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A Review of Cross-layer Design in Dynamic Spectrum Access for Cognitive Radio Networks

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Cognitive Radio (CR) is an intelligent radio that can dynamically access the radio spectrum. Secondary users in Cognitive Radio Network (CRN) can access the licensed spectrum without causing harmful interference to primary users. The performance of cognitive radio networking functionalities depends on the properties of the spectrum band in use. This necessitates a cross-layer design in the entire CR networking protocol stack. Current researches are investigating different techniques of using cognitive radio to reuse more locally unused spectrums to increase the total system capacity. This paper provides a comprehensive survey of cross-layer design in cognitive radio network. The cross-layer design approach jointly considers the functions of the layers to maximize the performance of CR networks.

Keywords: cognitive radio network, cross-layer design, secondary users

1. Introduction

Cognitive radio is an intelligent radio which will change its transceiver parameters dynamically depending upon the environment conditions (I. F. Akyildiz et *al*., 2006). In cognitive radio networks, each secondary user can dynamically access the spectrum without interfering with primary users in the network. A user node can join in a cognitive radio network, if it has wireless-communication, networking and cognitive radio capability. There are two types of users using the network; Primary Users (PUs) and Secondary Users (SUs). Primary Users are also called licensed users who will utilize the already allocated spectrum. Secondary Users are also called Cognitive Users or unlicensed users because, for communication, no fixed spectrum is allocated for SUs (E. Buracchini, 2000). SUs can utilize the spectrum of PUs without giving interference to the PUs.

The Quality of Service (QoS) parameters of network are bandwidth, end-to-end delay, jitter, throughput, etc. All the networks offer two types of quality of services: guaranteed QoS and best-effort QoS (Sanjay Shakkottai et *al*., 2003). For PUs, guaranteed Quality of Service is provided. For SUs, best-effort QoS is provided, as they use the unused spectrum of PUs when there is a need for communication. When a particular licensed spectrum is free, SUs will be using that licensed spectrum. When PUs come to access that spectrum, SUs will move to the other vacant spectrum without giving interference to the PUs. The vacant spectrum is called white space or spectrum hole and is

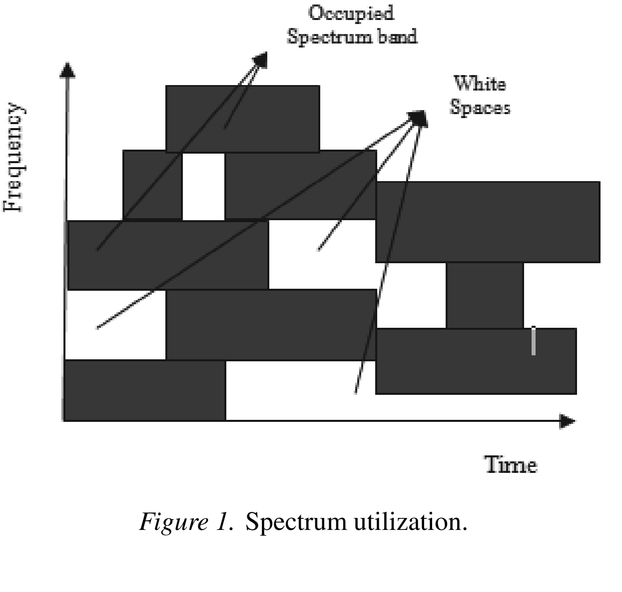

Figure 1. Spectrum utilization.

shown in Figure 1. Every spectrum hole includes several channels (I. F. Akyildiz et *al*., 2006) (H. Xianwei Zhou et *al*., 2009) and each channel can be used for communication when it is associated to a radio interface of some nodes.

Cognitive radio networks are classified depending upon the different network structure as shown in Figure 2.

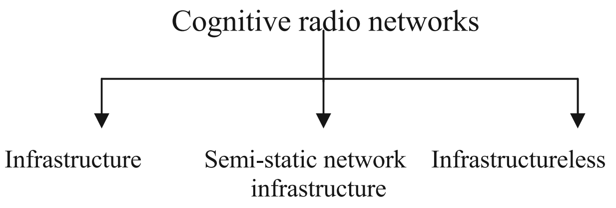

Figure 2. Classification of cognitive radio networks.

Infrastructured cognitive radio network is also called centralized cognitive radio network (Beibei Wang et *al*., 2011). In infrastructured cognitive radio networks, there will be separate base station for SUs and PUs. The base station used by SUs is called Secondary base station. Infrastructureless cognitive radio network is also called Cognitive radio adhoc network. In infrastructureless cognitive radio network, there is no base station. The SUs in the network will communicate among themselves typically like adhoc network, using the vacant licensed spectrum band. The Semi-static network infrastructure cognitive radio network is also called Cognitive wireless mesh network (Matteo Cesana et *al*., 2011). Wireless mesh network is self-organized and self-configured. It consists of mesh nodes which can get internet access through mesh routers. Mesh nodes are wirelessly connected in adhoc manner.

Cognitive node uses two different approaches to access the spectrum: spectrum overlay and spectrum underlay (I. F. Akyildiz et *al*., 2008). In overlay approach, secondary users occupy the unoccupied spectrum holes when the primary users are not occupying it. When the PU starts transmitting in that spectrum, SU move to another unoccupied spectrum hole and do not give interference to the primary users. On the other hand, in underlay cognitive system, secondary users use the spectrum when the primary users are transmitting. SUs operate at low power and below the interference threshold of the primary users.

2. Various Approaches in Cross-layer Design

To make communication between two different devices, a seven layer OSI Reference model was modeled by ISO. Later, for internetworking, TCP/IP model was introduced. In that, Application, Session and Presentation layers are combined and the combined layer is called Application Layer. The information available at each layer will be useful for analysing performance of the protocol. In physical layer (Vijay T. Raisinghani and Sridhar Iyer, 2004), the information about transmit power, bit-error rate, adaptive coding and modulation are available. The various information available at datalink layer are current Forward Error Correction (FEC) Scheme, number of frames retransmitted, adaptive frame size and hand-off related events.

The information available at network layer is hand-off initiation/completion events and network interface currently in use. The transport layer information is round-trip time, maximum transmission unit, receiver window, congestion window, number of packets lost and actual throughput. The application layer communicates to the lower layers for its quality-of-service needs such as delay tolerance, acceptable delay variation, required throughput and acceptable packet loss rate.

In wireless networks, the layered architecture of protocol design cannot provide optimal performance. Also, to achieve high end-to-end throughput, to increase the network capacity and utilization and to reduce interference and power consumption for various applications, a cross-layer design is proposed. The cross-layer design can be done between physical and datalink layers, datalink and network layer, network and transport layer, datalink and transport layer etc (Vineet Srivastava and Mehul Motani, 2005) and is shown in Figure 3.

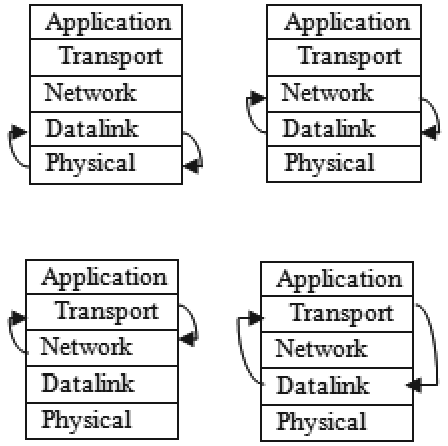

Figure 3. Various cross-layer designs.

In cognitive radio networks, the cognitive engine at the heart of cognitive radio will leverage on cross-layer information exchange and interactions with different wireless interfaces and devices in order to achieve the best quality of service for all communications (Nicola Bala and Michele Zorzi, 2008).

3. Survey on Cross-layer Design Between Physical and Datalink Layer

The function of physical layer is to transmit data in the form of bits with minimum bit errors and with suitable power (Vijay T. Raisinghani and Sridhar Iyer, 2004). The function of datalink layer is to provide link-to-link communication and fragment data into frames so as to ensure reliable transmission with minimal overhead. The authors (Rui Wang et *al.*, 2009) have jointly done a cross-layer framework by combining spectrum sensing and subcarrier adaptation for downlink Orthogonal Frequency Division Multiple Access (OFDMA) based CR systems. This optimizes system utility and maximizes system throughput.

In the paper (Dan Chen et *al.*, 2012), a cross-layer design is proposed between physical and datalink layer of cognitive radio network. To maximize the throughput, physical layer adaptive modulation and coding (AMC) and datalink layer adaptive frame size (AFS) are jointly considered together with best-relay selection and power allocation. This cross-layer design follows underlay CR relay networks, guaranteeing that the primary transmission is provided with minimum rate for a certain percentage of time.

In (Rong Yu et *al*, 2010), cross-layer optimization framework is proposed by considering Call Admission Control (CAC) strategy and spectrum sensing scheme. The parameters of CAC and spectrum sensing are simultaneously tuned to minimize the dropping rate by satisfying blocking rate and interference threshold. The computation complexity of this cross-layer design is O (M^3N^9 logMN), where 'N' represents total number of channels and 'M' represents selection of stair number in multiple-stair Markov approximation. At M=4, acceptable computational complexity and satisfying accuracy are obtained.

The primary network can be of any existent wireless networks. The authors (Show-Shiow Tzeng and Ying-Jen Lin, 2013) considered a primary network, in which time is divided into slots and data transmission takes place in a time slot. The secondary user which attempts to send data in a time slot will start sensing the spectrum band sequentially. If the particular spectrum band is free, it transmits data with fixed frame size. This paper has presented forward and recall sensing policies. The forward policy senses bands one by one and recall policy senses a band, and records the related information for further communication. A cross-layer design is done between physical and datalink layer which selects optimal sensing time and frame size for the forward and recall sensing policies. Recall sensing policy gives a more effective throughput than other sensing policies at light channel load.

In (Jinchang Lu and Maode Ma, 2013), the authors have proposed a cross-layer CR-based Connection Admission Control to provide QoS guaranteed services to heterogeneous traffics in WiMAX systems. The proposed approach considers Adaptive Coding and Modulation information from physical layer and bandwidth allocation assignment from the scheduler to enhance QoS provisioning for real and non-real time traffics in the WiMAX systems and the accuracy of Connection Admission Control decisions can be improved. Thus, the WiMAX system can operate under more than one spectrum to improve the system capacity significantly.

The end-to-end TCP performance is improved by using a cross-layer perspective in (Changqing Luo et *al.*, 2009). In this, modulation and coding scheme in the physical layer, and frame size in datalink layer are jointly considered. Here a multi-channel access process in cognitive radio network is modeled as a special type of stochastic control problem called restless bandit system. The channel with the highest index is selected to access, which can achieve the highest end-to-end throughput. In (Hao Ma et *al.*, 2012), to maximize spectral efficiency with a target packet loss rate, a cross-layer design is done by considering aggressive adaptive modulation and coding at the physical layer with truncated automatic repeat request at the datalink layer.

The authors in (Ghada Hatem et *al.*, 2013) have done a resource allocation algorithm where each secondary user can transmit and receive variable number of packets at each time slot. The scheduling algorithm implemented in this increases the throughput and decreases the average packet delay of the secondary user. In this, the primary user suffers a small delay and spectrum underlay model is used. In (Changqing Luo et *al.*, 2010), the cross-layer design is done by jointly optimizing spectrum sensing, access decision, physical layer modulation and coding scheme and datalink layer frame size in cognitive radio networks. In this, the lower layer design parameters are jointly optimized to maximize the TCP throughput in centralized cognitive radio network.

In (Gengyu Li et *al.*, 2011), to improve the energy efficiency of TCP, a cross-layer design is done by considering the lower layer parameters such as signal-to-noise ratio, modulation in physical layer and frame size in datalink layer. The finite state Markov channel is used to model the fading channel and primary user state of each channel. The decision process is done by a restless bandit approach. In (Leila Musavian and Tho Le-Ngoc, 2012), Nakagami-*m* fading environment is considered, the secondary user uses adaptive-power adaptive modulation and coding in physical layer and automatic repeat request at the datalink layer to maximize the effective capacity of SU link under joint packet error rate and delay constraint.

A cross-layer framework is done by combining adaptive modulation and coding (AMC) with truncated automatic repeat request (ARQ) in an SU to achieve high spectral efficiency by maintaining target packet loss probability (Yuli Yang et *al.*, 2012). This minimizes packet error rate (PER) at each AMC transmission mode subjected to satisfying spectrum-sharing limitations. In (Leila Musavian and Tho Le-Ngoc, 2012), the spectrum sensing in physical layer is integrated with packet scheduling at MAC layer to quantitatively identify the tradeoff between the aggregate traffic throughput and the packet transmission delay in non-saturation network.

In (Yi Peng et *al.*, 2009), dynamic channel allocation is achieved by optimizing joint power control and link scheduling in OFDMA-based cognitive radio networks. A cross-layer antenna selection algorithm is used in (A. Ghosh and W. Hamouda, 2012) to achieve high transmission efficiency and beamforming is employed to cancel interference between cognitive users and primary users. The complexity of the algorithm increases as the number of transmits antenna increases. In (Amiotosh Ghosh and Walaa Hamouda, 2011), cognitive nodes access the spectrum by using spectrum overlay approach and each node is equipped with Multiple-Input Multiple-Output (MIMO) system to improve the spectrum utilization. The cross-layer antenna selection is used to improve the transmission efficiency and to reduce data rate variance among cognitive nodes and learning based algorithm is also used. The complexity of the antenna selection algorithm increases as the number of channel increases.

A cooperative communication is achieved between primary users and secondary users. In this, SU can access the channel depending on the services SU rendered to PU. Here, primary user throughput is achieved close to the optimum level. In (Dongyue Xue and Eylem Ekici, 2013), a throughput-optimal cross-layer scheduling algorithm is proposed, in which secondary users are provided a guaranteed throughput proportional to the primary user data they relay (acting as intermediate node). The above algorithm is implemented in spectrum overlay approach. In (Juan Liu et al., 2012), to minimize the overall probability of message transmission failure, cooperative beamforming in physical layer and optimal opportunistic scheduling in

Authors	Network Considered	Parameters Considered	Observation	Approach
Dan Chen et *al.*, 2012	Cognitive Radio Adhoc Network	Physical layer: AMC, best-relay selection, power allocation Datalink layer: Adaptive Frame Size	Maximization of throughput	Underlay
Rong Yu et *al*, 2010	Cognitive Radio Network	Physical layer: Spectrum Sensing Datalink layer: Call Admission Control	Reduced dropping rate	Overlay
Show-Shiow Tzeng and Ying-Jen Lin, 2013	Time-slotted Cognitive Radio Network	Physical layer: Optimal Sensing time Datalink layer: Frame Size	Recall sensing policy gives effective throughput	Overlay
Hao Ma et *al.*, 2012	Coginitive Radio Network	Physical layer: Aggressive AMC Datalink layer: Truncated ARQ	Maximize Spectral efficiency with target packet loss rate	Underlay
Ghada Hatem et *al.*, 2013	Infrastructure Cognitive Radio Network	Physical layer: Resource allocation Datalink Layer: Scheduling	Throughput is maximized and average packet delay is reduced	Underlay
Changqing Luo et *al.*, 2010	Infrastructure Cognitive Radio Network	Physical layer: AMC and Spectrum Sensing Datalink layer: Frame Size	Maximization of end-to-end throughput	Underlay
Gengyu Li et *al.*, 2011	Cognitive Radio Network	Physical layer: Modulation and SNR Datalink layer: Frame Size	Improves energy efficiency	Overlay
Leila Musavian and Tho Le-Ngoc, 2012	Cognitive Radio Network	Physical layer: Adaptive-power and AMC Datalink layer: Adaptive Repeat request	Maximize effective capacity of SU link	Underlay
Yuli Yang et *al.*, 2012	Cognitive Radio Network	Physical layer: AMC Datalink layer: Truncated ARQ	High Spectral efficiency and minimizes packet error rate	Underlay
Yi Peng et *al.*, 2009	Cognitive Radio Network	Physical layer: Power Control Datalink layer: Link Scheduling	Dynamic Channel Allocation	Overlay
Juan Liu et al., 2012	Cognitive Radio Adhoc Network	Physical layer: Cooperative Beamforming Datalink layer: Optimal Opportunistic Scheduling	Overall probability of message transmission failure is minimized	Underlay

Table 1. Comparison of different cross-layer design techniques between physical and datalink layers.

MAC layer are considered. This work is carried out for single-hop cognitive network and analyses have to be done for multi-hop network. A different comparison of different cross-layer design techniques between physical and datalink layer is shown in Table 1.

4. Survey on Cross-layer Design Between Datalink and Network Layer

The collaboration between routing and spectrum managements is considered in (H. Xianwei Zhou et *al.*, 2009). A colored multigraph based model for temporarily available spectrum bands is proposed. The proposed routing and interface assignment optimizes the hop number of routing and interference between adjacent hops is locally optimized. The computing complexity of the algorithm in (H. Xianwei Zhou et *al.*, 2009) is $O(n^2)$, where 'n' is number of nodes in a cognitive radio network. This algorithm will be more effective if adjacent hop interference is globally optimized.

To minimize wastage of resources used by packets in their previous hops, the authors in (Satish C. Jha et *al.*, 2011) proposed a cross-layer design between datalink and network layer. The link layer resource allocation is done by considering the hop-count information from the network layer module. If a packet is lost in the higher hop count, this results in wastage of resources in the previous hops. To overcome this, after channel reservation, packets travelling for maximum number of hops, the power is distributed among packets and transmitted through the best available channel without any degradation in throughput and outage performance.

The authors in (Yuh-Shyan Chen et *al.*, 2011), presented a cross-layer protocol to reduce the handoff transmission time and spectrum mobility ratio. The cross-layer design is done between spectrum mobility in datalink layer with the handover in network layer in cognitive Long−Term Evolution (LTE) networks.

5. Survey on Cross-layer Design Between Physical, Datalink and Network Layer

The authors (Lei Ding et *al.*, 2010) have proposed routing and dynamic spectrum allocation (ROSA) algorithm. This algorithm dynamically allocates spectrum resources based on locally collected information to maximize the network throughput. In a multihop path, the available spectrum band is different for each relay node because spectrum occupancy is location dependent. In ROSA algorithm, nodes adjust their transmission power to maximize the link capacity. In (V. Brik et *al.*, 2005), the dynamic spectrum access protocol is centralized. With local information and low complexity, ROSA algorithm gives 75% performance of the centralized solution in (V. Brik et *al.*, 2005).

The authors in (Yi Shi Zhou et *al.*, 2010) jointly considered power control, scheduling and routing to maximize data rates for a set of user communication sessions. This distributed cross-layer algorithm achieved a global scaling factor of 5.24, which is 96.7% of the upper bound. The upper bound global scaling factor is 5.42. By using this cross-layer design, the upper bound complexity is $O(|N|^5|M|^2|L|^2|+|N|^6|M||L|^2)$ and the actual complexity is less than this. Here ‘N’, ‘M’ and ‘L’ represent a set of nodes, frequency bands and user communication sessions respectively.

In (Alexandre de Baynast et *al.*, 2008), based on the prior acknowledge (ACK) signal optimum transmission parameters are found using genetic algorithm optimization technique. A set of decision variables at the physical, datalink and network layers are considered, which improves the quality of service parameters in cognitive radio network.

A cross-layer distributed control algorithm (DCA) in (Ghalib A. Shah et *al.*, 2013) jointly optimizes routing, medium access and physical layer functions to yield reliable and high capacity links for wireless communication in smart grids. The DCA maintains service guarantees in terms of reliability, latency and data rate for each flow, according to the priority of classes.

6. Survey on Other Cross-layer Design Approaches

The cross-layer approach can also be done between lower layers (Physical, Datalink, Network) and upper layers (Application and Transport).

6.1. Cross-layer Design between Physical and Network Layers

For communicating between several secondary sender and secondary destination pairs, a cross-layer design is done by combining information-guided transmission at the physical layer and network coding at the network layer to increase throughput, reducing delay and enhancing robustness in (Yuli Yang and Sonia Aissa, 2008).

6.2. Cross-layer Design between Physical and Transport Layers

A joint congestion control and power control (JCPC) cross-layer framework is introduced to achieve the optimal power allocation for each link per subcarrier in OFDM based multihop CRN in (Mui Van Nguyen et *al.,* 2012). The proposed algorithm in (Mui Van Nguyen et *al.,* 2012) is coupled with congestion control mechanism in existing TCP to obtain spectrum utilization and to increase SU aggregate throughput.

6.3. Cross-layer Design between Physical, Datalink and Transport Layers

The communication efficiency in centralized cognitive radio network is improved by having interactions between physical, MAC and transport layers. In (Muhammad Faisal Amjad et *al.,* 2013), the cross-layer approach is implemented in base station without changing any parameters in the end systems. The split TCP approach is used by the base station which breaks the end-to-end semantics of a TCP connection.

6.4. Cross-layer Design between Physical, Datalink and Application Layers

The cross-layer optimization module in (Haiyan Luo et *al.,* 2011), calculates the expected video distortion parameter at the video encoder in the

Authors	Network Considered	Parameters Considered	Observation	Approach
Yuh-Shyan Chen et *al.*, 2011	Cognitive LTE network	Datalink layer: Spectrum Mobility Network layer: Handover	Reduce Handoff transmission time and Spectrum Mobility ratio	Overlay
Yi Shi Zhou et *al.*, 2010	Multi-hop Cognitive Radio Network	Physical layer: Power Control Datalink layer: Scheduling Network layer: Routing	Throughput is maximized	Overlay
Alexandre de Baynast et *al.*, 2008	Cognitive Radio Adhoc Network	Physical layer: Transmission Power Datalink layer: Packet Size ontention window size Network layer: Variable Transmission range	Throughput is maximized, Power consumption and Bit Error Rate is minimized	–
Yuli Yang and Sonia Aissa, 2008	Cognitive Radio Relay Network	Physical layer: Information-guided information Network layer: Network Coding	Throughput is increased and delay is reduced	Underlay
Mui Van Nguyen et *al.*, 2012	Multi-Hop Cognitive Radio Network	Physical layer: Power Control Transport layer: Congestion Control	Increase SU throughput	Underlay
Haiyan Luo et *al.*, 2011	Centralized Cognitive Radio Network	Physical layer: AMC Dalink layer: MAC Scheduling Application Layer: Video distortion parameter calculated by the video encoder	Achieved best user-perceived video quality for SUs	Underlay

Table 2. Comparison of different other cross-layer design techniques in Cognitive Radio Network.

application layer. Depending on this parameter, MAC scheduling, transmission and modulation and channel coding are adjusted to achieve best user-perceived video quality for secondary users in CR users. In (J. A. Msumba and H. J. Xu, 2011), the cross-layer approach is considered for transmission of multimedia applications in cognitive radio network. Depending upon spectrum sensing, channel estimation is performed and instantaneous SNR of a link is calculated. The transmission rate of multimedia traffic is chosen based on the estimated SNR. This provides QoS guaranteed multimedia traffic in cognitive radio network.

6.5. Cross-layer Design between Physical, Datalink, Network and Transport Layers

The proposed cross-layer design in (Chen Guang-quan et *al.,* 2010), guarantees the end-to-end goals of data flows by fully utilizing the network resources. In this, each source individually adjusts its rates, depending on the current link capacity determined by the physical layer. Scheduling in link layer is determined based on the previous information from its neighbors and routing is done by using AODV protocol. This improves average source rate and throughput.

6.6. Cross-layer Design Between Physical, Datalink, Network and Application Layers

The authors in (Si Chen and Alexander M. Wyglinski, 2009) proposed a cross-layer optimization architecture to minimize the bit error rate, out-of-band interference, power usage and to maximize the overall throughput. The conventional genetic algorithm is modified and is called serial subcarrier-wise genetic algorithm which uses multi-objective fitness function. To further minimize the out-of-band interference, partial quantization within one transmission can be used.

The detailed comparison of different other cross-layer design techniques in cognitive radio network is shown in Table 2.

7. Conclusion

Cognitive radio provides an ultimate spectrum-aware communication paradigm in wireless communications. In this survey, fundamentals of cognitive radio characteristics, classification of cognitive radio network and various cross-layer frameworks which are designed to improve the QoS of secondary users are presented. The reviews provided in this article give cross-layer design in cognitive radio network. However, most of these earlier works are carried out in the physical and datalink layers. But to ensure efficient spectrum aware communication, more research work needs to be carried out in the cross-layer approach. For efficient communication between secondary users in cognitive radio network, end-to-end transmission from source to receiver is to be considered. For this, TCP provides reliable transmission.

The literature survey clearly reveals the necessity for suitable modifications in the current cross-layer design approaches.

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