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State of the Art in Cross-Layer Design for Cognitive Radio Wireless Networks

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Abstract

Cognitive radio is a revolutionary technology, which can significantly improve the utilization of limited radio spectrum resources. The limited ability of conventional layered protocol architectures has motivated the introduction of cross-layer design solutions that allow optimized operation. In this paper, we extensively and exclusively present an overview and discussion of the general methodology for cross-layer design and investigate cross-layer optimization schemes and algorithms between different layers. In addition, we conclude the paper and provide highlight trends in cross-layer design and identify areas for future work.

1. Introduction

Radio spectrum is considered as one of the most scarce and valuable resources for wireless communications. In traditional wireless networks, the spectrum resources are managed by static spectrum management strategy, where governmental agencies assign wireless spectrum to license holders (primary user). However, with the increasing demand for spectrum, the current policy faces spectrum scarcity in particular spectrum bands [1], [2]. In fact, most of the already allocated frequencies are used sporadically. Hence, it is necessary to assign those channels to users (secondary user) that have no legal right to access the spectrum when the channels are unoccupied by the primary users in space and time [3]. In order to utilize the licensed spectrum efficiently, the Federal Communication Committee (FCC) has suggested a new policy for allocating the spectrum dynamically [4]. Consequently, a promising technique called cognitive radio (CR) has been put forward as a way to solve spectrum inefficiency problems by exploiting the existence of spectrum holes.

The basic idea of cognitive radio is simple, but the efficient design of cognitive radio networks imposes new challenges that are not present in traditional wireless networks [5],[6],[7],[8]. For example, providing individual QoS guarantees and hybrid fairness for multimedia services are challenging issues [9], [10]. What's more, identifying time-varying channel availability imposes a number of important design problems to MAC layer [11], [12]. Even more challenging is how the secondary users decide when and which channel they should tune to in order to transmit/receive the secondary users' packets without affecting the communications among the primary users.

The wireless medium offers some new modalities of communication that layered architectures don't provide [13], [14]. The layered architectures either don't solve the new problems existing in wireless networks or don't exploit new opportunities sufficiently created by the wireless links [15], [16]. Hence, cross-layer design is absolutely necessary in cognitive radio wireless networks. The central idea of cross-layer design is to make the protocol stack responsive to the variations in the underlying network conditions so that an optimal performance is always maintained [17]. Recent researches on cross-layer design show a substantial improvement in routing efficiency, throughput, fairness and delay variance among different applications [18]. To further enhance users' satisfaction, it is imperative that various protocol layers adapt and collaborate dynamically to optimize the network performance [19].

The rest of the paper is organized as follows. In section 2, the methodology for cross-layer design is presented. In section 3, the detailed cross-layer design proposals for CR wireless networks are introduced. In section 4, we conclude this paper and give directions for future work.

2. General cross-layer design methodology

Recently, cross-layer design approach is widely investigated to improve the performance of the network. In this section, we will present the methodology for cross-layer design in cognitive wireless networks.

A cross-layer design approach can be either evolutionary or revolutionary. Evolutionary approach only modifies the protocol stack partially. However, revolutionary approach designs a new structure, discarding the existing protocols and layered architecture [20]. Cross-layer design approaches can be executed in two ways: loosely coupled and tightly coupled [21]. In this section, we classify the existing cross-layer design proposals according to the kind of architectural

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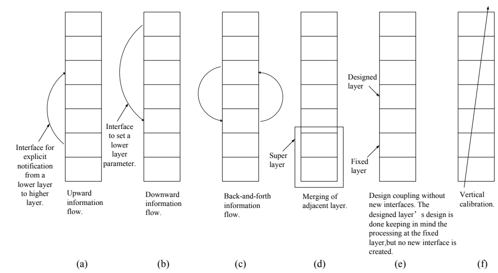

Figure 1. Different kinds of cross-layer design proposals (The rectangular boxes represent the protocol layers)

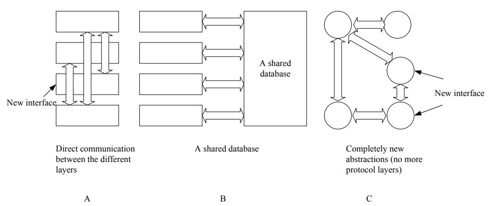

Figure 2. Proposals for architectural blueprints for wireless communications

violations they represent [19]. There are several kinds of architectural violations such as creating new interfaces (Figure 1. (a), (b), (c)), merging of adjacent layers (Figure 1. (d)), designing coupling without new interfaces (Figure 1. (e)) and vertical calibration across layers (Figure 1. (f)). Depending on the direction of information flow along new interfaces, creation of new interfaces between layers can further be categorized as upwards, downwards, back and forth. Some preliminary approaches have been proposed in the literature, which can be classified as three categories: allowing the layers to communicate with each other, a shared database across the layers and completely new abstractions (Figure 2.) [17].

A. Communication between layers

This method means making the variables at one layer visible to the other layers at run-time. There are many ways that layers can communicate with each other. These proposals are mainly used in the case that only a few cross-layer information exchanges in the system. By these approaches, the system's performance can be improved to some extent. But a number of implementation issues such as managing shared memory spaces should be considered at the same time.

B. Create new abstractions

A common database can be accessed by all layers, which provides the service of storage or retrieval of information to all layers. This approach is suitable for vertical optimizations [22]. An optimization can be implemented through the shared database providing the related information from other layers. The main issue from this approach is how to design the interactions between different layers and shared database.

C. A shared database across layers

Braden et al. [23] present a new way to organize the protocols in heaps not in stacks. Bai et al. [24] introduce a similar concept that breaks the protocols into smaller units called building blocks. Hence, the interactions in the network are between different building blocks. Such novel proposals are appealing because they provide sufficient interactions between building blocks and offer great flexibility in designing and optimizing the protocols. But Braden et al. also discuss some new problems caused by this approach.

3. Cross-layer design for CR wireless networks

In this section, we take stock of the ongoing researches in the area of cross-layer design in CR networks and present examples of cross-layer design for some representative layers.

A. MAC/Physical cross-layer design

As we know, real-time interactions between MAC and physical layer occur more frequently than that between any other layers. Hence, the cross-layer design between the two layers is always needed in nature [21]. In CR networks, the MAC layer should be able to adapt to the availability of the communication resources and change user configuration including density and mobility [1]. The advanced physical layer techniques, including typical categories such as multiple coding and modulation schemes, advanced antenna techniques, MIMO and OFDM technologies and ultra-wide bandwidth, provide a great potential of improved performance of delay, throughput and packet loss, etc [21]. In all, making use of channel knowledge at MAC layer allows opportunistic usage of the channel and results in performance improvements.

Zhao et al. [25] address joint design of both the spectrum sensor at physical layer and the cognitive protocol at MAC layer to maximize spectrum efficiency while limiting the interference to primary users. Su et al. [11] propose the cross-layer based opportunistic multi-channel medium access control protocols, which integrate the spectrum sensing at physical layer with the packet scheduling at MAC layer for wireless ad hoc network. In conventional CR protocols, waiting for idle timeslots may induce large packet delay and loss and result in poor quality of service for the secondary user. To overcome this disadvantage, Chen et al. [26] put forward a joint coding and scheduling method for cognitive multiple access. Tian et al. [10] propose a novel cross-layer opportunistic scheduling strategy with efficient interference control at MAC layer for multiple cognitive users with diverse QoS requirements. In wireless networks, two most important factors are throughput enhancement and power consumption. However, throughput-maximizing and power-minimizing are conflicted with each other in practical situation. To solve this problem, Li et al. [27] present a cross-layer approach for joint link scheduling and power control in cognitive networks. By this method, the network throughput is enhanced without excessive transmit powers.

B. Routing/Physical cross-layer design

Cognitive radio permits dynamic control of fundamental wireless network physical layer parameters such as transmission power and constellation size. This dynamic control promises significant performance improvements compared with conventional radios with static resource allocation configurations. Akyildiz et al. [6] propose a cross-layer optimization framework to jointly design the spectrum sharing and flow routing with interference considerations in cognitive radio networks. Given multiple traffic demands from different source nodes to destination nodes, they formulate an optimization problem in the form of mixed integer linear programming (MILP) to provide a fair routing. Different from the existing work, they consider bi-directional links because the link level acknowledgements in an ad hoc network is necessary. For traffic routing, they allow multi-path for each traffic demand.

C. Transport/Physical cross-layer design

In a multi-hop wireless cognitive network, the capacity of a link is time-varying due to the factors such as interference, variable channel quality, fading and so on. In wireless networks, packet loss occurs for reasons such as congestion, channel error or node mobility etc [19]. To optimize an end-to-end transmission mechanism, the varying link capacity should be taken into consideration.

Cross-layer design between transport layer and physical layer for wireless networks has been researched for a long time. The relating methods in the literature can be classified into two categories. In the first category, the congestion-control algorithm of TCP can be optimized by taking the information collected from the physical layer into consideration. For example, we can use the information from physical layer to differentiate packet loss due to congestion or bad link-quality. Instead of passively taking action only in TCP, TCP and physical layer control scheme can be optimized jointly. Such schemes belong to the second category, which involve more complicated algorithms as well as more sophisticated protocols and implementations [21].

There are many parameters can be controlled in the physical layer. It is difficult and inaccurate to have one control mechanism to cover the optimization of all parameters. A practical scheme is to focus on one or two parameters in the control mechanism and assume that other parameters are fixed. For instance, Chiang considers the power control as the main mechanism of fine-tuning the physical-layer performance [28]. The routing path is assumed to be fixed in joint congestion and power control algorithm. When congestion occurs, a mechanism to avoid congestion is to find a better routing path.

D. Other couplings across multiple protocol layers

Apart from the couplings mentioned above, cross-layer optimization can be formulated across different protocol layers ranging from the application to the physical layer. An extreme case of cross-layer design is to merge different protocol layers into one layer. It can eliminate the overhead in cross-layer information exchange. But the shortcoming is that it may not match an existing protocol stack like the Internet exactly. To improve the network performance and maximize the users' interests, joint optimization between transport, routing, MAC and physical layer is necessary. Transport layer protocol is considered in the congestion control part, MAC and physical layers are considered in the scheduling part, and routing is considered in the interactions between congestion control and scheduling [21].

Besides identifying some generic mechanisms used by notification-based cross layer design approaches, researchers should also investigate the coexistence of cross-layer optimization and scheduling approaches [29]. An important question to be solved is how different cross-layer design solutions can harmoniously coexist with one another.

4. Summary and research perspectives

This article has taken stock of the current activity in the area of cross-layer design in CR wireless networks. As presented in previous sections, there is no doubt that the cross-layer design can significantly improve the network performance. However, issues can come together with benefits, as explained as follows.

The main challenges to design the ultimate cognitive cross-layer architecture are modularity, scalability, system complexity, protocol interoperability and compatibility, etc [30]. When coming to the actual implementation of the mentioned schemes, the modifications of protocols in different layers can impact the maintainability of the software, stability of different protocol modules and flexibility of porting codes to different platforms. With cross-layer design, the standard working mechanism in protocol stack is broken. Thus, a wireless network with cross-layer design may be incompatible with other networks. So, interoperation between different networks is difficult to maintain. We should note that such issues usually don't exist in a layered design scheme. To avoid these issues, tradeoff should be made between performance improvement via cross-layer design and benefit loss of layered design [21].

To summarize, cross-layer design proposals must be holistic. Deviser must consider the totality of the design, including the interactions with other layers, and also consider the long-term architectural value of the approach. Although a number of cross-layer ideas in this area have been proposed, we believe that further research efforts are needed to meet the challenges mentioned above and satisfy the users' interests.

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