamic routing in CR ad-hoc networks can be highly benefited by receiving and/or cooperating with the spectrum management services offered by the link layer. More specifically, routing in the network layer can be jointly designed with spectrum and power allocation. To this end, the joint routing and spectrum management process can take into consideration information on the availability of spectrum holes, which depends on the interference caused by neighboring primary or secondary nodes, and the traffic load in each node. As a result, routing traffic through congested paths can be avoided, improving the resource utilization in terms of throughput, fairness and delay [51], [52].

C. Information exchange

In order to provide the services defined in Section IV-A in the context of a CR network, the network layer will need to access information generated by several different layers of the protocol stack, and the reader can find the corresponding information bits in Tables V and VII. Table VI additionally provides a list of parameters that the network layer might/should exchange with the CE. In general, the network layer will be in charge of providing the information related to the status of the network nodes (at least for network-related aspects, such as end-to-end delay measurements).

V. THE HIGHER LAYERS WITHIN COGNITIVE RADIO

All layered models identified in Section I define a set of layers above the network, ranging between a very detailed subdivision (e.g. the set of transport, session, presentation, and application layers in the OSI model) and a broader one (e.g. the transport and application layers covering the same set of functions in the TCP/IP model). Irrespectively of the specific division, however, this set of layers has the goal of ensuring the interface between the network and the user application space. The generic layered model adopted in this work jointly defines these layers as a *Higher layers* entity, as illustrated in Figure 1.

Contrarily to the lower layers in the generic layered model discussed so far, which are widely affected by the introduction of the CR concept, the impact of CR on higher layers is so far less explored. In general, only few papers in the literature suggest the need of higher layers adaptation to the new requirements arising from the application of the CR networks, and typically in specific scenarios such as highly dynamic cognitive radio networks (with frequent spectrum handover), where it can be foreseen that higher-layer solutions and algorithms should be delay-tolerant. Indeed, intuitively the

TABLE VI
INFORMATION EXCHANGE BETWEEN THE NETWORK LAYER AND THE COGNITIVE ENGINE.

Parameter	Comments	Direction
End-to-end delay	The delay experienced by packets in an end-to-end connection can be used to monitor the performance of active routes and determine a change of routing strategy at the CE in case its value is consistently beyond a QoS threshold.	NET → CE
Network topology	**Network topology** refers to the topological information available at the network layer, including the set of nodes and of links between them. Specific routing protocols may store additional information, such as the average number of neighbors.	NET → CE
Routing metric / algorithm	The network layer will use this information to take routing decisions, e.g., by determining routes, updating routing tables and routing data packets accordingly.	CE → NET
Admission control strategy	The CE will determine the admission control strategy based on inputs provided by several layers, and transfer it to the network layer for actual implementation.	CE → NET

functionality of the higher layers will be influenced by the cognition ability of the wireless terminals or networks in a more subtle and indirect way. The remainder of this section will analyze the potential interactions between higher layers on one hand and the CE and lower layers on the other.

A. Services provided

An important aspect of the CE are its cognition capabilities, i.e., building knowledge based on its past experience and exploiting it for future decisions/actions. Higher layers provide knowledge-based services fundamental to achieve this goal, as described below.

Acquiring and learning user and context information. This service aims at learning on one hand user preferences and behavior and user device capabilities, and on the other network capabilities and characteristics. The service is required in all cases where interaction between user and network should be improved (e.g. to enhance the QoS provided to the user or the overall network capabilities by enrolling user devices). Examples of user information that may be targeted are:

- the set of potential configurations, e.g., the radio access technologies the mobile device is equipped with, as well as the associated spectrum and transmission power levels,
- the set of services that can be used and the corresponding set of QoS levels,
- the utility associated with the use of a service with a given Quality of Experience (QoE),
- the maximum price the user is willing to pay to use a service with a given QoE,
- user mobility behavior.

While for network information one can identify:

- data about available access technologies/operators in a given area and their corresponding status, e.g., used frequencies, available resources, coverage, etc.,
- information on the device status, e.g., coverage at the current location, power available, technology capabilities, etc.,
- information on the status of other devices in the area, e.g., activity, ability to cooperate, etc.

Management and enforcement of policy information. Policies are the rules that guide and govern the decisions of the networks and the devices. They are usually derived through the translation of high level business objectives in domain- or device-specific instructions and constraints. This service includes their management and enforcement given the existing user and context information. Therefore, information coming from the above service is used to define the policies to be activated in each case.

Learning related to the efficiency of decisions. This service builds knowledge to be used to evaluate, revise and optimize the decision process, by evaluating the actions taken based on the context information available before the action and the results of the action had, e.g., in terms of QoE (and in general beyond network performance indicators, as a similar process takes place at the network layer). The service will enable the CE to take efficient and quick decisions when facing again previously encountered problems/contexts.

B. Services required

The overall functionality of higher layers strongly depends on the set of services provided by the lower layers: rather than repeating them here, two examples of their use are provided below.

Transport protocol optimization. Spectrum management services provided by the link layer and spectrum sensing services provided by the physical layer can be used for the performance improvement of the transport layer operation. For instance, in [53], the TCP throughput is maximized by jointly considering spectrum sensing, access decision, physical-layer modulation and coding scheme, and link layer frame size. More specifically, based on the history of observations and decisions, the secondary user can decide whether to sense the channel and obtain the sensing outcomes, which are directly sent to the TCP layer. in the context defined in this work, the CE would take over the decision role, leaving to the transport layer the role of implementing and monitoring the decisions.

Application perceived quality maximization. The efficient provision of QoS at the application layer is a highly challenging issue in CR networks, mainly due to the increased dynamism of the networking conditions that cannot always guarantee the availability of the required resources. The application layer operations can be significantly enhanced by spectrum management services provided by the link layer. For example, channel selection for spectrum sensing, access decision, and intra refreshing rate are determined concurrently to minimize the distortion at the application layer in [54]. A formulation for the CR video multicast problem, taking into account various cross-layer design factors, such as scalable video coding, spectrum sensing, dynamic spectrum access, modulation, scheduling, error control, and primary user protection is introduced in [55]. Again, by adopting the framework discussed in this work the CE would gather information from application and lower layers and set the strategies to be implemented at the application layer.

C. Information exchange

The higher layers are indirectly affected by the introduction of the CR concept, as improvements achieved at the lower layers influence the higher layer as well. In addition, specific cases where higher layers protocols may benefit from CR-related information from lower layers were identified above: the corresponding information to be exchanged between the higher layers and the physical and link layers is summarized in Tables VII and V, respectively.

VI. Challenges for optimized decision making based on rich context information

The analysis carried out in Sections II-V lends itself to a few observations: 1) the set of parameters cannot be considered (nor it was meant to be) exhaustive, as one could easily identify other pieces of information that would be useful/necessary in specific deployment scenarios; 2) closer cooperation between all layers and CE can play an important role in the realization context-aware, application-oriented communication systems. The role of a rich information exchange between layers is exemplified in Figure 3, that highlights a few characteristic features and open issues in the deployment of a context-aware CR network:

Full mesh network - the protocol layers and the CE form a full mesh network, posing an optimization problem significantly harder than the one posed by the traditional layered model, where the lack of cross-layer interfaces significantly reduces the space of potential solutions, calling for research on achieving trade-offs between complexity and efficiency.

Unbalanced layer model - the number of parameters generated by lower layers stack is much greater when compared to those involving higher ones, in line with the fact that radio reconfiguration mostly involves the lower stack layers. It is however worth investigating whether a stronger involvement of higher layers in the decision making process might open new research areas, as suggested by the use case presented in Section VII-C.

Implementation and efficiency constraints - Intentionally, the model presented in this paper does not specify whether the CE is implemented in one real node (device, base station) or it is a separate entity, or whether it is a centralized unit or the result of distributed processing enabled by message exchanges between multiple CEs. Actual implementations will however have to deal with several constraints and limitations:

1) timing constraints in the collection, storage and exchange of context information. Highly dynamic information, such as real time path loss or instantaneous power distribution, should be stored as close as possible to the point of decision. Oppositely, information of less dynamic nature, such as maps and characteristics of a building, position of the access points, propagation and traffic pattern models, etc., could be stored in more distant databases.
2) spatial constraints: data that are computationally complex to be processed should be stored close to network elements with high computational power.
3) the amount of information to be processed as well as the required accuracy and level of complexity suggests that it will be all but impossible to collect all information in one place or entity (such as one specific layer or the CE), analyze it, make reliable decisions (especially if such decisions should be made in a short time scale), and report and execute these decisions in real-time.

The above observations clearly indicate that in a practical implementation some rapid decisions will be made locally by each layer (thus each layer will be equipped with some tools for making fast decisions), and the role of CE will be to monitor the overall situation based on the reports delivered from the layers, and to provide long-term guidelines and constraints for the layers, leaving to them decision making at the local- and short-time scale. Achieving a satisfactory trade -off between ”centralized” CE decisions and autonomous operation by the layers will be indeed one of the major research challenges in the design of CR networks.

VII. Use cases for interaction between CE and protocol layers

A. Capacity-aware MAC for interweave secondary systems

Cooperative spectrum sensing (CSS) is an extension of interweave secondary systems that enables a more reliable discovery of incumbent transmitters. However, a tradeoff exists between the sensing performance and the secondary system communication performance, and it is often more efficient for the CE to optimize the spectrum sensing process in terms of the secondary system's performance rather than simply the primary signal detection performance [56]. The MAC optimization process by the CE should thus solve the following problem [57]:

$$\max\{C_{su} = \Theta \frac{T - T_s - T_c}{T} (Q_{fa}) \left(1 - \frac{B_c}{W}\right)\} \quad (1)$$
$$s.t. Q_d \leq Q_{dmin}$$

where C_{su} is the secondary system capacity and T is the SU system frame duration, defined as $T = T_d + T_s + T_c$, denoting with T_d, T_s and T_c the duration of the data transmission period, the sensing period and of the sensed information distribution period, respectively. Θ is the Shannon's channel capacity and is defined as $\Theta = W \log_2 (1 + \bar{\gamma})$, where W denotes the SU system bandwidth and $\bar{\gamma}$ denotes the average SNR in the SU system, and finally B_c is the control channel bandwidth. Q_{fa} and Q_d are the false alarm and detection probabilities induced by the underlying CSS approach and sensing technique. Finally, Q_{dmin} is the lower bound of the detection probability of the underlying sensing technique, usually defined by regulatory bodies. Figure 4 depicts the achievable SU capacity ($R = C_{su}/\Theta$) in dependence of the SNR on the sensing channel, for the capacity-aware MAC for two CSS fusion techniques, Equal Gain Combining (EGC) and Majority Voting (MV) and for different number of cooperating nodes K. The figure shows that the optimal values of the sensing setup parameters (i.e. the number of signal samples N, noise samples M, and B_c) are different for different scenarios and depend on the CSS fusion technique, the number of

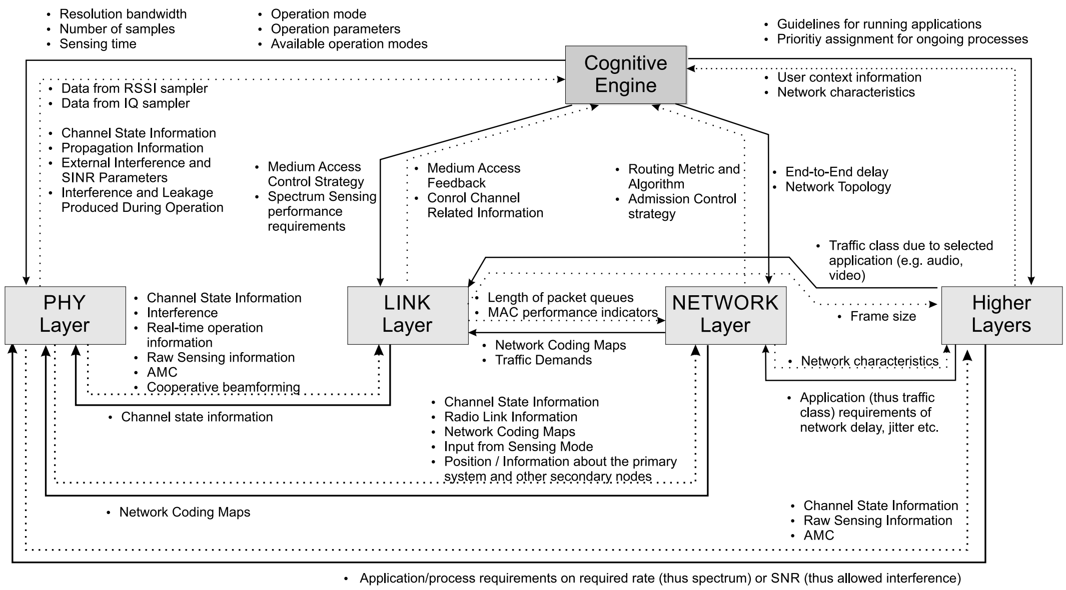
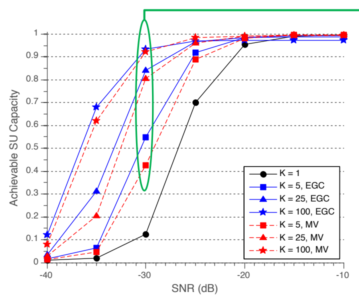


Fig. 3. Illustration of the possible messages exchanged between the layers and the CE



K, CSS	i	m	Bc (Hz)
5, EGC	21	13	$2*10^4$
5, MV	21	15	$1*10^4$
25, EGC	20	6	$6*10^4$
25, MV	20	12	$2*10^4$
100, EGC	18	10	$1*10^5$
100, MV	19	5	$4*10^4$

Optimal *i* ($N = 2^i$), *m* ($M = m*N$) and *Bc*

Fig. 4. Achievable SU capacity R (Q_{dmin}= 99%, T=1s) in [57].

cooperating nodes, and the SNR on the sensing channel. In order to achieve the optimal capacity, the SU system must take into consideration the optimization problem in Eq. 1 instead of using the conventional sensing, which maximizes the detection performance. Moreover, for low SNR regimes (e.g. <-30dB) the single sensing node approach ($K = 1$), is highly suboptimal and achieves negligible system capacity, calling for cooperation among sensing nodes in order to achieve higher SU system capacities, especially considering that in real-world scenarios the SU system must detect a DTT PU signal in $Q_{dmin} = 99\%$ of the time for received SNR values below -25 dB [58]. Inputs required from physical and link layers to solve the problem defined in Eq. 1 can be found in Tables I, II and IV.

B. Cross-layer routing in underlay cognitive networks

Routing is a network function that may significantly benefit from the introduction of a CE capable of collecting data from other layers and integrate it in the routing function. In [59] it was shown in particular by authors of this paper how routing in underlay cognitive radio networks can be improved by including two information bits provided by the physical layer and identified in Table VII: 1) position information and 2) radio link information, more accurately, maximum interference thresholds. [59] proposed in fact a routing strategy that a) uses position information to introduce beamforming and b) optimizes the route by considering interference constraints both in the underlay network and towards a coexisting primary network. Figure 5, obtained based on results presented in [59], shows indeed how mutual interference generated in the underlay network was significantly reduced by the proposed routing strategy even in presence of a large number of primary network terminals. The application of such a strategy requires however a central unit capable of determining the optimal routing algorithm and metric, and transfer them to the network layer for routing decisions: this central unit is indeed the CE, operating on the basis of the cross-layer information exchanges discussed in this work.

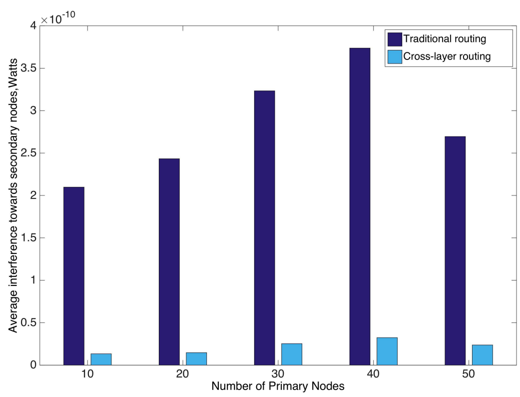


Fig. 5. Interference mitigation obtained by cross-layer routing in cognitive networks in [59].

C. Load prediction mechanism

This mechanism is capable of i) exploiting past data coming from diverse sources, ii) learning network behaviour in terms

of load with respect to them and iii) predicting the future state of the network in terms of load that will be encountered in the near or distant future. The mechanism learns the way (bank) holidays influence network load by describing the context of network operation with the following information: time, day, area and if it is a (bank) holiday or not. Such data can be obtained from physical and link layers, see Table III.
The mechanism is based on the unsupervised learning technique known as Parameterless Growing Self-Organizing Maps (PLGSOMs) [60]. PLGSOM clusters the data that describe the past experience of the network according to their resemblance and identifies the patterns among them. The mechanism relies on the clusters created by the PLGSOM in order to predict future network load as follows. Each situation is described using the context information introduced above and then mapped on the PLGSOM clusters (using the same algorithm that initially created them). The expected load will then be derived from past load values of the selected cluster. Fig. 6 depicts comparative diagrams between the predicted and the real load values of different access points and shows that although the mechanism predicts the average pattern of the load it fails to predict some of its peaks, due to unpredictable events that suddenly attract more users, such as a popular event occurring next to a specific access point or the failure of another one. These events are not captured by the selected context information and thus the mechanism cannot learn them or predict them: a richer context information provided by the user or a feedback loop informing the CE about the difference between the prediction and the actual load would further improve the performance.

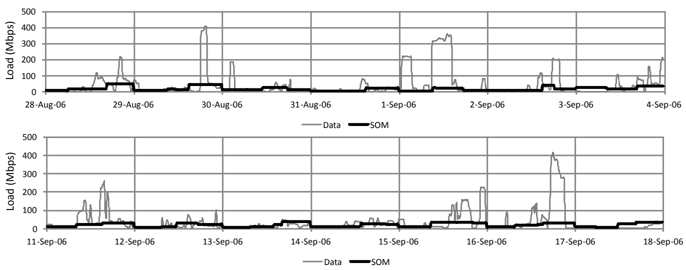


Fig. 6. Indicative examples of comparative diagrams of real and predicted load values for different access points.

VIII. Conclusion

This paper analyzed the role of cross-layer information exchanges in context-aware CR networks by adopting a generic layered model composed of physical, link, network and higher layers extended by introducing a CE. For each layer the services provided to and required from other layers were identified, and the corresponding information pieces to be exchanged with such layers and with the CE were identified. The analysis and classification effort was complemented by a set of use cases supporting the introduction of cross-layer exchanges and of a CE, and led to the conclusion that although current research activities focused mainly on the lower layers, significant performance improvements can be expected by including to a larger extent higher layers in the information exchange loop. The analysis also led to the conclusion that implementation of a CR network in a real-world scenario will most likely require the partition of decision making process between the CE and protocol layers.

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TABLE VII: Information exchanged between the physical layer and other layers of the protocol stack

<table>
<tr><th>Parameter</th><th>Comments</th><th>Direction</th></tr>
<tr><td rowspan="4">Channel state information</td><td>Knowledge of channel state information from neighboring nodes can be used to improve the efficiency of communication (e.g., interference decoding methods, beamforming, etc.). Part of this information is obtained by the physical layer (e.g., information on the channel state from other nodes to the device itself) but is used, in combination with other information (e.g., reported by other nodes), by the link layer.</td><td>PHY → LINK</td></tr>
<tr><td>In addition to the channel state information obtained by the device itself, information obtained by other elements in the network (e.g., information about the channels from the node itself to other nodes) is useful as well. This information is usually exchanged between nodes in the network at link layer level.</td><td>PHY ← LINK</td></tr>
<tr><td>Updated information about the channel from and to a given device is essential for network coding protocols to operate. The physical and link layers are the natural interfaces for obtaining this information that will have to be propagated to the network layer (as well as to the CE, as described in Section II-B1).</td><td>PHY → NET</td></tr>
<tr><td>The information on the wireless channel state can be very useful in the operation of the application layer that can adapt its performance towards improving the Quality of Service (QoS) [54], [55].</td><td>PHY → APP</td></tr>
<tr><td>Interference</td><td>The physical layer can measure values of the interfering signal that might be useful for link layer protocols. Examples of this information are interference power, activity of the interfering devices, etc.</td><td>PHY → LINK</td></tr>
<tr><td>Real-time operation information</td><td>The physical layer has direct access to the hardware resources for communication. The information on the static (e.g., due to the architecture of the device) and dynamic (e.g., due to the available battery) hardware characteristics are relevant.</td><td>PHY → LINK</td></tr>
<tr><td rowspan="3">AMC information</td><td>Adaptive Modulation and Coding (AMC) information can be considered at the link layer in order to improve the performance of Truncated Automatic Repeat reQuest (T-ARQ) [61].</td><td>PHY → LINK</td></tr>
<tr><td>The TCP throughput can be maximized by employing cross-layer schemes that adapt the Modulation and Coding Scheme (MCS) at the physical layer [46].</td><td>PHY → TRAN</td></tr>
<tr><td>The modulation and coding scheme plays an important role on the performance of the application layer, as it influences the achievable data rate and symbol error rate [55].</td><td>PHY → APP</td></tr>
<tr><td rowspan="3">Raw Sensing Information</td><td>The consideration of the sensing information allows the efficient exploitation of the spectrum holes of the primary users and the achievement of a significantly higher system throughput [62].</td><td>PHY → LINK</td></tr>
<tr><td>The secondary user can consider the results of the spectrum sensing performed in the physical layer to improve the TCP throughput [53].</td><td>PHY → TRAN</td></tr>
<tr><td>Cross-layer schemes that aim at improving the QoS at the application layer require information on the results of the spectrum sensing process in order to perform the required adaptations accordingly [54], [55].</td><td>PHY → APP</td></tr>
<tr><td>Cooperative Beamforming</td><td>In the case of cognitive relay networks, cooperative beamforming can be considered in order to enable forwarding of messages in busy timeslots without causing interference to primary users, so as to achieve a cooperative diversity gain and improve the QoS for secondary users without consuming additional idle timeslots or temporal spectrum holes [63].</td><td>PHY → LINK</td></tr>
<tr><td>(Radio) link information</td><td>Knowledge of the topology of the network is necessary for establishing the optimal routes for information. Therefore, updated information on the availability of the links, their capacities, latencies, etc., will have to be exchanged between the lower layers of the protocol stack. This is particularly important for wireless links, where this information changes over time.</td><td>PHY → NET</td></tr>
<tr><td>Network coding maps</td><td>In the cases where the network coding coefficients are directly chosen by the physical layer or network coding is performed directly over the signal space, e.g., [64], it is necessary to share this information with the network layer.</td><td>PHY → NET</td></tr>
<tr><td>Input from sensing module</td><td>The output of the sensing module can be taken into account in the selection of the end-to-end path in a multi-hop cognitive network. Depending on the class of cognitive network considered, this input can take different forms:
Underlay cognitive network: in this case the input may consist in the perceived power from nearby primary transmitters, and can be integrated in the cost function used by the routing protocol to evaluate the cost of a link.
Interweave cognitive network: assuming a network operating on multiple channels and trying to select on each hop a channel not used by the primary, the input may consist in an indication on which channels were considered as free/busy. In joint channel allocation/routing solutions, this information may also lead to the selection of paths characterized by the maximum stability or the lowest number of channel switches along the path.</td><td>PHY → NET</td></tr>
<tr><td>Position/ direction information about the primary systems and other secondary nodes</td><td>The position information, gathered, e.g., by dedicated hardware for Angle of Arrival (AoA) or Time of Arrival (ToA) estimation may be integrated in the routing protocol by adopting a position-aware routing algorithm. Positions of the primary systems can be used as constraints in the selection of the best end-to-end path.</td><td>PHY → NET</td></tr>
<tr><td>Network coding maps</td><td>Network coding achieves higher rates in the network by combining the information available at the nodes. In order to recover the information at the intended destination it is necessary to know how the information is combined through the network (e.g., knowledge of the network coefficients in the case of linear network coding). Both static and dynamic (i.e., random) network coding protocols have been proposed, and thus this information might be naturally available at different layers depending on the choice of protocol [65]. If the network coding coefficients are defined by the network layer, then this information has to be shared by the physical layer as well.</td><td>PHY ← NET</td></tr>
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