INVITED PAPER

Cross-Layer Design for QoS Support in Multihop Wireless Networks

Using network software designed with more-flexible concepts, streaming audio and video quality may be improved for networks where wireless-equipped computers forward data to each other.

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ABSTRACT | Due to such features as low cost, ease of deployment, increased coverage, and enhanced capacity, multihop wireless networks such as ad hoc networks, mesh networks, and sensor networks that form the network in a self-organized manner without relying on fixed infrastructure is touted as the new frontier of wireless networking. Providing efficient quality of service (QoS) support is essential for such networks, as they need to deliver real-time services like video, audio, and voice over IP besides the traditional data service. Various solutions have been proposed to provide soft QoS over multihop wireless networks from different layers in the network protocol stack. However, the layered concept was primarily created for wired networks, and multihop wireless networks oppose strict layered design because of their dynamic nature, infrastructureless architecture, and time-varying unstable links and topology. The concept of cross-layer design is based on architecture where different layers can exchange information in order to improve the overall network performance. Promising results achieved by cross-layer optimizations initiated significant research activity in this area. This paper aims to review the present study on the cross-layer paradigm for QoS support in multihop wireless networks. Several examples of evolutionary and revolutionary cross-layer approaches are presented in detail. Realizing the new trends for wireless networking, such as cooperative communication and networking, opportunistic transmission, real system performance evaluation, etc., several open issues related to cross-layer design for QoS support over multihop wireless networks are also discussed in the paper.

KEYWORDS | Cross-layer design; multihop wireless networks; quality of service (QoS) support

I. INTRODUCTION

As various wireless networks evolve into the next generation to provide better services, a key technology, multihop wireless network, has emerged recently. A multihop wireless network is dynamically self-organized and self-configured, with the nodes in the network automatically establishing and maintaining multihop connectivity among themselves. This feature brings many advantages to multihop networks such as low up-front cost, easy network maintenance, robustness, and reliable service coverage.

There are several types of multihop wireless networks designed for different types of application scenarios. In a *wireless ad hoc network*, every node has the responsibility to act as a router and forward packets for each other [1]. Because nodes normally have limited transmission ranges, multihop delivery is necessary for communication among nodes outside the transmission range. The topology of an ad hoc network is in general dynamic because the connectivity among the nodes may vary with time due to the node mobility, node departures, and new node arrivals. *Wireless mesh networks* are composed of two types of nodes: mesh routers and mesh clients [2]. Other than the routing capability for gateway/bridge functions as in a conventional router, a mesh router contains additional routing functions to support mesh networking. Through multihop communications, the same coverage can be achieved by mesh routers with much lower transmission power. *Sensor*

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network is currently a very active area of research [3] composed of a large number of sensor nodes that are densely deployed. In general, sensor nodes are limited in battery life, computational capacities, and memory size. The sensor nodes are usually scattered in a sensor field. Each of these scattered sensor nodes has the capability to collect data and route data back to the sink through a multihop delivery path.

In addition to traditional data services, multihop wireless networks have the potential to deliver exciting new real-time (RT) services such as voice over IP (VoIP), streaming music, or video, providing a competitive alternative to cellular networks, in particular, in areas where the latter are not available. To fulfill the above vision, it is essential to realize efficient quality of service (QoS) support over multihop wireless networks. Typical QoS metrics in general networks include available bandwidth, packet loss rate, estimated delay, packet jitter, hop count, and path reliability. For multihop wireless networks, there are also some other specific metrics, such as power consumption and service coverage.

The dynamic nature of multihop wireless networks is attributed to the time-varying channel condition, node movements, changing network topology, and variable application demands. Providing hard QoS (e.g., guaranteed bit rate and delay) in such a dynamic environment is almost impossible. Thus, throughout this paper, we are discussing the technologies that provide soft QoS [4] or better than best effort service, rather than guaranteed hard QoS. By soft QoS, it means that after the connection setup, there may exist transient periods of time when the QoS specification is not honored. Even targeting for soft QoS, the unique characteristics of multihop wireless networks impose great challenges.

- *Unreliable and unpredictable wireless channel conditions:* The wireless channel is highly unreliable and its capacity may vary dramatically. Therefore, QoS-aware protocols should not be sensitive to packet loss or rely on exact knowledge of channel capacity.
- *Contention due to shared nature of the wireless medium:* In a wireless network, transmission from a node not only uses local resources but also consumes the bandwidth of neighbors in the contention range. Thus, resource allocation for supporting QoS requirements is very complex, as such an allocation affects available resources at its contending neighbors, which may be outside of its communication range. Therefore, while performing resource allocation, it should also consider the impact on the neighboring flows.
- *Hidden terminal problem:* Hidden terminal problem happens when transmissions of two nodes, which are out of the transmission range of each other, collide at a common receiver. In a multihop network, the hidden terminal phenomenon will cause some nodes to have smaller contention probability than others (say, nodes in hidden position). Thus, different nodes will have different probabilities to win the channel access, which can result in severe unfairness and overall performance inefficiency [5].
- *Node mobility and route maintenance:* Mobility of nodes causes the network topologies vary dynamically. Such a dynamic nature of the network topology makes the precise maintenance of network state information very difficult. Thus, the procedure for route establishment has to be dynamic, and the routing algorithm in multihop networks has to be able to operate with inherently imprecise information.
- *Limited battery power and life:* Mobile communication devices are generally dependent on a battery with a limited supply of power. The higher the power usage, the better the transmission performance, and the shorter the battery life. Thus the resource allocation for QoS support should consider the residual battery life and the rate of battery consumption corresponding to the resource utilization.
- *No centralized control:* A multihop wireless network has no centralized control, and only local information is available to any node in the network. Therefore, QoS-provision protocols for multihop networks must use distributed algorithms and not rely on global information.

There are many studies that discuss the QoS provisioning in multihop wireless networks in recent years from the single-layer point of view. Because of the direct coupling among different layers, the traditional layered design is not sufficient for multihop wireless networks. Particularly, the physical layer affects the MAC and routing decisions by changing its transmission power and rate. The MAC layer is responsible for scheduling and allocating the wireless channel, which eventually will determine the available bandwidth and the packet delay. This bandwidth and packet delay will then affect the decision at the routing layer for link/path selection. The routing layer chooses proper wireless links to relay packets to the destination. The routing decision will change the contention level at the MAC layer, and accordingly the parameters at the physical layer. Finally, congestion and rate control in the transport layer will change the traffic volume in each communication link. Due to the nature of the wireless medium, different layers actually contend for the same shared network resources. Hence, all the controls in those different layers potentially have mutual impact, and it is necessary to consider all the controls across different layers jointly to optimize the overall performance. Thus, for a cross-layer design that satisfactorily enhances the network performance, it is essential to highlight the interactions among these layers.

In this paper, we will first review the work that provides QoS support for multihop wireless network from the single-layer point of view. Then the interaction among multiple layers and the corresponding cross-layer design framework is introduced, followed by some concrete cross-layered solutions.

It is exciting to see that there are some new trends for wireless technology development, which include cooperative communication and networking [6], opportunistic transmission [7], real system performance evaluation [8], etc. All these new directions bring opportunity and also challenges for cross-layer design on multihop wireless networks. A number of open issues and future research directions will be pointed out in this paper accordingly.

The remainder of this paper is organized as follows. In Section II, the solutions for QoS support in layered protocol are presented. Then, QoS provision with cross-layer design is reviewed in Section III. More specifically, the interaction among different layers, the theoretical study, and concrete solutions are presented in detail. Section IV presents the open issues for cross-layer design with the consideration of new technical trend. We conclude this paper in Section V.

II. QoS SUPPORT IN LAYERED PROTOCOL

In the literature, there are many studies that examine QoS provisioning in multihop wireless networks with a layered prospective, starting from the physical layer [9] and going up to the application layer [10]. Several good surveys [11], [12] have been conducted for QoS support in multihop networks. Here, we only focus on QoS-aware MAC and QoS routing in the network layer, which are the two most important components.

A. QoS-Aware MAC

Recently, many MAC schemes have been proposed aimed at providing QoS support for real-time services. However, these MAC protocols in general rely on centralized control, which is only viable for infrastructure-based architecture. IEEE 802.11e [13], the recently proposed specification adding QoS features to the existing 802.11 standard, belongs to this category. IEEE 802.11e supports up to eight priority traffic classes so that time-sensitive packets will be able to acquire better chance for transmission than other types of packets.

Many researchers have investigated the effects of dynamically tuning some parameters in 802.11 as well as general MAC protocols for ad hoc networks. Bononi *et al.* [14] propose a differentiated distributed coordination function (DDCF) scheme to implement node differentiation based on distinct node roles, which are assigned by the clustering method performed in the upper layers. The authors assume a certain virtual clustering method is available to determine different node roles such as cluster heads and leaf nodes. In general, a node belonging to a higher layer in the clustering structure will be given higher priority to access the channel than a node in a lower layer.

The black-burst (BB) mechanism has been applied in [15] in priority classification period to separate the higher priority stations from the lower priority ones. By having the transmission time of the BB proportional to the priority, stations with higher priority contend for the free channel first, while others have to wait until the transmissions of prioritized nodes are completed.

Holland *et al.* present a received-based auto rate (RBAR) protocol that adjusts transmission rate according to the channel condition [16]. In this scheme, channel quality estimation and rate selection are performed on the receiver side, since the channel quality experienced by the receiver actually determines whether a packet can be successfully received. RBAR has rather high overhead since channel quality estimation and rate selection are carried out on a per-packet basis through modified Request to Send (RTS)/Clear to Send (CTS) packets.

Leveraging multiple channels available in today's wireless radio, bidirectional multichannel MAC protocol is proposed to divide the bandwidth into one control channel and several data channels [17]. To utilize the multiple data channels, the format of RTS/CTS packets has to be modified to specify which data channel is to be used. The NAV field also has to be modified so that other nodes will be able to record the reservation information for each channel. Splitting one data channel into multiple channels is an interesting topic, and some follow-up research has been conducted to investigate the impact of such strategy on network performance.

B. QoS Routing

QoS routing is one of the most essential parts of the QoS architecture [18]–[24]. With QoS routing, the delivery paths for flows are determined with the knowledge of network resource availability as well as the QoS requirements of corresponding flows. Designers of QoS routing algorithms for multihop networks need to consider several issues: 1) metric selection (e.g., bandwidth, delay etc.) and path computation, 2) QoS state propagation, and maintenance, and 3) scalability. The QoS routing protocol also needs to deal with imprecise state information due to node (i.e., router) movement and topology changes. Furthermore, a QoS routing scheme for multihop networks should balance efficiency and adaptability while maintaining low-control overhead.

A QoS routing protocol called the core-extraction distributed algorithm is proposed in [18] that dynamically establishes a *core* of the network and then incrementally propagates the link state of stable high-bandwidth links to all the nodes of the *core*. The route computation is on-demand and performed by *core* hosts using local state only.

Xue *et al.* introduce a resource reservation-based routing and signaling algorithm, ad hoc QoS on-demand routing (AQOR) [19], that provides end-to-end QoS support in mobile ad hoc networks. A detailed calculation of the available bandwidth and the end-to-end delay is introduced assuming that access control to the shared wireless channel obeys a distributed collision-based MAC protocol and the ad hoc network is an unsynchronized system. These QoS metrics are used by AQOR to make admission and resource reservation decisions. Based on AQOR, the authors further propose wireless mesh routing protocol to support QoS for diverse applications (e.g., voice, video, and data) in a mesh wireless network with underlying wireless local-area network (WLAN) infrastructure [20].

In [22], courtesy piggybacking is proposed to alleviate the conflict between throughput and fairness for different prioritized traffic in ad hoc networks. The basic idea is to let the high-priority traffic help the low-priority ones by sharing unused residual bandwidth with courtesy. Making use of the channel and traffic dynamics, the piggybacking scheme can improve the system performance significantly. This piggybacking scheme can shorten the end-to-end delay when the traffic load is light and improve the packet delivery ratio for all priorities when the traffic load is high.

The authors of [23] believe that better QoS support can be achieved by either finding a route that satisfies the application requirements or offering feedback to the application when the requirements cannot be met. Thus, they propose a QoS-aware routing protocol that incorporates an admission control and a feedback scheme. The approximate bandwidth estimation is used to react to the network traffic. Two methods are proposed for bandwidth estimation. One is for hosts to listen to the channel and estimate the available bandwidth based on the ratio of the free and busy times. The other is for every host to disseminate information about its occupying bandwidth and for a host to estimate its available bandwidth based on the bandwidth consumption indicated from its two-hop neighbors.

All of the above schemes are called measurement-based routing without considering the potential interference from the to-be coming traffic (i.e., self-traffic). Yin *et al.* argued that self-traffic effect should be taken into account in the routing metric in order to get an accurate estimation of transmission time along the path, especially for the real-time communication (RTC) flow, which has critical delay and bandwidth requirements [24]. Since self-traffic will not appear until the RTC traffic is admitted and injected into the network, a mathematical model is needed to predict the path quality. They further propose a new traffic-aware routing metric PPTT, the sum of delay estimation on each link along the routing path, which consists of the packet service time and the queuing delay.

III. QoS SUPPORT WITH CROSS-LAYER DESIGN

A. Interaction Among Multiple Layers and the Cross-Layer Design Framework

In the initial stage, multihop wireless network protocol design is largely based on a layered approach, where each layer in the protocol stack is designed and operated independently, with interfaces between layers that are rather static. This paradigm has greatly simplified network design and led to the robust scalable protocols in the Internet. However, the inflexibility and suboptimality of this paradigm result in poor performance for multihop wireless networks in general, especially when the application has high bandwidth needs and/or stringent delay constraints. To meet these QoS requirements, recent study on multihop networks has demonstrated that cross-layer design can significantly improve the system performance [25]–[27].

Realizing cross-layer design is important for improving system performance for ad hoc networks. The National Science Foundation and Office of Naval Research jointly held a workshop on "Cross-Layer Design in Adaptive Ad Hoc Networks" [28] in 2001. A working group of the Internet Engineering Task Force has been studying the interlayer interactions and performance in mobile ad hoc networks. They summarized the interlayer interaction metrics and the benefits of such information exchange between the lower layers, network layer, and transport layer [29]. For example, the signal-to-noise ratio from the physical layer and the interference level from the link layer can be used for the route selection at network layer and transmission control protocol window size adjustment at the transport layer.

Cross-layer design breaks away from traditional network design where each layer of the protocol stack operates independently. A cross-layer approach seeks to enhance the performance of a system by jointly designing multiple protocol layers. The resulting flexibility helps to provide better QoS support given network dynamics and limited resources. It is known that different system parameters are controlled in distinct layers in a wireless network (see Fig. 1). For example, power control and modulation adaptation in the physical layer will change the overall system topology. Scheduling and channel management in the MAC layer will affect the space and time reuse in a network. Routing and admission control in the network layer will change the flow distribution. Finally, congestion and rate control in the transport layer will change the traffic volume in each communication link. All those controls potentially have mutual impact. Careful attention must thus be paid when applying controls in different layers. For instance (① in Fig. 1), assignment of channels to certain network interfaces changes the interference between neighboring transmissions. Moreover, it also defines the network topology that in turn

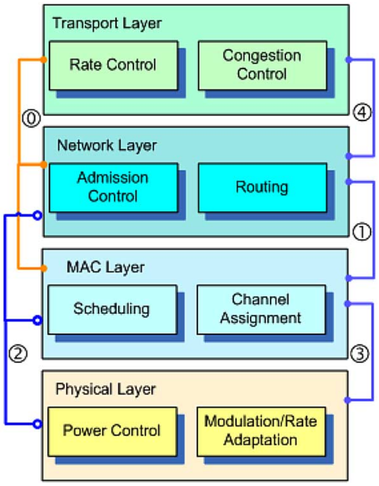

Fig. 1. ***Cross-layer framework and interaction among layers.***

influences routing. Another example can be that the power control in the physical layer changes the link status and the topology of the network, which in return affect the scheduling result in the MAC layer. On the other hand, the scheduling decides the link activation and the interference generated, and therefore changes the power required at each link to achieve certain QoS requirement (② in Fig. 1). It is necessary to consider that all the controls cross different layers jointly to optimize the overall performance.

Supporting soft QoS over multihop wireless networks can benefit substantially from the cross-layer design. In this design, interdependencies between layers are characterized and exploited by adapting to information exchanged between layers and building the appropriate amount of robustness into each layer. For example, routing protocols can avoid links experiencing deep fades, or the transport layer can adapt its transmission rate based on the underlying network condition. Fig. 1 illustrates the cross-layer framework and the potential interaction among layers. Several potential interactions among multiple layers are listed from ⓪ to ④. In the rest of this section, examples of evolutionary and revolutionary cross-layer approaches from different aspects are reviewed in detail.

B. Cross-Layer Network Capacity Planning

One of the main goals in the design of wireless multihop networks is capacity planning. Network capacity planning is concerned with the cost-effective deployment of a communication infrastructure to provide adequate coverage, throughput, and QoS support for end users. Within this realm, the QoS requirements will be represented as a set of end-to-end demands. Multiple network capacity planning schemes have been proposed for different design goals for which a network can be optimized, e.g., maximizing system throughput, minimizing end-to-end delays, or minimizing the total energy consumption.

In [30], Wu *et al.* address the network planning problem as allocating the physical and the MAC layer resources or *supplies* to minimize a cost function while fulfilling certain the transport layer communication *demands*. They model the demands in a network as a collection of multicast sessions, while modeling the allocation of supplies as a timesharing within a collection of possible physical layer states. This formulation necessitates an interaction across the network protocol stack, with which the key is to find an appropriate abstraction of each layer. The physical layer can be abstracted as a set of elementary capacity graphs (ECGs). An ECG is a capacity graph that represents a physical layer state, corresponding to an arrangement of concurrently active links among neighbors. At the MAC layer, by time sharing among different physical states, convex combinations of the ECGs can be achieved, hence presenting to the upper layers a set of supported composite capacity graphs. The network layer transforms the end-to-end traffic demand into a link-by-link one compatible with a supported capacity graph. Integrating these components, an iterative cross-layer optimization is proposed. Two objectives, minimizing an aggregate congestion measure and minimizing power consumption, are considered in that paper.

To tackle the capacity planning issue in fixed multiradio multichannel multihop wireless networks, Kodialam *et al.* develop algorithms to jointly optimize routing, channel assignments, and scheduling in order to obtain upper and lower bounds for the capacity region under a given objective function, i.e., QoS requirement [31]. They develop a network model with a limited number of orthogonal channels and with multiple radios at each node. This model provides both necessary and sufficient conditions for a feasible channel assignment and schedule in the network. Both the upper bound and lower bound of the system capacity are given in the paper.

C. Joint Routing and Rate Allocation for Media Streaming

Multihop wireless networks with mesh topology can often be characterized by a multitude of paths between a given source and destination. In general, multipath streaming has the following advantages over single path streaming. First, it can potentially provide higher aggregate bandwidth to applications (given the multiple paths are not sharing the same bottleneck). Secondly, data partitioning over multiple paths can reduce the short-term loss correlation in real-time traffic, thus improving the performance of streaming application. Thirdly, the existence of multiple paths can help to reduce the chance of interrupting the streaming service due to node mobility. Thus, a mechanism that takes advantage of these multiple paths is bound to perform better in supporting QoS than traditional single-path approaches [32]. For such a mechanism, routing or path selection is very important for supporting multimedia sessions over multiple paths.

Coupled with the path-selection strategy is computing the optimal media encoding rate, as well as the allocation of this media rate across the selected paths, in a way that maximizes the media quality at the receiver.

To better support multipath streaming, Rojviboonchai *et al.* believe that the packet losses due to different causes, such as congestion, channel error, and route change/break, should be differentiated. For instance, when the packet loss rate due to wireless channel error is increasing, the streaming application should increase the error control level; if the loss rate increment is due to congestion, increasing the error control level might be of no use and reducing the sending rate should be the right decision; if the loss rate increment is due to route change or break, then stopping transmission of the data until a new path is found (or the old route is reconnected) is the correct reaction. Based on such an observation, an ad hoc multipath streaming protocol (AMTP) is proposed [33]. Tightly coupled with a multipath routing protocol, AMTP exploits the cross-layer information such as routing and path status to accurately detect different network states and therefore differentiate different types of packet losses. Moreover, AMTP can choose multiple maximally disjointed paths with best QoS to maximize aggregate end-to-end throughput.

In [34], the authors provide a guideline on choosing a set of optimal paths and rate vectors that would effectively deliver the best media. The formulation not only captures the rate allocation for each media session but also splits the optimal rate over a set of paths such that the overall media quality is optimized. For video streaming over ad hoc networks, when multiple streams are present, the chosen rate and routes for each stream would also affect the performance of the other steams [35]. Thus, both the rate allocation and the route selection need to be jointly optimized for all the streams in the network. In [36], Zhu *et al.* study a convex optimization formulation of the joint routing and rate allocation problem for multiple streams. A centralized solution based on optimal flow assignment is derived as an upper bound of performance. A distributed scheme is also proposed, where the allocated rate at each stream depends on both the distortion-rate characteristic of the video and the network congestion increment.

D. Joint Channel Assignment and Routing

One of the major challenges for providing soft QoS support in wireless networks is the capacity reduction due to the interference among multiple simultaneous transmissions. In multihop wireless networks, providing a part of nodes (e.g., mesh routers in mesh networks) with multiple-radio multichannel capability can greatly alleviate this problem. With multiple radios using orthogonal channels, nodes can transmit and receive simultaneously or can transmit with neighbors simultaneously. Then, one needs to consider how to efficiently leverage multiradio and multichannel to conquer/reduce the wireless interference that widely exists in multihop wireless networks. To effectively mitigate interference, both routing and channel assignment (CA) should be carefully designed. It is apparent that CA and routing are coupled in multihop networks, as discussed below. On one hand, CA determines the connectivity between radios and hence the network topology because two radios can only communicate with each other when they are in a common channel. As we know, QoS-aware routing decisions are made based on the network topology. Thus, CA has a direct impact on routing. On the other hand, to achieve a better result, CA should be dynamically adjusted according to the traffic status and traffic demand of each link, which is determined by a QoS-aware routing algorithm. Therefore, routing and CA are tightly coupled and should be jointly optimized to improve the system performance.

There are some studies to investigate the performance of joint CA and routing from the theoretical perspective. Assuming a radio interface is capable of switching channels rapidly, recent work [37] analyzes the asymptotic lower and upper bound of the throughput capacity and concludes that it is dependent only on the ratio of the number of channels to the number of radios per node. Interestingly, they have shown that, in a random network, a single interface suffices for utilizing multiple channels as long as the number of channels is not too large. Motivated by the flexibility introduced by multiradio and multichannel, [38] formalizes the problem for joint routing and channel switching in multihop networks with multiple homogeneous radios and uses column generation method to solve the problem. There is also some theoretical work that does not assume a radio interface can switch channels on a per-packet basis. Raniwala *et al.* propose a centralized joint CA and routing algorithm [39]. The CA part considers high load edges first, and two different CA algorithms are developed. The first algorithm performs CA based only on network topology. The second algorithm reaps the full potential of proposed architecture by further exploiting traffic load information. The joint CA and multipath routing algorithm then proceeds in an iterative fashion. Their algorithm is based on heuristics and a worst performance bound is not investigated in that paper. Targeting at wireless mesh networks where the aggregate traffic demands and network topology do not change frequently, Alicherry *et al.* formulated the joint CA and routing problem that can model the interference and fairness constraints [40] and is also able to account for the number of radios at each of the wireless node. The goal is to maximize the bandwidth allocated to each traffic aggregation point subject to fairness constraint. A nice flow transformation technique is used to design an efficient CA algorithm that can assign channels to node radios while ensuring maximum data can be transmitted on specified traffic routes. For the first time, a constant approximation algorithm for this NP-hard problem is presented.

All of the above theoretical work is based on the perfect MAC without considering interference/collisions. From those theoretical works, it is not that easy to derive distributed algorithms because of the perfect MAC assumption and real-time information exchange overhead.

There have been several works dedicated to the study of the distributed protocol considering both CA and routing for multihop wireless networks. Reference [41] provides a combined solution consisting of CA and routing by assuming each node has enough homogeneous radios and assigns some of the radios fixed on a certain channel only for receiving. Both [42] and [43] propose a mesh-based framework for routing and CA, where the focused mesh has access points connected by a wired network.

In [42], with a single network interface, a node can only operate on one channel at a time. A node can switch its operating channel, but at the cost of channel switching delay. To maximize channel utilization, the channels should be assigned so that traffic load is equally balanced among channels. The authors argue that traffic load observed locally by each node does not accurately reflect the actual load, and thus cannot be used as a base for selecting routes. A new method for estimating the traffic load and selecting the best route according to load information is proposed.

In [43], Kyasanur *et al.* discussed the scenario wherein the number of interfaces per node is smaller than the number of channels. The authors divide the total available interfaces into two subsets, i.e., *fixed interfaces* and *switchable interfaces*. The main idea of the interface assignment is to receive data using the fixed interface. The switchable interface of a node X is used to transmit data whenever the fixed channel of the destination is different from the fixed channel of X. By carefully balancing the assignment of fixed interfaces of different nodes over the available channels, all channels can be utilized, and the number of contending transmissions in a neighborhood significantly reduces.

In [44], Wu *et al.* proposed a nice software solution, JCAR, to jointly coordinate channel selection on each interface and route selection among interfaces based on the traffic information. Since interference is one of the major factors that constrain the performance in a multihop network, an important channel cost metric (CCM) is introduced that reflects the interference cost and is defined as the sum of expected transmission time weighted by the channel utilization over all interfering channels. In CCM, both the interference and diverse channel characteristics are captured. Based on CCM, a distributed algorithm is proposed that effectively selects the JCAR pattern that has the smallest CCM value among a subset of potential JCAR patterns. JCAR is designed to perform CA and routing jointly at a time scale of seconds or longer considering the practical overhead of the off-the-shelf hardware on channel switching, so the algorithm does not require tight clock synchronization among neighbor nodes.

E. Joint Scheduling and Rate Adaptation for Opportunistic Transmission

To achieve high utilization of the scarce wireless resource, opportunistic transmission exploits the variations in channel conditions to improve overall network throughput. In wireless networks, there are two main categories of opportunistic transmission. The first one is to exploit time diversity of individual links by adapting the transmit rate to the time-varying channel condition [16], [45]. In [45], the authors proposed an opportunistic auto rate (OAR) scheme in which a flow transmits with higher data rate and more back-to-back packets when its channel condition is better. Exploiting multiuser diversity is another class of opportunistic transmission that jointly leverages the time and spatial heterogeneity of channels. It is first observed in the context of cellular networks that selecting instantaneous "on-peak" receiver with the best channel condition improves system performance [46], [47]. Motivated by this effect, practical opportunistic scheduling schemes have been implemented in Qualcomm's high-data-rate (HDR) system [48]. In multihop wireless networks, it is usual that a node concurrently communicates with several neighbors. Since channel quality is time-varying and independent across different neighbors, this provides a node an opportunity to choose one of its neighbors with good channel quality to transmit data before those with bad channel quality. Thus, it is interesting to explore the scheme for scheduling the packet transmissions to its neighbors and adjusting the transmission rate to improve the performance.

In [49], Wang *et al.* present a MAC protocol, i.e., opportunistic packet scheduling and auto-rate (OSAR) that takes advantage of both multiuser diversity and rate adaptation. Specifically, based on MultiRTS channel probing, only one of the backlogged users with channel quality better than certain level is allowed to access media. In [50], based on OSAR, the authors proposed a contention-based prioritized opportunistic scheme to reduce the probing overhead in which the channel conditions can be replied simultaneously by using BB contention method. In [51], the authors further proposed a new scheme, opportunistic medium access and auto rate (OMAR), to efficiently utilize the shared medium in 802.11-based ad hoc networks by taking advantage of diversity, distributed scheduling, and adaptivity. In OMAR, each node with a certain number of links is enabled to form a cluster and function as the cluster head to coordinate multiuser communications locally. In each cycle of data transmission, the cluster head initiates medium access, and then the cluster members in a distributed way make medium access decisions based on the observed channel conditions, where the proposed scheme can guarantee only the user with the best normalized instantaneous channel quality wins the channel.

However, the schemes mentioned above do not consider the interaction among neighboring transmitters, i.e., a sender individually makes its local decision for its own performance. Considering the cochannel interference caused by the shared wireless medium, the neighboring transmitters should jointly determine the "on-peak" flows. Moreover, again due to the shared medium feature, to fulfill a certain QoS requirement, the neighboring transmitters should be coordinated to reserve the shared wireless bandwidth to reduce the potential collision.

In [52], Chen *et al.* propose a cooperative scheduling to exploit multiuser diversity and time diversity for ad hoc networks. The opportunistic scheduling problem is formulated taking the interaction among the neighboring transmitters into account. The authors present the optimal scheduling policy, which finds the globally best set of simultaneously transmitting flows, to maximize network throughput while satisfying the QoS requirement of each link. Moreover, we use a cooperative and opportunistic scheduling scheme in which two aspects of cooperation are introduced to approximate the optimal scheduling. The first aspect is to exchange average data rates supported, QoS factors, and contention relationship among two-hop neighboring nodes for scheduling decision making. Another aspect is to coordinate the transmissions of neighboring flows by deferring the unscheduled transmitters.

F. Joint Rate Control, Admission Control, and Scheduling for Service Differentiation

In general, RT services are likely to coexist with best effort (BE) data services over a multihop wireless network. Using the de facto standard, IEEE 802.11 DCF MAC, delay-sensitive RT traffic such as VoIP and audio/video packets must compete with delay-insensitive BE data traffic. Although a QoS-enhanced IEEE 802.11e MAC mechanism, eDCF, has been developed for infrastructure-based WLANs, it does not provide adequate service differentiation in multihop wireless networks because of the hidden terminal and other interference problems. Thus, admission control is needed to make sure the real-time services will not overwhelm the system. Moreover, collaboration with neighboring nodes to regulate the prioritized traffic volume is necessary, e.g., it reduces contention of RT traffic by cutting down interfering BE traffic in a distributed way. In other words, the joint design among transport layer (rate control), network layer (admission control), and link layer (scheduling) is essential to achieve service differentiation.

Targeting at supporting VoIP service over multihop wireless networks utilizing off-the-shelf IEEE 802.11 NICs, the authors proposed a scheme called SoftMAC [53]. The key idea behind SoftMAC is to employ "coarse-grained" control mechanisms coordinate and regulate network load and packet transmission of both RT and BE traffic among neighboring nodes in a distributed manner. The objective is to keep channel busy time and collision rate below appropriate levels, and thus ensure acceptable VoIP quality. The proposed SoftMAC consists of three components.

i) distributed admission control module to regulate the amount of VoIP traffic that is "admissible" in a "neighborhood" and also "reserve" bandwidth for a VoIP flow along its path;
ii) a rate control module to control transmission of BE traffic so that the collision probability and impact to RT traffic on other nodes is under control;
iii) a priority queuing module to provide non-preemptive priority to VoIP traffic at each node.

A key feature of SoftMAC is that it achieves distributed coordination without requiring either tight clock synchronization or fine-grained transmission scheduling among neighboring nodes, both of which are difficult to implement in multihop networks.

G. Joint Power Control, Scheduling, and Routing

It has recently become evident that a traditional layering network approach, separating routing, scheduling, and power control, is not efficient for providing QoS support for ad hoc networks [54]. More and more people realize that especially in multihop networks, there is strong coupling among the traditional network, MAC, and physical layers. In the past several years, the problem of coupling routing with access control in ad-hoc networks has been addressed [38], [55]. Moreover, a joint scheduling and power control algorithm is studied in [56]. Having the observation that a change in power allocation or schedules on one link can induce changes in capacities of all links in the surrounding area and changes in the performance of flows that do not pass over the modified link, the joint design among power control, scheduling, and routing is essential.

In [57], Li *et al.* assume a time-division multiple-access based ad hoc network, where all nodes share the bandwidth by occupying different time slots. For the scheduling part, links are assigned slots depending on their link metrics. The algorithm gives priority to the links that have larger queue length and block less traffic from neighboring links. The authors conclude that with joint power control and scheduling, the network achieves significantly larger throughput and less delay. But for some unbalanced topology, bandwidth requirements cannot be satisfied by scheduling only; rerouting is needed to lead some packets to go through alternative route and release congestion. Routes are then selected periodically according to both the energy consumption and the traffic accumulation. It can be seen that the rerouting decision is made iteratively with joint power control and scheduling.

A similar idea can be found in [58], where the authors seek to find subsets of simultaneously active links as well as the associated transmission powers in order to minimize the total average transmission power in the network. A duality approach for finding the optimal scheduling and power control policy is proposed. In this paper, the authors also consider the problem of routing, and hence determination of the required data rates on each link, for a given traffic demand rate matrix.

In [59], Radunovic *et al.* want to find scheduling, power allocation, and routing that achieves the max-min fair rate allocation. This is a highly complex nonconvex optimization problem for a general network topology. In order to obtain results for larger networks, they focus on one-dimensional symmetric network topologies, where all nodes are aligned on a straight line. These topologies represent a large class of existing networks, from car networks on highway to networks on coast or mountain valley. The authors found that for small power constraints it is better to relay, and for large power constraint it is better to send data directly to destinations. They characterized optimal scheduling and power allocation for two different types of routing policies, i.e., direct and minimum energy routing policies, respectively.

IV. OPEN RESEARCH ISSUES

Although many schemes with cross-layer design have been proposed for multihop wireless networks, there are still some open issues that need to be addressed. First, the potential complexity brought by the cross-layer design needs to be analyzed. Moreover, the performance gain that can be achieved by the "best" cross-layer design needs to be studied. Secondly, with the evolvement of emerging wireless technologies, such as cooperative communication and networking, as well as opportunistic networking, one needs to investigate their impact to efficient the cross-layer design. Lastly but not least important, more real-system development is needed to evaluate the real value of the cross-layer design.

A. Performance Gain Versus Design Complexity

Although many studies have demonstrated that significant performance gain can be achieved, a cross-layer approach to network design can significantly increase the design complexity [60]. Indeed, protocol layers are extremely useful in allowing designers to optimize a single protocol layer design without the complexity and expertise associated with considering other layers. Thus, cross-layer design should not eliminate the design advantages of layering. Keeping some form of separation, while allowing layers to actively interact, appears to be a good compromise for enabling interaction between layers without eliminating the layering principle. In such a structure, each layer is characterized by some key parameters, which are passed to the adjacent layers to help them determine the operation modes that will best suit the current channel, network, and application conditions. There are several fundamental questions remaining to be answered related to such a tradeoff between system performance gain and protocol design complexity.

- How to characterize the essential information that should be exchanged across layers and be adapted to? For example, the link layer might be characterized by parameters representing channel quality, such as signal-to-(interference plus- noise) ratio, or link-layer state information such as the bit error rate or supported data rate. Similarly, the network and MAC layers might exchange the requested traffic rates and supportable link capacities.
- How should global system constraints and characteristics be factored into the protocol designs at each layer? How to minimize the impact of imperfect measurements or decisions at one layer to the overall system?
- Cross-layer design diminishes the advantages of modularity. It can create unintentional interactions between layers, which may cause undesirable consequences on the stability of the system. Moreover, protocols by cross-layer design no longer can be developed in isolation, and renewing of any of them maybe accompanied with a reimplementation in a cross-layer fashion. How to improve the reusability of certain cross-layer design is a challenging and important issue.

B. Performance Analysis

A multihop wireless network is characterized by a distributed, dynamic, self-organizing architecture, while each node in the network is capable of independently adapting its behavior. Analytical models to evaluate the performance of multihop networks have been scarce due to the distributed and dynamic nature of such networks. Game theory offers a suite of tools that can be used effectively in modeling the interaction among independent nodes in a multihop network. So far, game theory has been applied to the modeling of a multihop network at the physical layer (distributed power control [61]), the link layer (medium access control [62]), the network layer (packet forwarding [63]), and the transport layer [64].

There is significant interest in cross-layer optimization for multihop wireless networks. Often in a distributed multihop networking game, node decisions at a particular layer are made with the objective of optimizing performance at some of the other layers. With an appropriate formulation of the action space, game theoretic analysis can provide insight into approaches for cross-layer optimization. Game theory offers a tool to model adaptations that may occur at different layers of the protocol stack and to study convergence properties of such adaptations [65]. However, there are only a few works on this area; more study is needed align this direction so that the "real" benefit of cross-layer design to multihop wireless networks can be fully exploited.

C. Node Cooperation for Cross-Layer Design

Since neighboring transmissions will have mutual interference and mutual impact once one device takes any control, cross-layer adaptation inside a single device is

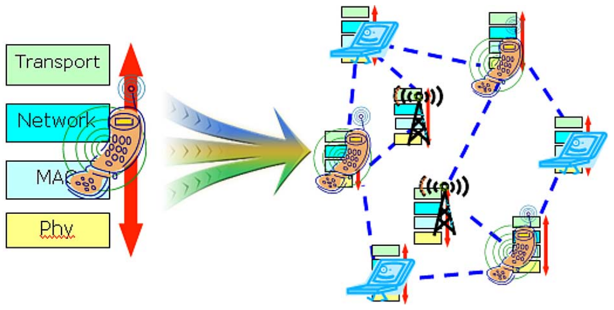

Fig. 2. *Node cooperation for cross-layer design.*

not good enough for efficient multihop wireless networking. The group of devices should collaboratively analyze the network situation and coordinate to find the "best" communication device, radio, networks, and protocols. More specifically, the devices should work together to exploit the range of available channels, extend coverage by collaborating with other nodes, jointly detect bad links, and find alternative ones with other end-systems.

As a new paradigm, research topics related to cooperative communication and networking are drawing a lot of interest recently [6]. The National Science Foundation in 2005 and 2006 sponsored two workshops specifically to discuss the related research issues: "WICAT Workshop on Cooperative Communications"[1] and "MSRI Workshop: Mathematics of Relaying and Cooperation in Communication Networks,"[2] respectively. However, most of the existing works discuss the cooperation from the single layer, especially physical and MAC layer, point of view.

Nodes cooperation is a stack-wide issue and should be jointly considered with the cross-layer adaptation (see Fig. 2). This is a rather new direction, and much work needs to be conducted to align with this direction. Besides the concrete protocol design, how to enforce cooperation [66] across different layers is also an interesting and open issue.

D. Opportunistic Transmission Across Multiple Layers

In practice, wireless channel quality varies significantly, both for mobile and for stationary nodes. Though traditionally viewed as a source of unreliability that needs to be mitigated, recently there have been some interesting works on opportunistic transmission that exploit the variation in channel conditions to improve overall network performance. The channel fluctuations can be exploited opportunistically when and where the channel condition is good.

In the MAC layer, there are two main classes of opportunistic transmission: time diversity of individual link [45] and multiuser diversity among multiple neighbors [49], [67], respectively. Taking the interaction among neighboring transmitters into consideration, a cooperative and opportunistic scheduling is proposed that leverages both time and multiuser diversity to improve system performance while satisfying QoS requirements of individual flows [7].

In the network layer, an opportunistic multihop routing protocol, ExOR, is proposed [68]. The basic idea is that the source broadcasts the packet and some subset of the intermediate nodes receives the packet. The node in the subset that is the closest to the destination will continue to broadcast the packet. ExOR improves performance by taking advantage of long-distance but lossy links that would otherwise have been avoided by traditional routing protocols. Further exploring the feature of network coding, a COPE scheme is introduced [69]. COPE is an opportunistic approach to network coding, where each node snoops on the medium, learns the status of its neighbors, detects coding opportunities, and codes as long as the recipients can decode.

Note that all the work mentioned above tries to exploit the opportunistic transmission from a single-layer point of view. With the closed interaction among different layers, if one layer takes a certain strategy in terms of opportunistically transmitting, then the other layers may be affected and even may not have further opportunity to be explored. Thus, how to jointly consider the opportunities among different layers to maximize the system performance would be an interesting issue to discuss.

E. Security Assurance With Cross-Layer Design

Security can be considered as one of the QoS attributes. Wireless communication with the nature of broadcast is more prone to security risks than others, and multihop wireless networks are no exception. Multihop wireless networks are even vulnerable to security attacks. For instance, there is no centralized trusted authority to distribute a public key in multihop networks due to the distributed system architecture. Current proposed security approaches may be effective to a particular attack in a specific protocol layer. However, there still exists a strong need for a comprehensive mechanism to prevent or counter attacks in all protocol layers.

The first cross-layer design presented in [70] allows the ad hoc routing protocol layer to share information with the MAC layer. The goal here is to assure that unidirectional links are not used by an ad hoc routing protocol if the underlying MAC layer requires bidirectional links, such as with the IEEE 802.11 MAC protocol. The second cross-layer design presented in that paper allows the application layer and the transport layer to share information. If an application is sending time-sensitive information that should be transmitted within a specific maximum delay, an application should wait for the previous transmission to be completely acknowledged before sending a next message.

Having many interactions among different layers and their impact on the security factor has not been well

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[1] http://www.wicat.poly.edu/wicatworkshop/index.html.

[2] http://www.eecs.berkeley.edu/~gastpar/MSRI/.

studied yet. Many interesting topics can be figured out with more studies conducted.

F. Real System Evaluation for Cross-Layer Design

Limited fidelity of simulators has prompted researchers to build a wireless testbed for real system performance evaluation. Many multihop wireless test beds built so far are designed for the specific projects on which the researchers are working. Among those testbeds, many of them are dedicated to design for evaluating the performance of the proposed multihop routing protocols.

The CMU-Dynamic Source Routing (DSR) testbed [71] is built to test the implementation of the DSR protocol for ad hoc networks. In order to facilitate mesh networking research, the Roofnet project built a 50-node testbed [72] spread across volunteers' rooftops in Cambridge, and external antennas are mounted on the chimneys of volunteers' houses. Microsoft research has built a 23-node testbed in a typical office building to verify the performance of their proposed multiradio multihop routing scheme, Link Quality Source Routing (LQSR) [73]. Each node has two 802.11 radios, and the node density was deliberately kept high enough to enable a wide variety of multihop path choices. To achieve manageability and reconfigurability, the authors architected the miniaturized wireless network testbed (MiNT), which is a *reconfigurable* miniaturized mobile wireless network testbed in [74]. Using commercial off-the-shelf hardware, MiNT provides a flexible experimentation environment through a comprehensive set of control mechanisms and data analysis tools. In [76], the authors present analysis of extensive field measurements of physical- and application-layer performance for access and backhaul links. They also present application-layer throughput measurements of contending multihop backhaul flows driven by multiple traffic types. A measurement-driven deployment methodology has been developed for two-tier mesh access networks by leveraging the measurement data. To exploit MAC layer diversity in wireless networks, the authors in [77] conduct experiments to demonstrate that multipath fading effects are seen at the MAC layer. These effects appear at timescales on the same order of the IEEE 802.11 protocol and, therefore, interact negatively with the RTS-CTS-DATA-ACK handshake.

One thing worth drawing attention to is that the vast majority of the devices adopted in today's testbed use IEEE 802.11 wireless LAN adapters. For those, a large part of the MAC functionality is realized very close to the hardware, in the proprietary firmware. This makes modifications to the MAC layer for real-world experiments with cross-layer functionality nearly impossible, and this in turn prevents many protocol designs from being verified in a real setup. Thus, how to build an efficient testbed for evaluating cross-layer design of multihop wireless networks is still an open issue.

Realizing the above challenge, Jesschow *et al.* try to tackle this question by leveraging the Embedded Sensor Board (ESB) sensor nodes in their testbed. In [75], Camp *et al.* have presented a software framework on the basis of the ESB sensor network platform. This framework allows for the easy implementation and evaluation of cross-layer ad hoc protocols, including those with a modified MAC layer. However, as the authors admitted, ESB node only has a single-channel transceiver and uses a simplified CSMA/CA MAC. Thus, this non-802.11 compatible physical layer cannot provide a direct performance comparison to an 802.11-based network, and the observations from the testbed may not be applicable to 802.11-based multihop networks.

V. CONCLUSION

The unique characteristics of multihop wireless networks call for new design paradigms for QoS support that move beyond conventional layering. This paper has taken stock of the current activity in the area of cross-layer design for QoS support in multihop wireless networks. After summarizing the key challenges and presenting the overall framework for a cross-layer design, we survey the existing work by examining the ideas of some representative cross-layer design proposals. More specifically, the work related to joint routing at network layer and rate allocation at transport layer, joint channel assignment at MAC layer and routing at network layer, joint scheduling at MAC layer and rate adaptation at physical layer, joint rate control at transport layer, admission control at network layer, and scheduling at MAC layer, joint power control at physical layer, scheduling at MAC layer, and routing at network layer were reviewed in detail.

Then, we highlighted some open challenges in this area and discuss issues that, in our opinion, will make the ongoing cross-layer design work more holistic and complete. As we pointed out in this paper, many challenging problems lie ahead, and the question of optimal cross-layer design is far from being resolved. While cross-layering provides significant performance advantages, it can also greatly increase design complexity, which can make it more difficult to obtain insights about the "real" performance gain bring by cross-layer design. Moreover, the new trends of wireless technology evolvement present many important areas of future research. ■

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