Cross-Layer Architectures for Bandwidth Management in Wireless Networks

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Contents

1 Introduction

1.1 Overview

In recent times, there has been a proliferation in the use of wireless communication all over the world. Several wireless networking technologies such as cellular networks, wireless local area networking (WLAN) and Bluetooth are commonly used in different environments. One problem spanning all types of wireless devices (e.g., cellular phones, PDAs, laptops, etc.) and networks, is the scarcity and variability of resources such as battery power, processor speed, memory, and wireless bandwidth. A major portion of research in wireless networking thus addresses the problem of how to effectively manage and optimally use these scarce and variable resources.

1.2 Focus

The topic of resource management in wireless networks is a very broad one. There are a number of research thrusts pertaining to different network technologies and different resources whose usage is to be optimized. Resource management is required for all types of wireless networks such as cellular networks, wireless LANs, mobile ad hoc networks and sensor networks. In this work, we focus on resource management schemes meant only for networks based on, or compatible with, the widely used and deployed IEEE 802.11 standard [1]. We consider Single-hop ad hoc ("pervasive" environments) [1], Access-point based [2, 3], as well as Multihop [4, 5, 6] network environments.

Furthermore, while there exists an extremely large body of work dealing with power control in wireless networks, and also work on processor-management, in this survey, the only resource whose management we address is *wireless bandwidth.*

Bandwidth, or channel capacity, in a wireless network is a resource shared by a number of wireless nodes in the vicinity of each other. The

[1]Some of the projects we refer to, e.g. [2, 3, 4], pre-date the standardization of the IEEE 802.11 protocol, but the approaches discussed are still applicable to it.

more time spent by a wireless node on the channel, the more data it can transmit and the greater its throughput. Thus, bandwidth management must be co-ordinated amongst the nodes that share the wireless channel. In the absence of bandwidth management, nodes sharing a wireless channel will attempt to completely capture it in order to maximize their throughput. Due to location dependent errors and due to interference, each node perceives a different channel capacity. The channel capacity perceived by each node also varies as a function of time. An application working over a wireless channel must be designed to dynamically adjust the quality of service (QoS) it provides its user(s). These factors make the problem of bandwidth management and allocation in wireless networks a challenging one.

1.3 Cross-Layer Design

In our study of bandwidth management architectures for different types of IEEE 802.11-based networks, we found one prominent common trait. All the major schemes that we focus on employ some kind of interaction, at each wireless network node, between the protocols at the different layers of the OSI protocol stack. This kind of interaction is not present in the protocol stack of a wireline network node.

There exist individual mechanisms at every layer of the protocol stack that assist in some way in controlling the usage of the wireless channel. Distributed fair scheduling [7, 8, 9, 10, 11, 12] and bandwidth monitoring and estimation [1, 5, 6] at the MAC layer, QoS routing at the network layer [13, 14, 4, 15], and rate adaptation [2, 6, 1, 5] at the transport and application layers are all examples of these individual mechanisms. The architectures we describe in detail in the following sections involve, with varying degree, *co-operation* between individual mechanisms at different layers of the protocol stack, usually through the sharing and exchange of state information between them. They hence deploy a cross-layer design for their services and protocols.

1.4 Outline

The rest of this survey is organized as follows. In the Section 2, we present a list of essential tasks in performing bandwidth management in wireless networks. In Section 3, we present brief summaries of the six cross-layer bandwidth management architectures we have chosen for the survey. We describe their salient characteristics, especially the internals of their respective essential tasks that we list in Section 2. Section 4 compares and contrasts the six architectures. We once again use the respective schemes' design of critical bandwidth management tasks as the criteria for their comparison. Section 5 lists some future directions and improvements that we might see in various tasks such as network-layer signaling, available bandwidth estimation, etc. Section 6 concludes this survey.

2 Essential Tasks in Bandwidth Management

In this section, we list the essential tasks in bandwidth management that are common to all the architectures we survey. This list of tasks forms a *methodology* for our study. In the subsequent sections, we examine in detail how the architectures go about accomplishing these tasks, compare and contrast these methods, and suggest improvements. Each of these tasks might occur at a different layer of the OSI protocol stack, and exchange information with the other tasks at other layers, thus bringing about cross-layer interaction.

1. *Available bandwidth estimation and monitoring:* Before distributing the channel capacity among the flows contending for it, a bandwidth management scheme must first have an estimate of the available bandwidth. This is likely to be less than the theoretical channel capacity (1, 2, 5.5 or 11 Mbps for IEEE 802.11 networks) due to the presence of location-dependent contention and physical errors. If these phenomena are rampant, the channel state is bad and available bandwidth is less. Most of the architectures described in this survey either assume or implement an available bandwidth estimation or channel quality monitoring module. Usually, the stimulus for rate adaptation arises from this module: when it detects a change in available bandwidth or channel quality, rate adaptation on the behalf of one or more flows must occur. Note that channel quality, and hence available bandwidth, are *location-dependent* features. Available bandwidth from the same source to different destinations can be different, depending on the location of the destinations.

2. *Signaling:* All the architectures we study employ a signaling protocol to carry reservation state over the network. The need for a signaling protocol in multi-hop bandwidth management is obvious, since

resources have to be reserved at each hop of the flow. However, a signaling protocol may be required even in single-hop wireless networks because the reservation state may be maintained centrally in such networks and a communication mechanism is required between the centralized reservation table and the mobile wireless hosts. The Utility-fair scheme [3] uses MAC-layer signaling while the BM [1] has its own signaling messages. The signaling protocol must be lightweight as it may have to be frequently employed due to bandwidth re-negotiations during the flow.

3. *Bandwidth allocation policy:* Once the available bandwidth is known and the requirements of the flows are known, the next step is to allot bandwidth amongst the competing flows. Some architectures simply adopt a first-come first-serve (FCFS) policy in which, if the bandwidth request is no more than the available bandwidth, the entire request is satisfied. Other architectures attempt to ensure fair sharing or price-based sharing of the available bandwidth. The bandwidth allocation policy comes into play at the time of bandwidth re-negotiation and for flow-dropping, in the absence of sufficient resources, also. Some schemes [4, 6] do not specify which flows must adapt their sending rate and which need not, when resources become scarce. In these schemes, fairness is hence impacted and providing even coarse rate or channel time guarantees becomes impossible.

4. *Reservation state:* Based on the bandwidth allocation policy, flows are admitted and allotted some portion of the available wireless channel bandwidth. Most of the architectures in this survey employ a *reservation-based*, as opposed to differentiated-services, approach to bandwidth management. All the architectures, except for SWAN [6] which keeps aggregate state, maintain per-flow reservation state. The state maintenance can be centralized or distributed. It is required at the time of admission control and rate allocation to know how the available bandwidth is being consumed by the existing flows. It is possible to keep per-flow reservation state only if the number of flows traversing a single wireless or ad hoc subnet is small. This is an implicit assumption of the schemes. In the Internet, it is impractical to maintain per-flow reservation state due to the presence of a large number of flows. SWAN eschews per-flow state not because storing it is costly (it is not costly, in fact, if the number of flows is small), but because

keeping the reservations coherent in a continuously changing environment is non-trivial. Other approaches also recognize this problem of keeping reservation state coherent. They work to keep the overhead of adaptation, which causes change in reservation state, minimal, while still attempting to optimize performance. SWAN's not maintaining per-flow state could result in decreased fairness and hence a degradation in quality of admitted flows. The guarantees provided by all the schemes are *channel-conditioned*, but those provided by SWAN are slightly weaker than those provided by other schemes, due to the absence of per-flow reservation state.

The architectures that maintain per-flow reservation state utilize *soft-state* reservations that need to be periodically refreshed. All reservation state must be maintained as soft-state in order to deal with drastic conditions (e.g., mobility, link breakage, device turn-off, etc.) that might cause a flow to terminate abnormally without even being able to properly release its reserved resources. Unless the resource reservations are time-out, the resources will be permanently lost to the network as a consequence of the abnormal termination of the flow.

5. *Rate control:* Once a flow has been allotted a certain portion of the available channel bandwidth, it must restrict its packet transmission rate to conform to its allotted share. This is essential to the co-operative sharing of the available bandwidth. Rate control may be done at various layers of the OSI protocol stack. Some schemes [5, 1] modify the application to adapt its quality and only generate packets at a rate no greater than the allotted bandwidth. Other possible rate-control and bandwidth share enforcement mechanisms are: employing a rate-based transport-protocol, priority-aware packet dropping, MAC-layer fair packet scheduling, and traffic shaping using token-bucket or leaky-bucket flow control.

6. *Application and flow adaptation:* A common feature of all the architectures is the presence of several adaptive levels at which the application is assumed to be able to operate. This is a vital requirement of the applications for them to be able to function uninterrupted in a continuously changing wireless environment. The stability of resource availability in wireline networks means that one-time admission control of a flow is often sufficient [1]. In a wireless network, the flows have to continuously adapt to the changing conditions. Even when

resource availability is low and flows are forced to lower their transmission rates, the application must still be able to provide the user *some* service, perhaps at a degraded quality.

The stimulus for flow adaptation may come from the available bandwidth monitor at the MAC layer, via network mechanisms such as ECN and in-band signals, or from the centralized reservation manager. The reaction to the stimulus could be a demand/release of bandwidth or a change in the packet transmission rate of the flow.

3 Description of Cross-Layer Architectures

This section contains brief descriptions of six cross-layer architectures that we have chosen to concentrate on for the purposes of our survey: TIMELY [2], Utility-fair [3], INSIGNIA [4], dRSVP [5], SWAN [6], and BM [1]. We present the architectures in the order in which they were published.

3.1 TIMELY

The TIMELY [2] adaptive resource management architecture considers a multi-cell wireless network that consists of a set of wireless access points connected to a wireline backbone, such as a cellular network or a group of inter-connected wireless LANs. The TIMELY architecture includes many components at different layers: 1) link layer scheduling, 2) resource reservation and advanced reservation, 3) resource adaptation, and 4) a priority-aware transport protocol. A key feature of the architecture is the coordination of resource adaptation among different layers, such that each layer may perform its task more intelligently and effectively.

TIMELY targets two problems in a multi-cell wireless network. First, wireless channel resources are highly dynamic. Second, resource reservation should be taken care of in advance before hand-off. To this end, TIMELY divides the bandwidth management task into three sub-tasks: 1) resource (or bandwidth) reservation for a flow; 2) advanced reservation before band-off; and 3) adaptation of the ongoing flows when resource variation occurs. Before starting, each flow specifies a range for each resource requested, such as low and high bandwidths, to the network, and the network performs admission control test over each link of the path in a centralized manner. The admission control test succeeds when the new flow can be admitted without violating the minimum rates of the ongoing flows. For best-effort traffic, the network has reserved certain portion of bandwidth for them and they do not need to go over the admission control procedure. The bandwidth of each link is assumed to be known by the network. In resource adaptation, TIMELY differentiates two types of flows. A *static* flow is a flow with both end-points residing in their respective cells over a threshold period of time, otherwise, it is a *mobile* flow. The goal of resource adaptation in TIMELY is to maximize the resource allocated to the static flows, and maintain only the minimum requested rate for the mobile flows (i.e, no adaptation), because the mobile flows are likely to be handed off to another cell. TIMELY's adaptation algorithm is based on the notion of network *revenue*. The network earns certain *admission fee* when it admits a flow, which is related to the flow's granted rate in such a way that, the marginal network revenue decreases for each unit of bandwidth beyond the flow's minimum requested rate. When the network changes a flow's rate, it has to pay an *adaptation credit* to the flow, or if the network drops the flow, it has to pay a larger *termination credit*. Because the network aims to maximize its long-term revenue, it has to make sure that the benefit it will receive by adapting or dropping a flow out-weights the credit it has to pay. As a result, the allocations for the ongoing flows are kept relatively stable. TIMELY relies on a conservative heuristic to select a set of flows to adapt, and decides how to adapt using a special weighted max-min algorithm [2]. In advanced reservation, TIMELY predicts the next hand-off cell(s) of a mobile host, and invokes the reservation procedure to reserve resource for the flow both in the predicted hand-off cell(s) and along the new path(s). As mentioned earlier, only the minimum rate is maintained for a hand-off flow. At the transport layer, each flow relies on a special adaptive protocol (called HPF) to interleave multiple packet sub-streams with different priorities in a single stream. When bandwidth reduction happens, only the most important sub-stream will be transmitted. HPF also relies on the resource adaptation signal from the network layer to react to dynamic resource changes.

3.2 Utility-Fair

The utility-fair adaptive service model [3] is a data link control model that accounts for the adaptation of wireless bandwidth variation, as well as application specific adaptation dynamics including adaptation time-scales and policies. It targets the data link layer in last-hop wireless systems, such as a wireless LAN, where an access point controls both uplink and downlink communications between the access point and a set of mobile devices.

In this service model, the bandwidth requirement of an application is represented by a *utility curve*, which maps the application's bandwidth into a utility (or satisfaction) level representing the application's perceived quality. Generally, an application requires a minimum level of bandwidth to operate, and is able to adapt to bandwidth variation beyond that. The minimum bandwidth requirement is served by the *sustained rate service* class of the data link layer. Beyond that, an application can choose from two adaptation classes. An *active adaptation service* class allows the application to control the application specific adaptation time-scale and policies. Adaptation time-scale is the smallest time that the application can successfully adapt to, and adaptation policy accounts for the granularity and amount of bandwidth variation that the application can tolerate during the adaptation process. The other adaptation class is the *passive adaptation service* which assumes that the application is able to adapt to any bandwidth variation at any time.

The data link control architecture employs a *centralized controller* at the access point, as well as a set of *distributed handlers* at each of the mobile devices. The central controller admits each application based on their sustained portion of bandwidth requirement, and allocates the rest of the channel bandwidth to the admitted flows according to their utility curves. It does *not* allocate the bandwidth equally to each application, since that will lead to different perceived quality levels for each application. Instead, the bandwidth allocation algorithm is based on the "utility-fair" criterion, which gives each application certain bandwidth such that all the applications perceive the *same* quality. The computation of utility-fair allocation is not complex when the utility curves are piece-wise linear [3]. After allocating the bandwidth for each application, the central controller advertises the allocation to those applications who require active adaptation service. The distributed handler, which acts as a proxy on behalf of the application, decides whether and how to accept the advertised bandwidth. For instance, the handler may implement a discrete adaptation policy to accept only certain level of bandwidth, or a hand-off adaptation policy to increase sending rate only after a hand-off. This allows great flexibility for the applications to program different adaptation dynamics. For those applications using the passive adaptation class, the central controller does not need to hear from them. After the bandwidth allocation process, the wireless access point enforces the allocated rates of different applications at the MAC layer.

3.3 INSIGNIA

INSIGNIA [4] is an end-to-end QoS framework that supports adaptive service in a multi-hop mobile ad hoc network. It targets adaptive real-time applications with two layers of media quality, i.e., a base layer and an enhanced layer. INSIGNIA provides fast, per-flow bandwidth reservation along a flow's path, and reacts quickly to route change by restoring the reservation status along the new path. It is designed to be light-weight and responsive to bandwidth variation and network topology changes.

The key part of INSIGNIA is an in-band signaling protocol coupled with a soft-state resource (bandwidth) management module at each router. In-band signaling means that the control information is carried with the data packets. Each data packet has a special IP header that contains the relevant INSIGNIA control information. When a flow needs to reserve bandwidth, it sets the *service mode* of the data packets to RES, which indicates that a reservation is being solicited, together with a MAX and a MIN bandwidth requests corresponding to its base and enhanced layers of traffic. At each router, a bandwidth management module decides whether the MAX or MIN requests can be granted, based on the current bandwidth of the wireless link and the set of admitted flows. If MAX or MIN bandwidth can be granted, the router sets an indicator in the special IP header, and keeps the flow's reservation status as a soft-state; if nothing can be granted, it changes the service mode of the packet from RES into BE, in order to notify the downstream routers that no reservation should be made for it. As a result, the bandwidth allocation policy at each router is first-come first-serve. After receiving the data packet, the receiver learns the reservation status from the IP header, and may notify the sender to scale up or scale down the media quality. The sender then controls its sending rate according to the quality permitted. After route change, INSIGNIA can quickly restore the reservation status along the new path when the data packets travel through it. Therefore, it is well suited for a dynamic, mobile, and variable bandwidth ad hoc network.

INSIGNIA's bandwidth management function is done independently at each router. It assumes that the router is able to obtain available bandwidth information from the link layer for admission control purpose, and that the link layer is able to provide QoS-driven access to the shared media for the adaptive and best-effort packets.

3.4 dRSVP

The dRSVP [5] protocol is a scheme to support per-flow dynamic QoS in a variable bandwidth network, such as a mobile network with wireless links. Although dRSVP is designed within the context of QoS, its core component is a bandwidth allocation and reservation algorithm that provides dynamic bandwidth guarantees for the passing flows at each router, therefore, it can also be considered as a bandwidth management scheme in wireless networks. dRSVP is a fully distributed scheme that can be applied to a multi-hop mobile ad hoc network, as well as a scaled down single-hop ad hoc network.

Similar to RSVP, dRSVP provides end-to-end bandwidth guarantees for a flow by reserving bandwidth along the flow's path. Unlike RSVP, a flow's bandwidth request in dRSVP is over a *range*, i.e., between a low and a high value, rather than using a single value, and the reserved bandwidth for the flow is at some point within the range. By using a range, the likelihood that a flow's bandwidth request can be maintained is increased, even when the wireless link's available bandwidth changes. In dRSVP, each router is assumed to be able to obtain the current available bandwidth from the link layer, and then allocates the bandwidth to the current flows, which is kept in soft-state, using a special bandwidth allocation algorithm. The bandwidth allocation algorithm divides up available bandwidth among the flows with consideration of the desired range for each flow, as well as their bottleneck allocations at other routers. Each router in dRSVP allocates and reserves bandwidth independently, and a flow's bottleneck reservation is carried to its upstream and downstream routers via a signaling protocol similar to RSVP. On start-up of a flow, it has to go through the admission control test which attempts to reserve bandwidth along the path. Once succeeded, the flow can start to send out packets according to the actual allocation it received, i.e., the sender assumes the responsibility of rate control. The sender also has to refresh its allocation state periodically with the routers, similar to the soft-state approach taken by RSVP. In dRSVP, each router is an independent component without any coordination between them, therefore, a sub-net link layer "bandwidth manager" may be needed to help coordinate their access to the shared wireless media.

3.5 SWAN

SWAN [6] is a distributed and stateless network model to support the delivery of real-time traffic over a multi-hop ad hoc network. It manages two different types of traffic: real-time and best-effort. Real-time traffic is guaranteed minimum delay at each node. SWAN does not maintain per-flow state at each node, and it requires only a best-effort 802.11 MAC layer without any QoS capability. Therefore, it is a simple and scalable proposal suitable for a large-scale ad hoc network.

SWAN has two important components: a *rate controller* at each node to restrict best-effort traffic, and a *sender-based* admission control procedure to admit a real-time flow. The rate controller is based on the observation that, MAC layer packet *delay* is a fairly good hint of the medium access contention. In order to support real-time traffic with minimum delay, the sending rate of *every* node in a neighborhood area should be throttled to avoid excessive contention. To this end, the rate controller obtains the packet delay measurement from the MAC layer, and throttles the best-effort traffic rate using a well-known AIMD (Additive Increase Multiplicative Decrease) algorithm normally found in TCP. This rate control algorithm is essentially a distributed bandwidth management technique where the nodes in a neighborhood area *coordinate* with each other to back-off their rates if necessary. When a real-time flow starts, it sends a *probing* packet to the destination, with a "bottleneck bandwidth" field in the packet. Each intermediate router decides an admissible rate for the flow by subtracting the current aggregate real-time traffic rate from the current available bandwidth, and updates the probing packet's "bottleneck bandwidth" field accordingly. On reception of the probing packet, the destination node extracts the bandwidth information and returns it to the sender. The sender can now start the real-time session with a rate within the admissible limit, hence rate control is the responsibility of each application.

When the current admitted real-time traffic can no longer be supported at a SWAN node, for instance, due to re-routing of some real-time flows or variation of wireless bandwidth, the node will notify the real-time flows by the way of marking their packets' explicit congestion notification (ECN) fields. On reception of such ECN marking, a real-time flow should stop sending packets and re-establish its admissible rate by probing the path again. To avoid synchronization effect, SWAN recommends randomly marking a subset of the real-time flows to alleviate congestion. As a result, no fairness can be guaranteed between flows. This is because SWAN keeps no flow state information and therefore has no way of knowing exactly which real-time flow to mark. By design, SWAN is a simple, distributed, and stateless architecture to support real-time traffic with coordinated bandwidth management techniques.

3.6 Bandwidth Management (BM)

The bandwidth management scheme proposed in [1] targets a wireless network where all the mobile nodes are within each other's transmission range, and packet transmission between them takes place in a *peer-to-peer* manner. This *single-hop ad hoc network* is a representation of many practical networking setups commonly found in smart-rooms, in-home networking, and hot-spot networks. The ad hoc mode in the IEEE 802.11 MAC protocol's DCF (Distributed Coordination Function) supports such a network.

A major challenge to support multimedia streaming over this network is that, wireless bandwidth cannot be guaranteed for each flow due to their unco-operative contention in accessing the shared medium. A flow's data rate may be highly fluctuating, and often cannot meet the minimum rate required in streaming the media. To this end, the bandwidth management (BM) scheme [1] proposes to include admission control and dynamic bandwidth management functions into the network. The key part of this scheme is a centralized bandwidth manager (BM) which runs at a node in the network rich in CPU and memory resources. The BM node can be a dedicated server which advertises its service to the adjacent mobile nodes as part of service discovery, or it can be dynamically elected using a simple leader election algorithm. Before starting a flow, the flow sends a message to the BM to request for certain *channel time proportion*, which is defined as the fraction of unit time for which the flow can have the channel to itself for transmission. Essentially, the resource to be shared in this network is the channel time, and the total channel time in the network is 100%. The reason a flow requests for channel time, instead of bandwidth, is that the *perceived bandwidth* of a source-destination pair may be different throughout the network due to location-dependent channel conditions, and such knowledge is only available at the source (or destination), not the BM. To this end, each node runs a *total bandwidth estimator* at its link layer, in order to measure the actual throughput that it can achieve between itself and the destination. The measured throughput, therefore, has taken into account the effect of channel contention as well as physical layer conditions. Using the estimated channel bandwidth, the flow is able to *map* its bandwidth requests, represented by a range of high and low bandwidths, into their corresponding channel time proportion requests.

The BM performs admission control for a new flow after receiving its requests. The admission control test successes when the new flow and the admitted flows can be granted at least their minimum channel time proportions. Beyond their minimum requests, the remaining channel time is allocated to them in a max-min basis. In other words, BM's bandwidth allocation is max-min fair with minimum rate guarantee. The admitted flows then control their transmission rates according to their granted channel time, so that co-operation between flows is achieved and the channel is fairly shared. The BM also provides dynamic bandwidth management for the set of admitted flows during their session life-time, for instance, when a flow perceives a different channel bandwidth at the link-layer bandwidth measurement, or when it needs to re-adjust its minimum or maximum requests due to change of traffic pattern such as in VBR flows. In this case, the flow sends a re-negotiation message to the BM to request a change. The BM then re-calculates the bandwidth allocation and distributes it to all the flows. Note that a flow may be cut out if the minimum requirement can no longer be supported. The resource reservation state is maintained at the BM as soft-state with a time-out period, but a flow may still send a tear-down message to explicitly release its allocated resource. By sharing the channel co-operatively, the BM scheme is able to better deliver multimedia traffic, using the commercially available best-effort IEEE 802.11 hardware without any QoS capability [1].

4 Comparison

In this section, we compare and contrast the various cross-layer architectures described in the previous section, with respect to how they perform their critical tasks. Figure 1 puts the comparison in a nutshell.

The second row of the table pertains to the adaptivity of the flow. Most of the architectures assume highly flexible flows that are adaptive over a continuous range of bandwidths. INSIGNIA is an exception: it assumes a flow can have only three bandwidth levels of operation. Mobile flows (flows in which at least one end-point is mobile) in TIMELY are pinned to their minimum bandwidth request.

The third row of the table pertains to the fairness in bandwidth allocation. Most schemes provide some notion of fairness or price-weighted allocation. However, INSIGNIA and SWAN are exceptions. Admission control is first-come first-serve (FCFS) in these schemes: flows are admitted while resources last. Which flows must adapt in response to available bandwidth variations, and how much they should adapt, is not deterministic.

The fourth row indicates how the decision to allocate bandwidth is made.

In the case of TIMELY, while the bandwidth allocation is decided by the weighted max-min servers, the reservation state is communicated via an RSVP-like signaling algorithm and maintained distributedly. The weighted max-min servers ensure co-ordination that is lacking in fully distributed allocation decisions. (See Section 5.) In fully distributed schemes, per-flow state is maintained at multiple nodes in the network. SWAN is an exception; it maintains aggregate flow state at each node in the network. In centralized schemes, per-flow state is maintained centrally. In both types of schemes, a signaling protocol is needed to communicate state information.

As evident from row 6 of the table, even some of the reservation-based schemes such as TIMELY and INSIGNIA provide differentiated services based on packet priorities. This is because reservations in a wireless environment are not hard, but are subject to dynamic variations in topology and channel characteristics. Packets are marked as low or high priority and when available bandwidth becomes unexpectedly scarce and rate control needs to be performed, preferably the lower priority packets are dropped.

5 Future Directions

In this section, we point out some of the weaknesses in the existing bandwidth management architectures and present some possible future directions of research in this area.

5.1 Improving Accuracy of MAC-layer Available Bandwidth Estimation

Most of the architectures studied in this survey involve a MAC-layer monitor to estimate the available bandwidth on each wireless interface. In actual fact, the available bandwidth is different over each wireless link, out of the same wireless interface. As illustrated in Figure 2, the available wireless bandwidth over node A's wireless interface to node C, 1.8 Mbps, is different from that over the same wireless interface but to node B, 1.4 Mbps. (Assume a 2 Mbps wireless channel.) This is because the level of contention and fading/interference experienced by packet transmissions is different over the two links. If the errors resulting from these phenomena greatly affect a wireless link, then a greater length of time must be expended towards sending a single IEEE 802.11 MAC frame, over the link, so the effective available bandwidth of the link (reciprocal of the time expended) is smaller.

Since the contention, fading and interference effects are different in different neighborhoods, different wireless links have different available bandwidths.

The MAC-layer monitors that estimate the available bandwidth out of each wireless interface usually *average* the available bandwidths to different neighbors to obtain a single value of available bandwidth. Thus, the available bandwidth out of node A's wireless interface is estimated to be 1.6 Mbps. This single value of available bandwidth may not be precise enough for accurate admission control.

In order to deal with this problem of inaccurate available bandwidth estimation in the face of location-dependent errors, the BM scheme [1], introduces per-*neighbor* available bandwidth estimation. It then uses the concept of *channel time proportion* (CTP) for more accurate admission control. In Figure 2, there are two flows requesting admission: the flow from A to B requests 1.2 Mbps and the flow from A to C requests 0.4 Mbps. Both flows are admissible if the single value of available bandwidth, 1.6 Mbps, is used, since their sum does not exceed the estimated available bandwidth out of A's interface.

If CTP is used, however, both flows cannot be simultaneously admitted. If the maximum available bandwidth from node A to node B is 1.4 Mbps, and a flow requests 1.2 Mbps, then it is, in effect, requesting $\frac{1.2}{1.4} = 85.7\%$ of unit time out of node A's wireless interface. The concept of channel time proportion may be better understood using frames per second as the unit of bandwidth, rather than bits per second. If 10 frames of some size can be sent from A to B and a flow requires a throughput of 8 frames of the same size per second, then in effect, it needs to spend eight-tenths of a second on A's wireless interface transmitting to B. In [1], frames per second throughput is normalized over different frame sizes to obtain a bits per second throughput over each wireless link.

The flow from A to B requests $\frac{1.2}{1.4} = 85.7\%$ of the channel time and the flow from A to C requests $\frac{0.4}{1.8} = 22.2\%$ of the channel time. Since the sum exceeds 100% of unit time out of node A's wireless interface, both flows are not simultaneously admissible.

Admission on the basis of a single available bandwidth value (1.6 Mbps in the example) can be considered a false admission [6]. Due to the presence of dynamic regulation of real time flows in SWAN to deal with false admissions, this architecture can mitigate the negative effects on performance, but fairness is nevertheless affected. Like in the BM scheme, future MAC-layer available bandwidth monitors will need to consider at flow admission time, that the available bandwidth out of the same interface is different for different neighbors, due to location-dependent errors. An increase or decrease in location-dependent errors may also trigger dynamic rate adaptation during the course of operation of a particular flow on an interface, after it has already been admitted.

Taking into consideration location-dependent errors still does not guarantee perfectly accurate admission control, although it does eliminate some false admissions. It is difficult to predict beforehand, the effect of admitting a new flow to a channel, on MAC transmission delays and effective throughput of existing flows. One of the most challenging problems is to determine a priori precisely how much of a deterioration will be produced in existing flows' quality by the admission of, say, a 200 kbps flow. Dynamic adaptation of the flow rate can help in mitigating this problem. If the admission of a new 200 kbps flow causes existing flows' available bandwidth to be adversely affected, they can perform dynamic rate adaptation in order to compensate.

5.2 QoS using IEEE 802.11e

The IEEE 802.11e draft specification is an upcoming effort to support QoS in wireless LANs [19]. It has two modes: the Enhanced Distributed Co-ordination Function (EDCF) mode and the Hybrid Co-ordination Function (HCF) mode. The EDCF mode is an improved version of the DCF mode of base IEEE 802.11, to provide QoS via differentiated service. QoS support is realized with the introduction of Traffic Categories (TCs). Upon finding the channel idle or after a collision occurs, higher priority TCs are likely to wait a shorter interval before attempting to transmit, while lower priority TCs wait longer. Thus higher priority TCs are likely to get first access to the channel.

The HCF mode is an improvement of the legacy IEEE 802.11 PCF mode. It supports both a contention-free period and a contention-period, as in the case of PCF. During the contention-free period channel access is solely through polling from the Hybrid Co-ordinator (HC). During the contention-period, channel access can be via listen-before-talk EDCF distributed co-ordination *as well as* through polling, when the HC's poll pulse wins the contention. The transition between the two periods is signaled using a beacon. A special time interval is set aside for mobile hosts to send the HC their resource requests, which the HC uses in determining polling frequency and length of transmit opportunities for the respective hosts, so that their requests can be satisfied. This solves the problem of unknown transmission times of polled stations in legacy IEEE 802.11 PCF.

The IEEE 802.11e EDCF could prove useful to the bandwidth management architectures which need packet classification and differentiation [2, 4, 6]. It remains to be seen whether vendors implement the IEEE 802.11e HCF mode, however. The legacy IEEE 802.11 PCF mode has problems with beacon delays that hinder its implementation, and this problem persists in IEEE 802.11e HCF also. If the IEEE 802.11e HCF is implemented, reservation-based bandwidth management schemes will be benefited because a protocol to make resource requests and a polling-based scheme for enforcement of allocated channel fractions will become available. However, a channel allocation policy that takes into account requests and computes allocated channel fractions will still need to be plugged in at the HC. A simple queue backlog based fair policy for this purpose is described in [20]. Other schemes, such as the max-min fair with minimum guarantees scheme of [1] could also be used. A mechanism will also be required to track variations in channel quality so that requests can be modified when this happens.

5.3 Network-Layer Improvements

One interesting feature of the bandwidth management schemes for multi-hop mobile ad hoc networks (MANETs) [5, 4, 6] is the *decoupling* of routing and resource management-related functions such as signaling, resource monitoring and resource reservation. In order to discover a route that supports the bandwidth requirements of the flow, the protocols rely on an underlying routing protocol, e.g. DSR [16], TORA [17] or AODV [18], to first discover all paths to the destination. They then check whether the resources available on each of these paths can support the bandwidth requirements of the flow, and determine the most optimal of the candidate routes. On the other hand, QoS-routing schemes [13, 14, 15] take network resource availability into account in the routing algorithm. They attempt to simultaneously optimize the resource-richness and path length of the route. While the latter approach may outperform the former, many researchers advocate the former because of its simplicity and flexibility: different resource management functions can be plugged into different routing protocols, rather than having an immutable resource management model built into the routing algorithm itself. The result of using such a simplified network-layer resource management scheme is that the routing protocol used is a simplistic fewest-hop shortest-path based one such as TORA, DSR or AODV. Future bandwidth management architectures for wireless networks might see the employment, at the network layer, of sophisticated congestion-aware routing algorithms and pre-emption of flows from routes by other flows. If a number of paths are available from source to destination, congestion-aware routing algorithms pick one with large available bandwidth. If another connection must use this, and only this, chosen route, the connection with multiple possible routes can be pre-empted from its chosen route onto another possible route. These more intelligent routing schemes will result in minimization of blocking factor and maximization of overall network throughput and lifetime.

5.4 Co-ordinated Bandwidth Allocation

In the fully distributed approaches described in Section 3, INSIGNIA, dRSVP, and SWAN, admission control is inaccurate due to the presence of *hidden flows* Figure 3 illustrates this problem. Node B is within the transmission range (solid circumference) of node A and there exists a 1 Mbps flow from A to B. Assume maximum channel capacity of 2 Mbps. Also assume that nodes perform unutilized channel capacity monitoring, prior to flow admission, as in INSIGNIA or SWAN. Node A is outside the interference range (dashed circumference) of node C, but node B is within C's interference range. Assume Now, if a 1.5 Mbps flow is admitted at node C, its transmissions from C will collide with node A's transmissions to node B. Hence, the throughput of the flow from node A to node B will be severely degraded.

There exists thus a problem of *co-ordination* between the flows in their admission control. The solution to this is that node C should be aware of the flow from node A to B and only admit flows requesting upto 1 Mbps channel bandwidth. Another possible solution is to have a subnet bandwidth manager, as suggested in [5], which can possess global knowledge of all flows and nodes in a neighborhood and co-ordinate the admissions at the respective nodes. The weighted max-min servers in TIMELY perform the co-ordination function. Obviously, both of these solutions violate the distributed and autonomous nature of the admission control in the respective schemes.

The regulation of the real-time flows in SWAN, to respond to mobility and false admission, also mitigates the problem of hidden flows. Admission in spite of the existence of a hidden flow can also be considered a false admission, although the term false admission is defined slightly differently in [6]. In the example of Figure 3, both the 1 Mbps and 1.5 Mbps flows will have to be regulated after they have both been admitted to deal with the problem of false admission. In [5], it is mentioned that a subnet bandwidth manager is required for co-ordination, but the details of its design are not provided. In the future, the design of an admission control scheme for multi-hop wireless networks will need to consider the problem of co-ordination between flows in a neighborhood that are hidden from each other to ensure accurate admissions and rate allocation.

6 Conclusion

Bandwidth is a scarce and variable resource in all types of wireless networks. Tracking the available bandwidth and having all applications using the wireless channel adapt their quality of service (QoS) to the available bandwidth is a complex procedure. It requires several adjustments at each layer of the OSI protocol stack. Moreover, the procedures at each layer of the stack must co-operatively interact with those at the other to ensure maximum satisfaction for users.

In this survey, we picked six approaches that each adopt such a *cross-layer* approach towards monitoring and adapting to the variable channel capacity. We briefly described the salient features of the six architectures and compared and contrasted the methods they employ at each layer of the protocol stack. We also give our views on future directions in cross-layer design for bandwidth management in wireless networks.

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