A Survey of Cross-Layer Designs in Wireless Networks

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***Abstract*—The strict boundary of the five layers in the TCP/IP network model provides the information encapsulation that enables the standardizing of network communications and makes the implementation of networks convenient in terms of abstract layers. However, the encapsulation results in some side effects, including compromise of QoS, latency, extra overload, etc. Therefore, to mitigate the side effect of the encapsulation between the abstract layers in the TCP/IP model, a number of cross-layer designs have been proposed. Cross-layer designs allow information sharing among all of the five layers in order to improve the wireless network functionality, including security, QoS, and mobility. In this article, we classify cross-layer designs by two ways. On the one hand, by how to share information among the five layers, cross-layer designs can be classified into two categories: non-manager method and manager method. On the other hand, by the organization of the network, cross-layer designs can be classified into two categories: centralized method and distributed method. Furthermore, we summarize the challenges of the cross-layer designs, including coexistence, signaling, the lack of a universal cross-layer design, and the destruction of the layered architecture.**

***Index Terms*—Cross-layer design, wireless networks, QoS, security.**

I. Introduction

THE END-TO-END connection in TCP/IP networks is established through the collaboration of all of the five layers (application layer, transport layer, network layer, data link layer, and physical layer), which are designed to maintain a limited interface between two neighbor layers [1]-[5], [10]-[20]. The layers can be organized as a top-down or bottom-up architecture. In either way, the exchange of data and service calling takes place only between two adjacent layers and forms a significant black box feature of the TCP/IP model [22]. The black box characteristic in TCP/IP networks leads to the abstraction of the internal details of each layer. This is also called information hiding. However, the abstraction of the internal details may cause side effects in the networks [22]. Although the strict boundary between the layers makes the network easy to be deployed, the encapsulation of the layers prevents some necessary information sharing between layers. For example, in TCP/IP wireless networks, the layer abstraction hides the root cause of the connection termination, and the status about the connection termination is not utilized for the repair or re-establishment of the connection [14]. If the wireless channels are noise, the encapsulation in TCP/IP networks causes too many connection terminations even when a connection is temporarily disconnected for a short time, and the reestablishment of the connection costs a lot of time because of the reestablishment of the links in all of the five layers through all the nodes in the link route [44]. To solve such a problem, cross-layer designs which consider the interrelationship and the reconfiguration capability of the five layers are needed to identify and improve the weakest link in the link route before the connection fails. Furthermore, an individual TCP/IP protocol normally aims at solving one specific set of problems without considerations of the end-to-end performance, and therefore the deployment of these protocols does not always satisfy the increased performance requirements [22]. A lot of works have confirmed the poor performance of current TCP/IP implementations without cross-layer designs in wireless networks [33], [36], [37], [39], [40], [42], [47], [48].

Therefore, to mitigate the side effect of the encapsulation between the abstract layers in the TCP/IP model, a number of cross-layer designs have been proposed. Normally, any attempt to violate the black box characteristic in the TCP/IP model is considered as a cross-layer design [22]. Attempting to break the virtually strict boundaries among the five layers in the current TCP/IP model, the cross-layer design is an escape from the waterfall-like concept of current TCP/IP wireless networks. Numerous research efforts have been presented to provide the solutions to achieve cross-layer designs in wireless networks. Without cross-layer designs, only two adjacent layers can achieve the service calling and the data exchange. Cross-layer designs do not destroy the five layer structure of TCP/IP networks, but provide the inter-layer communication between two non-adjacent layers. Moreover, cross-layer designs may also allow the disclosure of internal status and parameters that are kept by each layer but now reveled to the other layers. Cross-layer designs may allow information sharing among all of the five layers. Furthermore, cross-layer designs may allow a layer to determine its behavior based upon the data that it retrieves or receives from the other layers. Therefore, cross-layer designs imply that each layer is able to share parameters, status, and other information with other four layers, without breaking the five layer structure of computer networks.

Moreover, cross-layer designs allow information sharing through the layer boundaries to enable the compensation for the network performance and reliability, e.g., increasing throughput, reducing latency, and minimizing bit error rate, by control the input to another layer [22]. Cross-layer designs are able to make the hidden information (e.g., channel state information) in each layer visible to other layers [22], [44].

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Many of the cross-layer designs propose alternated methods in the network layer, the data link layer, or the physical layer [6], [21], [22]. For example, the cross-layer design in [6], [54] supports an optimization for delay-sensitive applications such as the real-time video streaming. The frameworks in [6] and [21] incorporate the alternative protocol stack to leverage the flexibility offered by optimization of design parameters. The cross layer design in [54] incorporates both the data link layer and the physical layer. There are also many other cross layer design schemes [24], [55]-[58].

In this paper, a survey on cross-layer designs in wireless networks is presented. Security, quality of service (QoS), and mobility are three issues that cross-layer designs consider, and they can be viewed as three goals of cross-layer designs. To achieve these goals, a cross-layer design may allow one layer to exchange and share data with other layers, may allow one node to exchange and share data with other nodes as well. The sharing scheme inside one node may be: a) the non-manager method, which allows one layer directly communicate with other layers; b) the manager method, which introduces a vertical plane as a public library of the cross-layer information. The sharing scheme among the nodes in a network may be: a) the centralized method, which uses a central node or tier structure to control the cross-layer information sharing; b) the distributed method, which organizes information sharing without a central node. Therefore, we have two kinds of classifications for cross-layer designs. Cross-layer designs can be classified into two categories (i.e., the non-manager method and manager method) by how to share the information among the five layers [7], [22], [25], [44]. Meanwhile, cross-layer designs can be classified into two other categories (i.e., the centralized method and distributed method) by the organization of the network [7], [22], [25], [44].

However, there are many disadvantages/challenges of cross-layer designs that are inevitable due to the characteristics of these designs, including aspects of coexistence, signaling, overhead, and the lack of a universal cross-layer design. Firstly, each cross-layer design has its specific cross-layer communication manner, and thus the coexistence and signaling are the two challenges that cross-layer designs have to deal with. Secondly, it is inevitable to result in an extra overhead when exchanging the cross-layer information in the cross-layer designs. Thirdly, a universal cross-layer design that is optimized for all the applications is unlikely existent, since different applications have distinct requirements for the cross-layer design. Finally, cross-layer designs destroy the encapsulation of the layers so that they may turn the well organized layered architecture to a flat and disordered design. It becomes difficult to make a modification for one layer without considering other layers in cross-layer designs. Therefore, the destruction of the layered architecture might be the fundamental disadvantage of cross-layer designs.

The aforementioned challenges are not caused by a specific design, but are common for cross-layer designs. Therefore, we summarize the challenges of cross-layer designs in this article and present possible solutions for these challenges.

The organization of this article is as follows. The goals of cross-layer designs are introduced in Section II. Two classifications of cross-layer designs are presented in Section III. The details of these two classifications are introduced in Section IV and V, respectively. The challenges of cross-layer designs are presented in Section VI. Finally, we conclude this paper in Section VII.

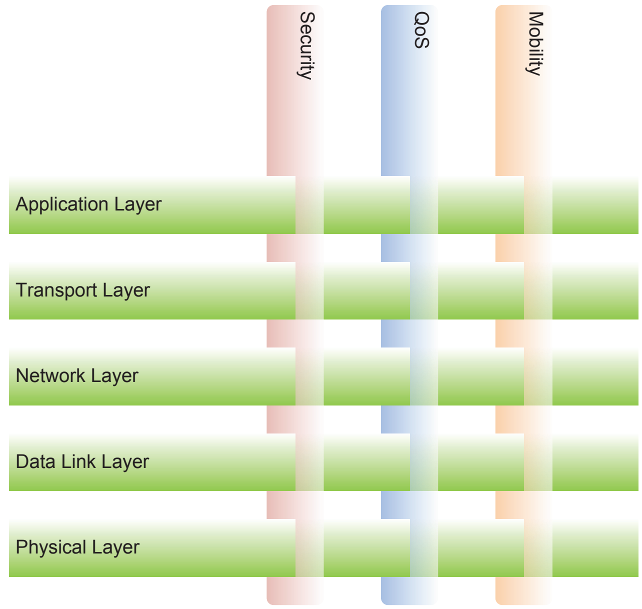


Fig. 1. The goals of cross-layer designs: security, QoS, and mobility [7], [22], [25], [44]. A cross-layer design scheme normally aims at least one of these three goals.

II. The Goals of Cross-Layer Designs in Wireless Networks

The goals of cross-layer designs are modeled as a coordination model that briefly describes the functionality that cross-layer designs might support [22], [25]. As shown in Fig. 1, the coordination model introduces three coordination planes (including security plane, QoS plane, and mobility plane) extending across the five TCP/IP protocol layers [22], [25]. Each coordination plane encapsulates a series of original designed protocols, revised protocols, or algorithms to support the cross-layer design functionality and to solve a specific problem in wireless networks [22]. The coordination model shows three goals of cross-layer designs: security, QoS, and mobility. A cross-layer design normally aims to achieve at least one of the goals that the three coordination planes represent.

A. Security

The security coordination plane encapsulates the protocols about security issues across the five TCP/IP layers [22], [80], [81]. Encryption methods, such as SSH and Wi-Fi protected access, might be deployed in this plane in a cross-layer design aiming at security communication [22]. The cross-layer designs in the following papers contain security plane: [45]-[48], [59].

A cross-layer design may deploy encryption methods for security: at the application layer (e.g., SSH and SSL for the end-to-end encryption), at the network layer (e.g., the IPSec protocol for the end-to-end encryption), and at the data link layer and the physical layer (e.g., IEEE 802.11 wireless networks) [22]. The authors in [45] point out that the abstract feature of TCP/IP networks is inadequate and inefficient for the security assurance in wireless sensor networks (WSN) and give an overview of the existing cross-layer designs in WSN for the security purpose.

The importance of cross-layer designs for the security mechanisms in multi-hop wireless networks is discussed in [46]. The cross-layer design in [46] shares the parameters in each layer to avoid multi-layer attacks. The performance comparison shows that the cross-layer design in [46] results in less routing overhead and much fewer acknowledgement packets.

The disadvantages of current security schemes in Wireless Metropolitan Area Network (WirelessMAN) are reviewed in [47] and a sub-linear rekeying algorithm with perfect secrecy is proposed to achieve security goals by using cross-layer designs in WirelessMAN. The evaluation results show a 4$\sim$7% performance improvement using the algorithm in [47] than that not using the cross-layer design, for both message counts and total communications.

A Cross-Layer Design Network Security Management (CLDNSM) is proposed in [48] to protect the system security by aggregating system information from layers and using it to obtain the optimal security settings. The numerical results show that the CLDNSM server is self-adapted in the dynamic environment to maintain and modify system resources. The CLDNSM security system in the simulation also suffers from severely system overload and is more appropriate for dynamic environments than the traditional non-cross-layer model.

In [59], a cross-layer design incorporates a blind video watermarking method and a middleman detection algorithm to enhance the medium access control (MAC) layer and the network layer in wireless networks.

B. QoS

The QoS coordination plane aims at improving the quality of service in the wireless communication across the five layers [22]. Due to the characteristic of the physical layer and the data link layer in wireless networks, the upper layers need to be aware of the information in the two lowest layers in order to improve the QoS in certain circumstances [22]. This requirement of the information sharing between the two lower layers and the three upper layers, however, is not supported in the current waterfall-like concept of the wireless network model [22]. The QoS coordination plane aims at achieve the cross-layer communication in order to improve QoS. The cross-layer designs in the following papers contain QoS coordination plane: [2], [3], [25], [26], [28], [30], [33], [35], [36], [37], [42], [43], [54].

There are plenty of factors affect the QoS in wireless networks [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79]. For example, the transmission error in wireless networks is one of the problems that we may solve by cross-layer designs in order to improve QoS. Transmission errors, e.g., package loss, in wireless network when using TCP as the transportation layer protocol are mainly caused by the bad performance of the MAC layer and the physical layer [22], [37]. The problems related with transmission errors existing in cross-layer designs in wireless networks are summarized in [34]. To reduce transmission errors, the authors in [36] present a protocol based on Explicit Loss Notification (ELN) in a wireless network which uses TCP as the transportation layer protocol. In [36], ELN mechanism is designed to notify the packet sender the reason for the transmission error of a packet. This mechanism specially informs the sender that the transmission error caused by the reasons unrelated to the network congestion when the network is not congested but transmission error occurs, so that the sender can schedule its retransmissions without considering the congestion control. If the receiver is aware that the transmission error is not due to the congestion, it sets the ELN bit in the TCP header and propagates it to the source [36]. In this way, the ELN mechanism shares the information in between the TCP and the MAC layers in the sender with the receiver. The evaluation results show that under certain error rates the performance improvement by ELN is a factor of 2 and the relative performance by the ELN is about 100% better than not using the cross-layer design.

Many applications in wireless networks use TCP as the transport layer protocol, and TCP is sensitive to the problems in the lower layers listed in the last paragraph. Channel fading may cause a route rescheduling. A transmission delay and high bit error rate may trigger a retransmission in a TCP connection. In addition, too many retransmissions may cause the congestion in a busy wireless network. Therefore, a lot of cross-layer designs improve the QoS by solving the problems specifically in the wireless link, e.g., channel fading, channel interference, bit error rate, transmission delay, etc [22].

The authors in [33] propose a forward error correction mechanism to share with other layers the transmission errors occurred in the MAC layer and the physical layer. This mechanism uses forward error correction along with ELN, in order to improve TCP performance for wireless cellular networks [33]. The forward error correction scheme is a solution to reduce the transmission error acknowledged by the upper layers, and the forward error correction cooperating with the explicit loss notification mechanism improves TCP performance by 10% in [33].

Similar as the scheme in [33], another revision of existing mechanisms is proposed in [35], called hybrid automatic repeat request, which is a cooperation of forward error correction mechanism and automatic repeat request. The authors in [35] optimize the mapping between the signal-to-interference-and-noise radio and the modulation-and-coding scheme in order to improve QoS.

An adaptive coded modulation to solve the channel interference problem is proposed in [42]. The authors in [37] point that the forward link is the bottleneck of a wireless network, and one of the reasons why this bottleneck exits is the interference. The adaptive coded modulation in [42] is used to solve the flat-fading channel problem. The authors in [42] present an adaptive modulation technique and the general principles of combining coset codes, and then apply their method to a spectrally efficient adaptive Mary Quadrature Amplitude Modulation (MQAM) technique to obtain the trellis-coded adaptive MQAM. The simulation results show that the

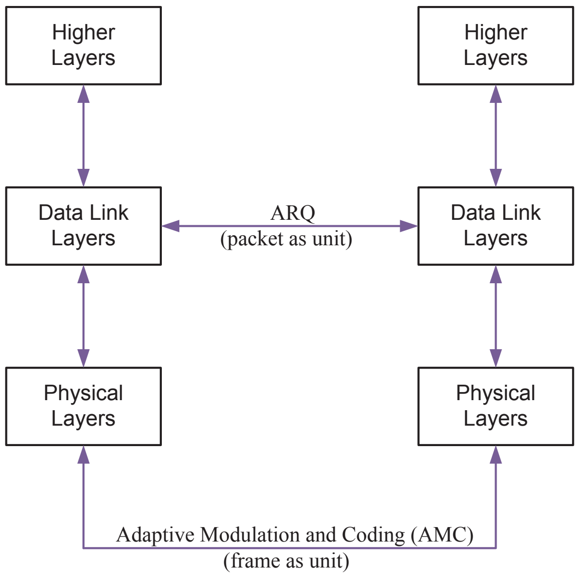


Fig. 2. A cross-layer design that aims at maximizing spectral efficiency consists of AMC in the physical layer and ARQ in the data link layer [39].

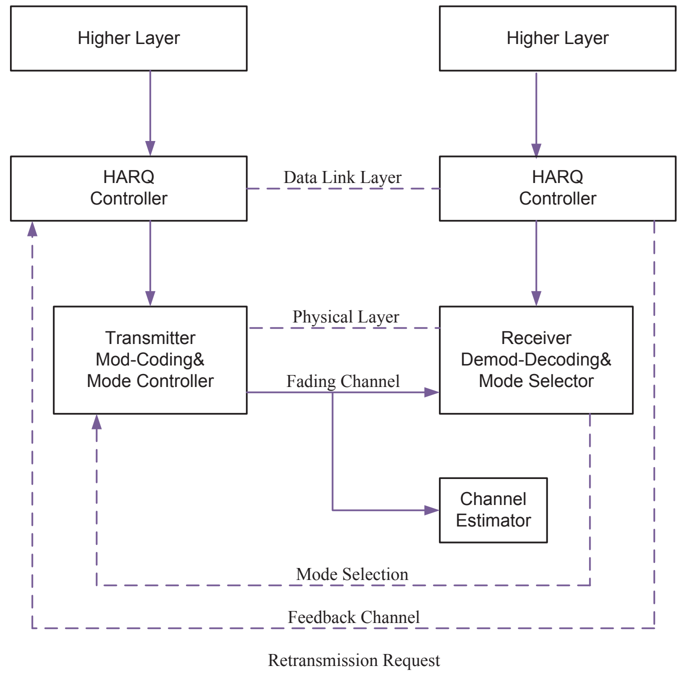


Fig. 3. A cross-layer design using AMC and HARQ [40].

adaptive coded modulation solves the channel interference problem and comes close to the Shannon capacity limit of fading channels [42].

Moreover, increasing the capacity of served users is another way to improve QoS. The capacity of served users is decided by the spectral efficiency [22]. In order to maximize the spectral efficiency, the authors in [39] propose a cross-layer design making use of the adaptive modulation and coding at the physical layer with a truncated Automatic Repeat reQuest (ARQ) protocol at the data link layer.

To increase the throughput in wireless networks which are in time-varying channel conditions, Adaptive Modulation and Coding (AMC) at the physical layer have been studied in [39]. The ARQ protocol at the data link layer is used to mitigate channel fading [35], [39]. As shown in Fig. 2, the cross-layer design in [39] consists of the AMC in the physical layer and the ARQ in the data link layer. At the physical layer, the AMC selector determines the modulation-coding pair; the AMC controller then updates the transmission mode at the transmitter; and the coherent demodulation and maximum-likelihood decoding are used at the receiver [39]. At the physical layer, a selective repeat ARQ protocol is implemented, and the ARQ controller arranges retransmission of the packets. The numerical results show a 3 Mb/s increase in the transmission rate when using AMC with truncated ARQ [39]. Moreover, the numerical results also imply that AMC reduces the average packet error rate at the physical layer and offers a much higher spectral efficiency than not using the cross-layer design [39].

Similar as [39], the cross-layer design in [40] makes use of both Hybrid Automatic Repeat Request (HARQ) at the data link layer and AMC at the physical layer. HARQ is a combination of ARQ and high-rate forward error-correcting coding.

Fig. 3 shows the cross-layer structure using AMC in the physical layer and HARQ in the data link layer in [40]. The work in [40] is based on IEEE 802.11/16 standards. In the data link layer of the sender, the error-correcting codes of HARQ code the packets from the higher layer. After AMC controller in the physical layer of the sender receives these packets, they are processed with the feedback from the AMC mode selector of the receiver. The AMC selector at the receiver determines the updated mode to send feedback to the sender. Then the feedback packets are decoded by the error-correcting codes of HARQ in the receiver and sent back to the sender. HARQ controller at the sender arranges the retransmission of the requested packet that is stored in the buffer [40]. The numerical results show that a small retransmission number can obtain the achievable spectral efficiency with less delay and buffer-size penalties [40].

C. Mobility

The mobility coordination plane aims at guaranteeing the uninterrupted communication in wireless networks [22], [82]-[95]. Node movements are common in ad-hoc networks, so that the events caused by the node movement, e.g., channel switch and route change, are necessary to be discovered and solved to assure the communication not to be uninterrupted. Two handover categories are presented in [22] to describe the types of node movements: horizontal handover and vertical handover. The former describes the movement of a node between access points (APs) of the same wireless access technology; the latter describes the movement of a node between APs of different wireless access technologies [23]. In both categories, the upper layers in a cross-layer design need to be aware of the events, e.g., channel switch and route change, taking place in the lower layers, so that the communication maintained by the upper layers will not be uninterrupted [23]. Channel fading, transmission delay, high bit error rate, and other failures that decrease QoS may affect the mobility as well. Therefore, some of the cross-layer designs in the last

TABLE I
THE GOALS OF CROSS-LAYER DESIGNS

Goal	Explanation	Examples
Security	Security issues across the five TCP/IP layers are considered in some cross-layer designs. Encryption methods, such as SSH, Wi-Fi protected access, might be deployed in a cross-layer design aiming at security communication.	An efficient sub-linear rekeying algorithm with perfect secrecy achieves security goals by using cross-layer design in WirelessMAN [47]. A cross-layer design network security management protects system security by gathering system information from layers and then using it to obtain optimal security settings [48].
QoS	To improve the QoS in the wireless communication across the five layers, some cross-layer designs enable the cross-layer communication between the upper layers (the application layer and the transport layer) and the lower layers (the physical layer and the data link layer) [22].	Some cross-layer designs aim at reducing transmission errors that are mainly caused by the bad performance of the MAC layer and the physical layer in wireless network when using TCP as the transportation layer protocol [22], [32]. A cross-layer design based on explicit loss notification in [36] increases TCP performance by information sharing of the lower layers. Forward error correction mechanism in [33] and hybrid automatic repeat request in [35] also share the transmission errors occurred in the MAC layer and the physical layer with other layers.
Mobility	Some cross-layer designs aim at guaranteeing the uninterrupted communication in a wireless network, since node movement, which would cause channel switch, route change, and other problems, is common in wireless networks.	TDMA and FDMA are used for increased the number of served users. Some cross-layer designs use CDMA/HDR to solve the time slot waste in wireless networks.

sub-section have the goal of mobility as well. The cross-layer designs in the following papers contain mobility coordination plane: [25], [34], [37], [42]-[44].

For example, ratio of served users is considered as one of mobility problems in cross-layer designs. In centralized networks, e.g., 802.11 Wi-Fi and cellular networks, the number of served users is limited due to the limited number of channels, channel interference, etc. Time-Division Multiple Access (TDMA) and Frequency-Division Multiple Access (FDMA) methods are developed to solve this problem [22]. It is obvious that TDMA causes a waste of time slots and the bandwidth even there is no data transmission between the base station and the mobile station due to the characteristic of TDMA [22], [34]. Cross-layer designs help to deal with the time waste problem due to the benefits of the cross-layer information sharing. The authors in [37] use Code Division Multiple Access/ High Data Rate (CDMA/HDR) to build a bandwidth-efficient wireless data service to solve the aforementioned problem. The main solutions in [37] are the channel measurement, channel control, and interference suppression and mitigation. The authors of both [34] and [37] use the information sharing in cross-layer designs to avoid wasting of time slots. The estimated maximum achievable throughput is evaluated in [37] in which a graph of a cumulative distribution function is present to show an additional 2 dB of margin to account for various losses and to show an increased throughput.

These three coordination planes (security, QoS, and mobility) describe the three goals of cross-layer designs. One cross-layer design scheme normally aims at least one of these three goals. Table I summarizes the aforementioned cross-layer designs and their goals.

III. TWO CROSS-LAYER DESIGN CLASSIFICATION

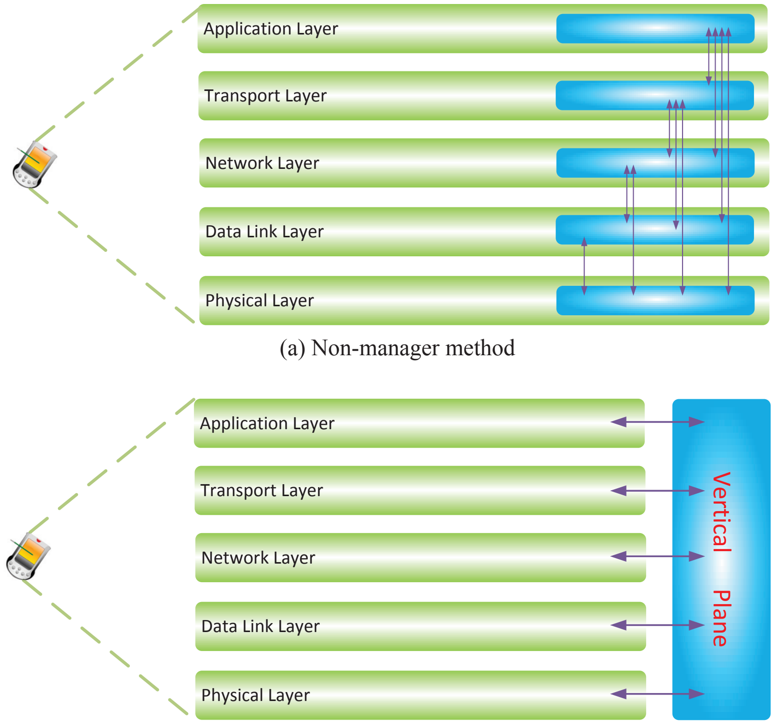
Cross-layer designs allow the information sharing between any two of the five layers in the TCP/IP model, and may allow a layer determines its activities based on the information that it retrieves or receives from the other four layers. Therefore, cross-layer designs allow each layer to be able to share its information, including parameters and status with other four layers, without breaking the five layer structure of the TCP/IP model. Some cross-layer designs even allow the cross-layer information sharing between different nodes in wireless networks.

But how these cross-layer designs achieve the three goals in the last section? For example, to improve the QoS in wireless networks, the QoS coordination plane is introduced as shown in Fig. 1, but a series of questions need to be answered: Does the cross-layer design need to be deployed in all the nodes or some of the nodes? Does the cross-layer design need to be deployed in the protocols in all of the five layers or some of the layers? Does the cross-layer design need to just revise the current protocols or build a totally new architecture? Is a centralized node necessary for QoS in a cross-layer design? To answer these questions, we summarize the existing cross-layer designs and present two kinds of classification for cross-layer designs. The first classification is that the cross-layer designs can be classified into two categories by how to share information among the five layers in one node: the non-manager method and the manager method. Meanwhile, cross-layer designs can also be classified into other two categories by the organization of the network for cross-layer information sharing: the centralized method and the distributed method. The non-manager method and manager method are used for sharing cross-layer information in one node, and the centralized method and the distributed method are used for sharing cross-layer information among nodes in a network.

Figs. 4(a) and (b) show the classification based on how to share the information among the five layers in one node: the non-manager method and the manager method.

Fig. 4(a) shows the non-manager method, which allows direct communication between any pair of layers in the TCP/IP protocol stack [22], [25]. This method does not change the five layers structure of the TCP/IP model, but changes the function of the protocols in certain layers by allowing the direct communication between two layers [22].

Fig. 4(b) shows the manager method, which introduces a vertical plane as a manager that share data with some (or all) of the layers in the TCP/IP protocol stack [7], [22], [25]. This



(a) Non-manager method

(b) Manager method

Fig. 4. The first classification of cross-layer designs is (a) the non-manager method and (b) the manager method, which are classified by how to share information among the five layers in one node [7], [22], [25], [44]. The data exchange takes place directly between any two layers in the non-manager method; there is a vertical plane in the manager method to manage data exchange between the layers.

method does not change the five layers structure of the TCP/IP model, but changes the function of the protocols in the layers by allowing the data sharing with the vertical planes [7], [22], [25].

On the other hand, the cross-layer designs can also be classified the centralized method and the distributed method for sharing the cross-layer information among the nodes in a wireless network.

Fig. 5(a) shows the centralized method, which introduces a centralized node (sometimes using a base station) or tiers which are in a hierarchical manner [12], [22]. The centralized node or tiers are introduced to manage the information sharing of the five TCP/IP layers between two nodes [12], [22]. The centralized method is typically used in cellular networks.

Fig. 5(b) shows the distributed method, which does not include any centralized node or any base station for the cross-layer information sharing. Since there is no centralized in this case, the multi-hop path from a node to another is possible during the cross-layer information sharing [22], [31]. The distributed method is typically used in ad-hoc networks.

Since the above two kinds of classification in Fig. 4 and Fig. 5 differentiate cross-layer designs by two standards, they are independent from each other. Therefore, it is possible that a cross-layer design belongs to one of the non-manager method and the manager method, and meanwhile it belongs to one of the centralized method and the distributed method as well. We introduce these two classifications in Section IV and Section V, respectively. Table II summarizes the aforementioned categories of the cross-layer designs.

IV. Classification of Cross-Layer Designs by How to Share Information Among Five Layers in One Node

The first kind of the classification of cross-layer designs composes of the non-manager method and the manager method, which are classified by how to share the information among the five layers in one node.

A. Non-manager Method

Fig. 4(a) shows the non-manager method, which allows the direct communication between any pair of layers in the TCP/IP protocol stack. This method does not change the five layers structure of the TCP/IP model, but changes the function of the protocols in some layers by allowing the direct communication between two layers [22].

For example, the authors in [30] propose a cross-layer design framework for 802.16e orthogonal frequency-division multiple access systems for the performance improvement by a cross-layer adaptation framework, and they present a design example of primitives for cross-layer operation between the MAC and PHY layers as well. This framework is composed of a user grouper, a MAC scheduler, and a resource controller [30]. The user grouper classifies the users, the MAC scheduler determines the scheduling of users and how to schedule packets in the current frame, and the MAC scheduler handles the mechanisms for appropriate data transport according to QoS of each data transport class [30]. The resource controller assigns frequency bands to each selected user (by applying subcarrier the allocation algorithm) after the scheduler determines the

TABLE II
THE CATEGORIES OF CROSS-LAYER DESIGNS

Classification	Method	Explanation	Examples
The first classification: by how to share information among layers in one node	Non-manager method	The data exchange takes place directly between any two layers in the non-manager method.	A cross-layer architecture in [2] improves the TCP performance by cross-layer communication directly between the TCP layer and the lower layers, and therefore it is a non-manager method cross-layer design. A cross-layer design framework for 802.16e orthogonal frequency-division multiple access systems in [30] provides performance improvement by cross-layer communication between layers. There is not a vertical plane that manages the cross-layer communication.
	Manager method	There is a vertical to manage data exchange between the layers.	A cross-layer design architecture called ECLAIR in [27] is composed of tuning layers and optimizing subsystems to achieve cross-layer communication. ECLAIR functions as the vertical plane that manages the cross-layer communication. A cross-layer optimization strategy in [26] uses a cross-layer optimizer as the vertical plane to improve the performance of video streaming in wireless networks. A proactive and adaptive cross-layer reconfiguration scheme in [44] uses an adaptation interaction interface as the vertical plane in order to achieve reliable communication in tactical networks.
The second classification: by network organization for cross-layer information sharing	Centralized method	The centralized method uses a centralized node or tier which is in a hierarchical manner to achieve communication between nodes. The centralized method is typically used in cellular networks.	A scheduling mechanism in [28] achieves cross-layer information sharing in the Universal Mobile Telecommunications System (UMTS) in which a base station can be considered as the centralized node in cellular networks. A cross-layer design in [29] is designed for real-time video applications in 3G the cellular network which has a centralized structure. M@ANGEL, an autonomic management mobile platform, is composed of two tiers in a hierarchical manner in [12], and therefore it is considered as a centralized cross-layer design.
	Distributed method	The distributed method does not use any centralized node or tier. The distributed method is typically used in ad-hoc networks.	A scheme called farcoopt in [1] is a cross-layer design that makes use of the farthest neighbor to increase QoS, to reduce energy consumption, and to increase throughput in multi-hop networks. This scheme does not use any centralized node. A cross-layer approach in [21] seeks to improve end-to-end performance in ad-hoc networks without using any centralized node. A proactive and adaptive cross-layer reconfiguration scheme in [44] is designed to achieve reliable communication in ad-hoc networks in which there is no centralized node.

scheduled users [30]. The above procedure is executed in order to maximize the throughput [30].

The framework in [30] is designed solely for 802.16e orthogonal frequency-division multiple access systems. It makes use of the MAC layer and the physical layer by implementing the cross-layer design. The disadvantage of this framework is that it does not fully make use of the other three layers. This framework is not easy to be implemented on other types of wireless networks.

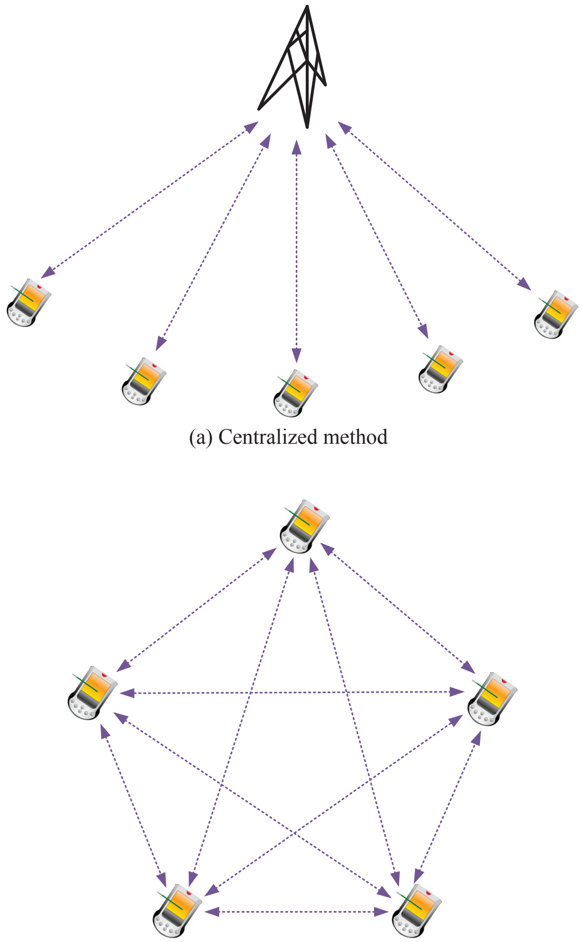
In a number of cross-layer design methods, Cognitive Network (CN) is developed as a new type of data networks which are expected to solve some problems that networks are facing with [4], [9]. According to [2], [9], [60]-[65], the CN network is a network with a cognitive process that perceives the current network conditions, and then plans and acts on those conditions. To take into account end-to-end goals, the CN network learns from current adaptations and uses them to make future decisions [9]. The authors in [2] present a cross-layer design in CN networks with primary users and secondary users to maximize the TCP throughput. The authors in [2] consider spectrum sensing, access decision, physical-layer modulation, coding scheme, and data-link layer frame size in CN networks. Secondary users, also called unlicensed users, can operate in the licensed spectrum bands, but they are considered lower priority to avoid interference to primary users in their vicinity [2]. In CN networks, primary users and secondary users share a block of a spectrum consisting of several radio channels [2].

Fig. 6 shows the cross-layer architecture in [2] that aims to increase TCP performance of secondary users. The secondary users (cognitive sensors) sense the channel to observe the channel and obtain sense outcomes that are sent from the physical layer to the TCP layer, as shown in Fig. 6 [2]. Based on these sensing outcomes, the TCP layer determines the frame size that is sent to the data link layer, access decision that is sent to the MAC layer, and modulation and coding scheme that is sent to the physical layer [2]. The authors in [2] also present a TCP throughput model, which gives the calculation of some variables, such as TCP throughput, bit error rate, roundtrip time, etc. Simulation results in [2] show that average TCP throughput and spectrum utilization in this architecture are higher than the traditional schemes. In the scheme in [2], the TCP layer directly communicates with other layers, and therefore it is considered as the non-manager method of cross-layer designs.

The advantage of this scheme is that it uses the TCP layer as the pivot of the cross-layer information sharing without an independent vertical plane, and, therefore, this architecture is concise but enough to handle the secondary users. But it might be difficult if we try to extend the functionality of this scheme, because the TCP layer is not able to handle all the behaviors of other layers.

B. Manager Method

Fig. 4(b) shows the manager method, which introduces one or more vertical planes that share the data with some (or all) of



(a) Centralized method

(b) Distributed method

Fig. 5. The second classification of cross-layer designs is by the organization of the network for cross-layer information sharing [22], [44]: (a) the centralized method and (b) the distributed method. The centralized method uses a centralized node or tier which is in a hierarchical manner to achieve communication between nodes; the distributed method does not use any centralized node or tier.

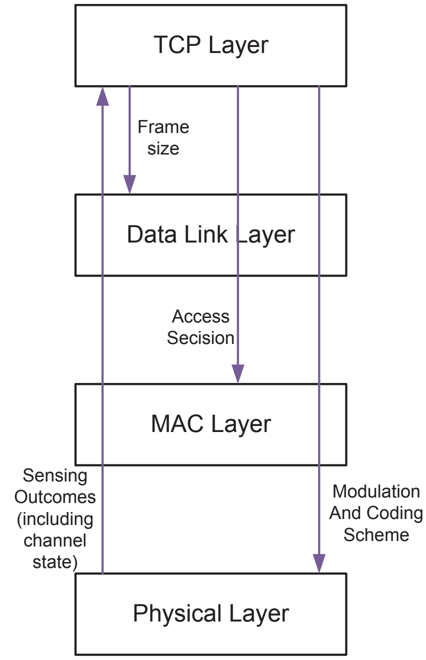


Fig. 6. An intra-layer cross-layer design in cognitive networks with primary users and secondary users to maximize the TCP throughput [2]. By using cross-layer design, the TCP layer determines the frame size that is sent to the data link layer, access decision that is sent to the MAC layer, and modulation and coding scheme that is sent to the physical layer.

the layers in the TCP/IP model. This method does not change the five layers structure of the TCP/IP model, but changes the function of the protocols in the layers by allowing the data sharing with the vertical planes. The main difference between the non-manager method and the manager method is: the former allows direct communications between any two layers; the latter requires a vertical plane for communications. For example, the proactive and adaptive cross-layer reconfiguration scheme in [44] introduces an adaptation interaction interface which functions as the vertical plane to manage the cross-layer communication.

A manager cross-layer method is proposed in [25] for the purpose of solving the problems in the performance of wireless links and mobile terminals, such as the high error rate of wireless networks, power saving requirements, unpredictable QoS in an increasingly dynamic network environment. The authors in [25] also propose a cross-layer design framework for 4G networks and summarize the known problems associated with current strictly layered protocol architecture. A cross-layer manager is introduced in [25], as shown in Fig. 7. Each layer shares its events with the cross-layer manager which can be considered as the vertical plane in Fig. 4(b), and the cross-layer manager shares all the state variables in the layers in TCP/IP and cellular networks.

The authors in [26] proposes a cross-layer optimization strategy that jointly optimizes the application layer, the data link layer, and the physical layer of the TCP/IP protocol stack using an application oriented objective function in order to maximize the user satisfaction. Aiming at a cross-layer design for video streaming in wireless networks, the authors in [26] focus on application-driven optimization. Moreover, they observe the trade-off between performance and the additional computation and overhead introduced by its cross-layer optimization [26]. As shows in Fig. 8, a cross-layer optimizer is introduced to optimize the parameters shared by the layers. The cross-layer optimizer jointly optimizes multiple network layers, makes predictions on their states, and selects optimal values for their parameters [26]. There are three steps in this cross-layer working process: 1) Layer abstraction computes an abstraction of the parameters in each layer [26]. The purpose of this step is to avoid transmitting too many parameters to the cross-layer optimizer [26]. The parameters being abstract include: Source rate, encoding format, compression, FEC, TDMA time slots, OFDM carriers, directional beams, bit error rate, frame rate, picture size, net transmission rate, modulation scheme, channel coding, etc [26]. 2) Optimization reconfigures the parameters to optimize a specific objective function [26]. 3) Layer reconfiguration distributes the reconfigured parameters to the corresponding layers and requires the layers to execute their actual operation [26]. Since the authors in [26] aim at cross-layer designs for video streaming, they present the detail on how to revise the value of the above parameters in the video streaming. After layer abstraction, the cross-layer

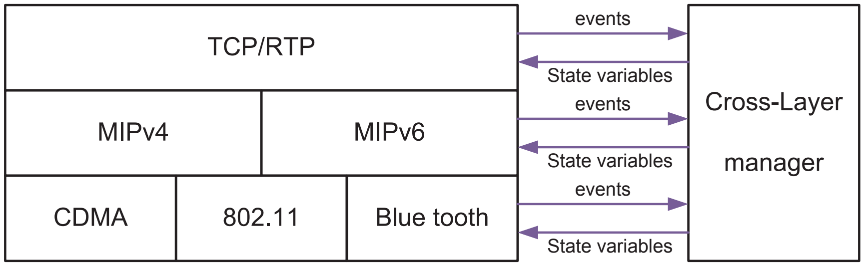


Fig. 7. An manager cross-layer design scheme for improving the performance of wireless links and mobile terminals [25].

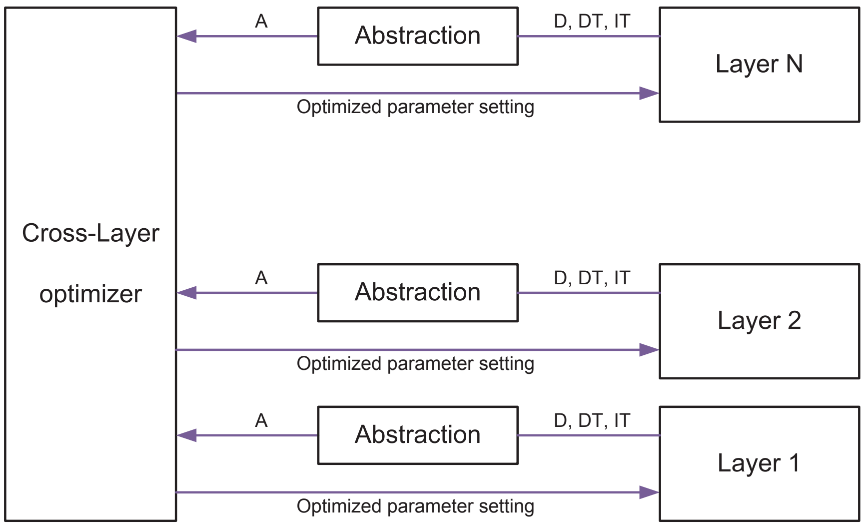


Fig. 8. A cross-layer design that uses a cross-layer optimizer for improving the performance of video streaming [26].

optimizer revises the value of the parameters, and then sends them back to the five layers. In this way, the five layers behave under the decisions of the cross-layer optimizer.

One of the advantages of the scheme in [26] is that it uses the layer abstraction to reduce the work load of the vertical plane. This scheme improves the video quality by allocating network resources in its cross-layer design as well. The disadvantage of this scheme is that it is designed solely for the video streaming, and it is not easy to expend to other applications. This is because the parameter revising for one application may not be suitable for another application. For example, the video streaming requires low TCP retry value, but the text transmission can endure long TCP retry limit in the bad network connection resulted by the channel interference.

The authors in [27] present a cross-layer design architecture called ECLAIR which is composed of interfaces (called tuning layers) and optimization algorithms (called optimizing subsystems) in each layer, as shown in Fig. 9. The tuning layer provides an interface to protocol data-structures that determine the protocols behavior [27]. In the TCP/IP model, a protocols behavior is determined by its control data-structures and the protocol implementation typically has data-structures for the control and data [27]. As the tuning layer is the interface to protocol data-structures, it reads and updates the protocol data-structure [27]. The authors in [27] give an example: in Linux, TCP control information is stored in a data structure called tcp_opt, and ECLAIR is able to read and update this data in order to control TCP behavior. Therefore, the communication and data exchange between two adjacent layers is conducted by the tuning layer [27].

Moreover, the optimizing subsystem in each layer contains the algorithms and data structures for cross-layer optimizations in that layer [27]. After the optimizing subsystem receives the control and data information through its tuning layer from another layer, the optimizing algorithms in the optimizing subsystem starts to optimize and adapt with the protocols behavior [22], [27].

The advantage of ECLAIR is that it does not destroy the five layer structure of the TCP/IP model and each layer has its tuning layer and optimizing subsystem to conduct cross-layer functions. This feature makes the structure of ECALIR clear and easy to be extended. The disadvantage of ECLAIR is that each layer communicates and exchanges data only with its adjacent layers, but not all the other layers. The behavior of a layer is determined by its optimizing subsystem which is only aware of its (at most) two adjacent layers. In this case, the application layer is not able to determine its behavior by the network layer, which might be crucial for the behavior of the application layer.

The non-manager method allows direct communications between any two layers; the manager method requires a vertical plane for the information sharing. Both of them achieve the cross-layer information sharing. The non-manager method has to affect the waterfall-like structure of the five layers, since the non-manager method is able to make any two layers

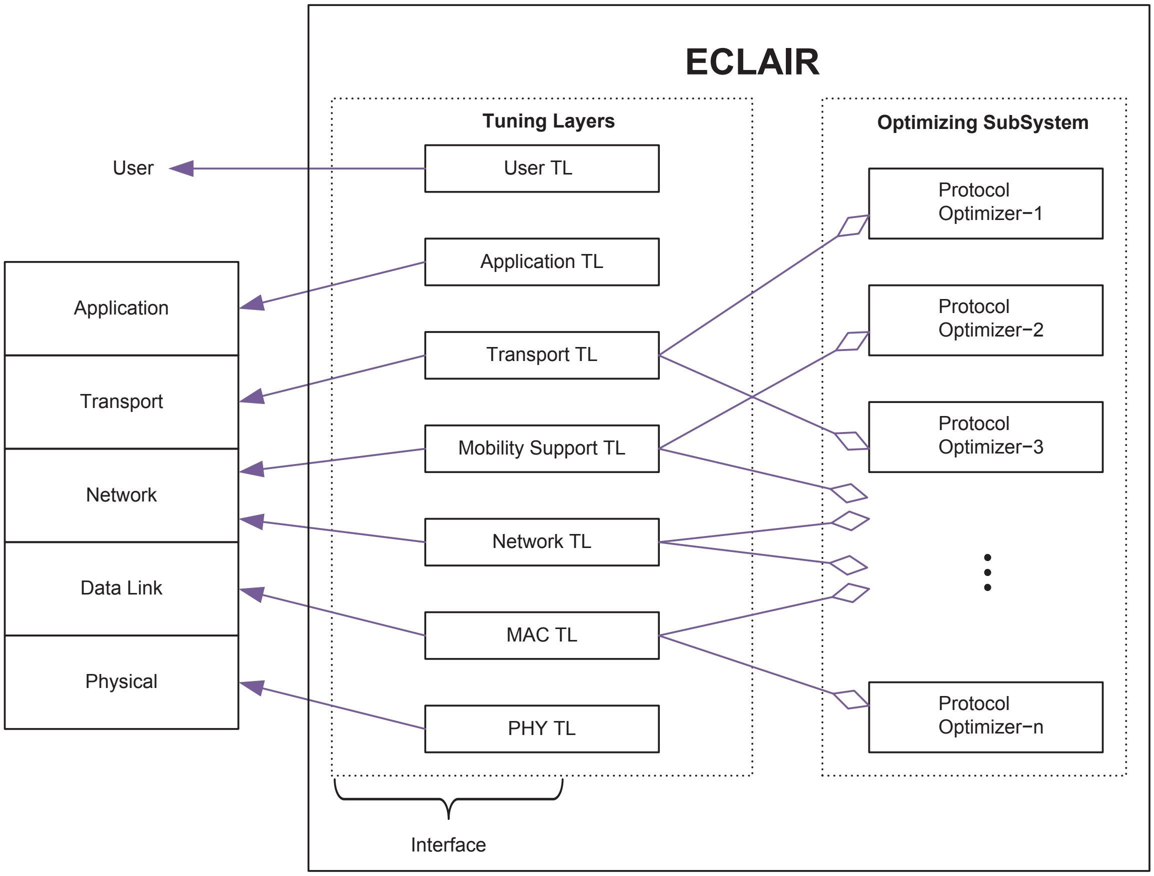


Fig. 9. ECLAIR, a Cross layer feedback architecture that functions as the vertical plane [27].

become adjacent. It is possible that some manager methods do not change the waterfall-like structure of the five layers by introducing a vertical plane, but the functions of the five layers could be changed.

V. Classification of Cross-Layer Designs by The Organization of Network For Cross-Layer Information Sharing

The second kind of classification of cross-layer designs composes of the centralized method and the distributed method, which are classified by the organization of the network for cross-layer information sharing. The non-manager method and the manager method are used for sharing the cross-layer information in one node, but the centralized method and the distributed method are used for sharing the cross-layer information among all the nodes in a network.

A. Centralized Method

Fig. 5(a) shows the centralized method, which introduces a centralized node (sometimes using a base station in cellular networks) or tiers which are in a hierarchical manner. The centralized node or tiers are introduced to manage the information sharing of the five TCP/IP layers between two nodes.

The authors in [28] describe the scheduling mechanism of the cross-layer information sharing in the Universal Mobile Telecommunications System (UMTS) downlink channel to take into account the fast power control information in UMTS. Using a low-complexity priority function that takes into account the channel state and variation of each user, the authors in [28] achieve significant performance improvement in UMTS. A base station is viewed as the central node in the network. A priority function that exploits the rapid channel fluctuations is used by the radio scheduler to prioritize transmissions attending its radio channel conditions [28]. After the priority function being set, the transmissions are scheduled in decreasing order of the priority function for each user [28]. The users that have better channel conditions should be allocated to a higher priority value, so that to these users can have better channel conditions, and thus these users can consume lower transmission power [28]. The determination of the priority is made by the base station. The priority function which is related with the MAC layer affects the capacity and delay, which are related with the transportation layer and the application layer. Therefore, we consider this cross-layer design as a centralized method.

The authors in [29] propose a cross-layer design for real-time video applications over time-varying CDMA channels in 3G wireless networks. In [29], the data link layer resource allocation is determined by the information from the application layer and the physical layer. The cross-layer signaling is also improved in [29]: the cross-layer information is stored in packet headers; a third-party network manages the cross-layer information; the TCP/IP layers can read and write the system profiles that stores cross-layer information. Fig. 10 shows the centralized cross-layer design in [29]. A centralized

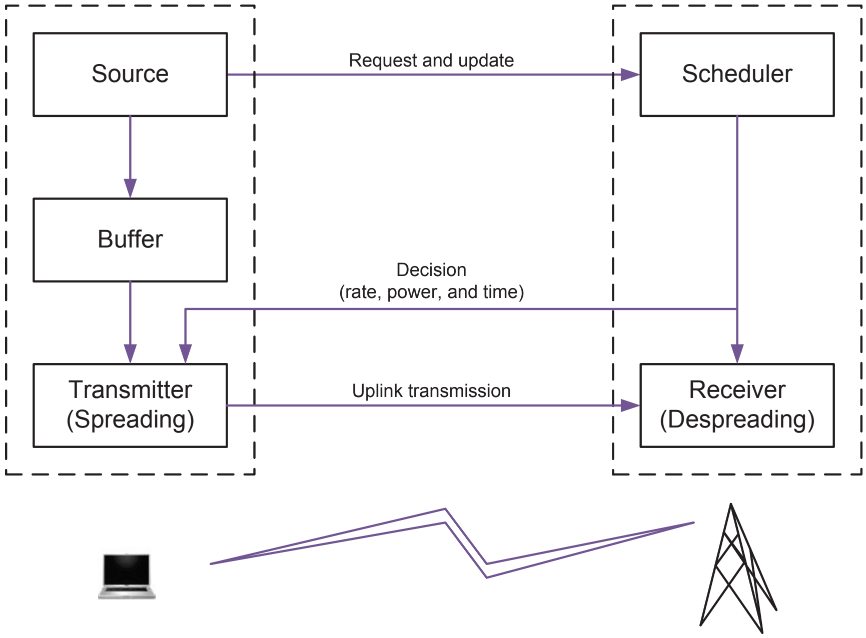


Fig. 10. A cross-layer design for real-time video applications over time-varying CDMA channels in 3G Wireless Networks [29]. The centralized scheduler is built for the uplink transmission.

scheduler at the base station receives and manages all the QoS requirements and cross-layer information from the mobile stations [29]. The base station maintains the information of the traffic status of each mobile station [29]. The request and update information from mobile stations to base station (shown at the top of Fig. 10) can be transmitted in piggybacked channel in the uplink packets to avoid the contention [29]. The cross-layer information of the mobile stations shared by this scheme can be stored at the base station as a system profile. The way that the base station responds to the mobile stations is relatively easy: the responding is done by broadcasting transmission decisions to mobile stations [29].

The scheme in [29] is designed for 3G wireless networks, and therefore it uses the base station as the centralized node to achieve the cross-layer information management. This base station determines the data link layer resource allocation for mobile stations based on the centralized information of each mobile station. The base station controls the resource allocation of the network and can try its best to avoid interference [29]. The disadvantage of centralized networks is that it relies on the base station which might be vulnerable. But the cellular network that is constructed in centralized structure is able to make use of this centralized cross-layer design.

An autonomic management mobile platform, called M@ANGEL, for seamless cognitive connectivity is proposed in [12]. This platform, in which the nodes dynamically change their configuration in order to adapt to environment conditions, aims at the provision of seamless cognitive connectivity in mobile networks [12]. By this way, this platform can provide powerful and affordable high-speed wireless access solutions [12]. The M@ANGEL architecture is composed of two tiers which are in a hierarchical manner: each entity in the lower tier, which consists of device-specific management mechanisms, manages a specific reconfigurable element; the entities at the second tier, which assists and coordinates the decisions of the lower tier management entities, control the network segments and the interfaces with the backbone network [12]. The requirements, states, and parameters of each layer are maintained by the nodes in the two tiers instead of the centralized node as in [28] and [29]. But this structure is also considered as a centralized cross-layer design, since it has a hierarchical structure.

Another example of the hierarchical structure is [9], in which the framework of CN is designed as a three-tier model: the requirements layer, the cognitive process, and the software adaptable network. The design detail of each of the three layers is left open to design and implement, but the framework is proposed clearly in [9]. The requirements layer of this framework maintains end-to-end goals, cognitive specification language, and resultant cognitive element goals [9]. The cognitive process is composed of algorithms that improve the nodes performance [9]. The algorithms may be based on historical data over a period of time without complete information about the environment [4], [9], [10]. The software adaptable network consists of modifiable network elements, network status sensors, configurable element, etc [9]. Through learning and reasoning, the cognitive network dynamically adapts to varying network conditions in order to optimize the end-to-end performance [9].

B. Distributed Method

Fig. 5(b) shows the distributed method, which does not use any centralized node or base station. Since there is no centralized node in the distributed method, a multi-hop path from a node to another is possible during the cross-layer information sharing [22], [31].

The authors in [31] describe the main obstacles in extending the work of the centralized cross-layer information sharing method to the distributed cross-layer information

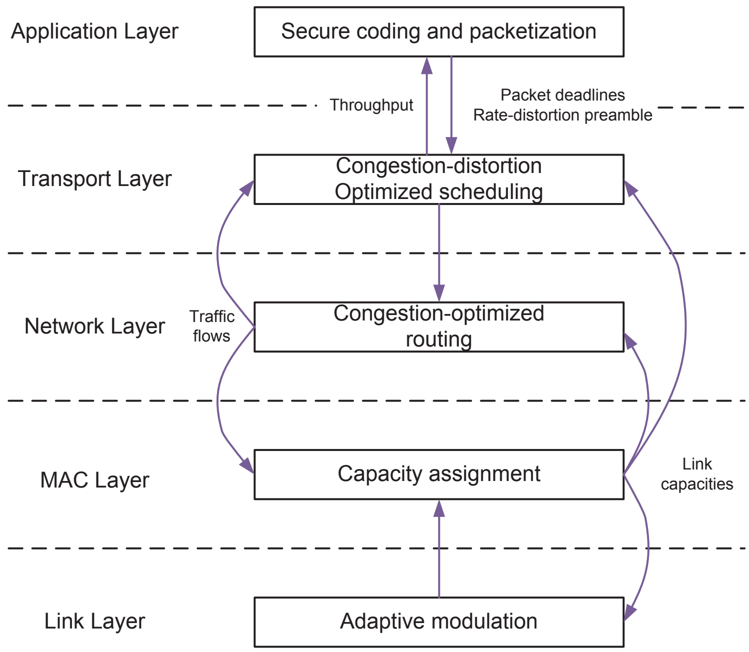


Fig. 11. A cross-layer design for low-latency media streaming over ad hoc networks [21].

sharing method in multi-hop wireless networks. The authors in [31] also indicate that comparing to the complex centralized cross-layer design, a simpler distributed cross-layer design is needed, although it might be potentially imperfect. The cross-layer information sharing in a multi-hop wireless network may cause an extra overhead and network congestion [31]. This problem can be solved by the cross-layer congestion control scheduling proposed in [31]. In this congestion control scheduling, a model of multi-hop wireless networks is built, and then node-centric and link-centric formulation are analyzed and compared to solve the potential congestion [31]. In addition, a distributed scheduling algorithm is proposed to allocate the network resource when the nodes request cross-layer information sharing [31]. The authors in [8] analyze the impact of the physical propagation environment on the performance of ad hoc networks, and model a cross layer design to reduce the impact of the physical propagation parameters in the airborne network environment as well. Another distributed cross-layer design framework is proposed in [39]. In this framework, the ARQ protocol is used to mitigate channel fading at the data link layer [35], [39]; the AMC selector determines the modulation-coding pair, and updates the transmission mode at the transmitter at the physical layer [39].

A cross-layer approach in [21] seeks to improve the end-to-end performance of ad-hoc networks by jointly designing multiple protocol layers in given network resources and dynamics. The framework in [21] requires upper layers to adapt their strategies to varying link and network conditions to support delay-constrained applications, e.g., video streaming, in ad-hoc networks. Fig. 11 shows the framework of the cross-layer design for the low-latency media streaming over ad hoc networks [21]. The framework in [21] can be considered as the non-manager method because there is no centralized node in the ad hoc network.

As shown in Fig. 11, to extend the achievable capacity region of the network at the data link layer, the adaptive modulation is used to maximize the link rates under varying channel conditions [21]. Based on link state information shared by the adaptive modulation, the MAC layer selects one point to assign time slots, codes, or frequency bands to each of the links [21]. The MAC layer operates jointly with the network layer to be aware of traffic flows to determine the set of network flows that minimize the congestion (shown as link capacities in Fig. 11) [21]. Successive suboptimal solutions are exchanged iteratively between the MAC layer and the network layer in order to find an optimal solution for the capacity assignment and network flows [21]. The transport layer uses congestion-distortion optimized scheduling to control the transmission and retransmission of video packets [21]. The application layer determines the encoding rate to achieve the most efficient streaming [21]. The aforementioned process is executed in a node in ad hoc networks, and there is no centralized node to control this process. Therefore this scheme is considered as a distributed cross-layer design method.

The authors in [1] present a scheme called farcoopt, which is a cross-layer design that makes use of the best farthest neighbor to increase QoS, to reduce the energy consumption, and to increase the network throughput. The farcoopt scheme is designed for multi-hop networks in which the separation problem (i.e., not all the nodes in the network are connected) is not rare [1]. Fig. 12 shows an example network for the farcoopt scheme, in which 1-2-3 is a part of a traditional route in this wireless network [1]. But in this network, Node 1 is able to directly communicate with Node 3, since they are within each others communication radius, and none of Nodes 4, 5, and 6 is within Node 1s communication radius [1]. In this case, Node 3 is Node 1s best farthest neighbor [1]. Therefore, instead of using the route 1-2-3, farcoopt chooses

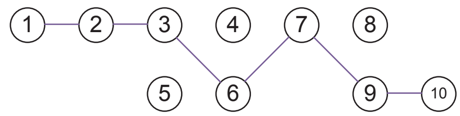


Fig. 12. An example of the farcoopt scheme, which is a cross-layer design that makes use of best farthest neighbor to increase QoS, to reduce energy consumption, and to increase the network throughput [1].

the route 1-3. In the farcoopt scheme, the confirmation of best farthest neighbor is decided by the MAC and PHY layers instead of the network layer, since the distance of nodes can be recorded or detected by the location of nodes and the paper assumes that the MAC and the PHY layer maintain this information [1]. Therefore, in farcoopt scheme, some behaviors of the network layer are based on the MAC and the PHY layers. Simulation results in [1] show that the farcoopt scheme increases the connectivity by 50% compared to traditional multi-hop approaches, and reduces the number of nodes necessary to provide full coverage of an area up to 35% [1]. A metric called network lifetime to evaluate the performance of cross layer designs is used in [1]. The network lifetime is defined as the time taken for 50% of the sensor nodes in a network to exhaust their power [1]. Simulation results show that the farcoopt scheme increases the network lifetime, because the farcoopt uses the best farthest neighbor to save power [1]. Simulation results also show that throughput in wireless networks deployed the farcoopt scheme is higher than traditional networks [1].

One benefit of using best farthest neighbor is that it reduces the overhead by reducing the length of the route, because instead of sending the data to the next node the farcoopt sends the data to best farthest neighbor [1]. This scheme also helps to save energy as while the nodes are communicating other nodes can sleep [1]. One disadvantage of this scheme is that it assumes each node in the network is aware of its exact position in order to determine the nodes best farthest neighbor. But the requirement that a node is aware of its position is not always satisfied.

This section introduces the second kind of classification of cross-layer designs, the centralized method and the distributed method, which are classified by the organization of the network for the cross-layer information sharing. The centralized method uses a centralized node or tiers to manage the cross-layer information sharing in the network, while there is no centralized node or tier in the distributed method.

VI. Challenges and Disadvantages of Cross-Layer Designs

Cross-layer designs intend to solve the problems in the waterfall-like concept of the current TCP/IP model, but cross-layer designs have some disadvantages. We have analyzed the weakness of the specific cross-layer designs in the previous sections. Moreover, there are some general disadvantages/challenges that we have to deal with in cross-layer designs. This section summarizes the disadvantages/challenges of cross-layer designs.

A. Coexistence of Cross-Layer Designs

Cross-layer designs are proposed by many researchers, but until now there is not a widely accepted cross-layer design coexistence scheme. This means that it is not easy to integrate two different cross-layer designs into a uniform design, due to the specific communication standard of each cross-layer design. Therefore, the coexistence problem is a challenge for cross-layer designs. The coexistence of the wireless networks using different technologies is determined by the standardization of interfaces. In order to communicate between the wireless networks using different technologies, cross-layer designs need to be implemented with the standardization of interfaces due to the heterogeneous characteristic of wireless networks [22]. The coexistence of different cross-layer designs is also determined by the standardization of interfaces and the transparent manner that how a cross-layer design is built.

A solution for cross-layer design coexistence is provided by [38]. The authors in [38] indicate that cross-layer designs need solve the following problems for the cross-layer design coexistence: a) Unintended cross-layer Interaction, which is caused by the interactions between layers and may lead to unforeseen dependencies; b) Stability of the network that uses cross-layer designs; c) Long-term Sustainability. This means only the cross-layer designs that consider coexistence in its scheme may be able to coexist with other cross-layer designs. Without a widely accepted protocol or design principle, different cross-layer designs cannot be easily integrated.

B. Cross-Layer Signaling

To store the cross-layer information in one node, local files (such as the system profiles in [29]) maybe used. To exchange the cross-layer information among the nodes in a wireless network, the cross-layer signaling must be considered. The cross-layer signaling controls the format and the exchange manner of the cross-layer information in the network, and thus it controls how to send and share the cross-layer information in a wireless network. The signaling is one of the most urgent problems that cross-layer designs should solve.

The first method of the cross-layer signaling is using packet headers. To make use of IPv6 headers, the cross-layer signaling can be stored into packet headers as the in-band message carriers to avoid designing a new signaling protocol [41], [50]. To make use of TCP headers, some unused bits in the header can be utilized to generate the in-band signaling [41], [51].

Moreover, ICMP messages which are able to contain more amount of data than packet headers can be used for the cross-layer signaling [41]. The motive of using packet headers and ICMP messages is to avoid implementing a new signaling protocol. However, the capacity of these headers and messages are limited and thus only some simple cross-layer parameters are able to be transmitted in this manner. Another disadvantage of these two methods is they rely on the specific layers even when the cross-layer signaling is generated by other layers.

The third method is to design a new network service for the cross-layer signaling [41]. A Wireless Channel Information Service is proposed in [52] to collect and exchange cross-layer parameters between mobile devices. A simple version of the

TABLE III
THE CHALLENGES OF CROSS-LAYER DESIGNS

Challenge	Reason	Solution
Coexistence of cross-layer designs	Each cross-layer design has its own standard in the communication between layers.	The standardization of cross-layer communication.
Cross-layer signaling	There is no uniformed format or exchange manner of cross-layer information exchange in the network.	Using packet headers, ICMP Messages, or network services for cross-layer data exchange.
Overhead caused by cross-layer signaling	To exchange cross-layer information between the nodes, cross-layer signaling results an extra overhead.	Although the overhead must be caused, a better design and implementation of cross-layer signaling may reduce the overhead.
The lack of the universal cross-layer design	Different applications have different requirements for the cross-layer design.	A universal cross-layer design is unlikely existent.

Wireless Channel Information Service was also implemented in [52] to prove its feasibility.

To exchange the cross-layer information among the nodes, the cross-layer signaling must result an extra overhead, especially when using the network service method. The generating of the extra overhead is inevitable for the cross-layer signaling, but there are solutions to reduce the overhead. Reducing the overhead caused by cross-layer designs is an open research issue. A layer abstraction concept is proposed in [26] to compute an abstraction of the cross-layer parameters and to avoid transmitting too many parameters. This layer abstraction concept may be used for reducing the overhead. An effective scheme for abstracting the parameters (including source rate, encoding format, FEC, directional beams, bit error rate, picture size, net transmission rate, channel coding) is proposed in [26] due to the correlations between the parameters. A distributed mechanism is proposed in [53] for reducing the cross-layer signaling overhead. This mechanism limits the overhead by optimizing the distributed end-to-end flow control and the resource management in wireless networks. Two low signaling schemes are proposed in [53] to achieve the overhead reducing by optimization of the mechanism.

C. Universal Cross-Layer Design

There are a number of application-driven cross-layer designs being proposed. Normally an application-driven cross-layer design focuses on a specific application, such as the video streaming, the secure transmission, etc. However, the cross-layer design for one application may not be suitable for another application. For example, the video streaming requires a low TCP retry value, but the text transmission can endure a long TCP retry limit in the bad network connection resulting from the channel interference [26]. One challenge of cross-layer designs is the lack of a universal cross-layer design that automatically adapts with different applications. The number of applications is not fixed, and this means the potential universal cross-layer design has to consider the requirements of all of the applications. Finding a universal cross-layer design is an open research issue. Based on our experience, a universal cross-layer design is unlikely existent.

However, there are some potential directions that partially solve this challenge. Although a universal cross-layer design for all purposes is unlikely existent, we may categorize the existing cross-layer designs based on the design purpose and try to find their common purpose. In this way, some partial universal cross-layer designs for certain applications may be proposed.

For example, the cross-layer design for the video streaming is a popular topic due to the larger amount of network resources cost by the video transmission. Some cross-layer designs for the video streaming are proposed in [6], [21], [26], [29]. It is an interesting topic to find the common schemes in these designs and finally design a scheme for the video streaming that makes use of the advantages of each design.

Secure transmission is another popular topic in cross-layer designs. Each of the designs for secure transmission has its own scheme. It would be interesting if we integrate SSH/SSL and WEP/WEA in [22], the parameter sharing in [46], the sub-linear rekeying algorithm in [47], and the system information aggregating in [48], and then we may make the design as secure as in [22], [46] and as effective as in [47], [48].

D. Destruction of the Layered Architecture

Aiming at the cross-layer communication, cross-layer designs may destroy the encapsulation of the layers and thus turn the well organized layered architecture to a disordered design. The layered architecture of the TCP/IP model makes it simple to improve the functions and performances of a single layer without being disturbed by the other layers. However, it becomes difficult to make such improvements in cross-layer designs since the modification has to satisfy the interaction with the existing dynamics between multiple layers [49]. Therefore, rather than modifying just one layer, all the layers must be considered for even a small modification in the system. The destruction of the layered architecture might be the most challenging issue and the fundamental disadvantage caused by cross-layer designs.

Table III list the aforementioned challenges of cross-layer designs.

VII. CONCLUSION

In the current TCP/IP model of the five abstract layers, only adjacent layers are able to communicate with each other. To improve the network performance and to mitigate the side effect brought by the waterfall-like concept, cross-layer designs are used to share the information among all the five layers.

Security, QoS, and mobility are three goals of cross-layer designs. To achieve these goals, a cross-layer design allows one layer to exchange and share the information with other layers in this node or in other nodes. The sharing scheme inside one node may be the non-manager method or the manager method. The sharing scheme among the nodes in a network may be the centralized method or the distributed method. Coexistence, signaling, the universal cross-layer design, and the destruction of the layered architecture are challenges that cross-layer designs have to face.

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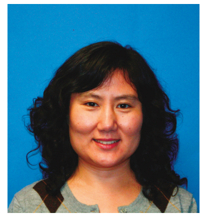

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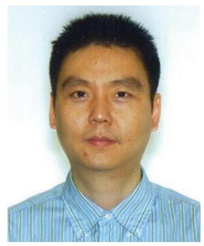

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