Chapter 8

QOS ISSUES IN AD-HOC NETWORKS

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Abstract Support for QoS is integral to the design of ad-hoc networks. Fluctuations in channel quality effect the QoS metrics on each link and the whole end-to-end route. In addition, the interference from non-neighboring nodes effects the link *quality.* QoS is thus an essential component of ad-hoc networks. The QoS requirements arise at the application layer in the form of restrictions on values of certain QoS metrics. The most commonly studied QoS metrics are bandwidth, delay and jitter. Bandwidth is the QoS metric that has received the most attention in the QoS literature. The QoS requirements are typically met by soft assurances rather than hard guarantees from the network. Most mechanisms are designed for providing relative assurances rather than absolute assurances. This chapter presents solutions and approaches for supporting QoS in ad-hoc networks at the physical, MAC, and routing layers. It also presents approaches at other layers and describes future challenges that need to be addressed to design a QoS enabled ad-hoc network.

Keywords: QoS, Ad-hoc, 802.11e

8.1 Introduction

The need for supporting QoS in the Internet is evidenced by an increasing activity in the IETF community for supporting the Diffserv [3] architecture. The initial designers of the Internet moved away from the telephone network design where the intelligence was in the network and the end-terminals were comparatively dumb. The telephone network design however provides QoS in the form of guaranteed connection and quality of voice, once a call is established. The initial Internet design idea of keeping the network simple and moving the intelligence to the edge and the end-hosts, did help in the rapid growth of the Internet. But with proliferation of applications requiring some notion of guarantee of service from the network, it is becoming essential to support QoS in the Internet. Multimedia communication and VoIP (Voice over IP) are two such applications that are rapidly gaining popularity. The performance of these applications largely depends on the QoS assurances provided by the network.

In ad-hoc networks, Quality of Service support is becoming an inherent necessity rather than an "additional feature" of the network. Following are the three main reasons that make a strong case for designing QoS enabled ad-hoc networks rather than adding such features as an afterthought.

- **Wireless channel fluctuates rapidly and the fluctuations severely effect multi-hop flows.** As opposed to the wired Internet, the capacity of the wireless channel fluctuates rapidly due to various physical layer phenomena including fading and multi-path interference. In addition, background noise and interference from nearby nodes further effect the channel quality. In ad-hoc networks, the end-to-end quality of a connection may vary rapidly as change in channel quality on *any* link may effect the end-to-end QoS metrics of multi-hop paths.

- **Packets contend for the shared media on adjacent links of a flow.** Contention between packets of the same stream at different nodes impacts the QoS metrics of a connection. Such contention arises as the wireless channel is *shared* by nodes in the vicinity. Unlike in the Internet, this phenomenon effects the QoS even in the absence of any other flow in the network.

- **Interference can effect transmissions at nodes beyond the neighbors.** Interference effects are pronounced in ad-hoc networks where typically a single frequency[1] is used for communication in the shared channel. In single-hop infrastructured wireless networks frequency planning is mostly used where nearby base-stations can be configured to function at different frequencies for reducing interference. Transmissions in the wireless media are not received correctly beyond the transmission range. But even beyond the transmission range, the remaining power may be enough to interfere with other transmissions. So, interference from non-neighboring nodes may result in packet drops.

In order to support QoS on multi-hop paths, QoS must be designed for the end-to-end path as well as for each hop. The physical and MAC layers are responsible for QoS properties on a single-hop. The routing layer is responsible for QoS metrics on an end-to-end route.

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[1] In some recent studies such as [17], the use of multiple frequencies has been explored for ad-hoc networks.

The concept of ad-hoc networking is not tied to any particular single-hop wireless technology. However, with increasing deployments of Wireless LAN (WLAN) devices at homes, offices and public hotspots, the term *wireless* is becoming synonymous with "Wireless LANs". Currently in the market there are products conforming to two competing WLAN standards, namely IEEE 802.11a and IEEE 802.11b. These standards differ from the original IEEE 802.11 standard in the specification of the physical layer. However, the MAC layer is unchanged in all these three protocols. In this chapter, we use 802.11 to collectively refer to the three standards. High speed (up to 54 Mbps with 802.11a), decreasing prices (Wireless Network Interface Cards are priced below $50) and proliferation of wireless integrated handheld devices, are the three main reasons for its popularity.

Most researchers assume CSMA/CA based 802.11 (specifies Medium Access (MAC) and Physical layers) to be the underlying wireless technology for ad-hoc networks. In this chapter we will also assume that 802.11 is the underlying technology. Researchers are also actively exploring the use of other medium access techniques such as TDMA [19], for ad-hoc networks. More recently, there has been a growing interest in applying ad-hoc networking techniques to different environments, such as acoustic ad-hoc networks [21] for marine exploration. Figure 8.1 shows a Wireless LAN and Figure 8.2 an ad-hoc network. The 802.11 standard has two modes of operation, namely the Infrastructure mode and the ad-hoc mode. These modes correspond to the WLAN and ad-hoc configurations respectively. In the WLAN configuration nodes communicate only via the access-point (AP). In the ad-hoc configuration, nodes communicate via multi-hop peer-to-peer wireless links formed by virtue of proximity with other nodes.

Figure 8.1. Wireless LAN

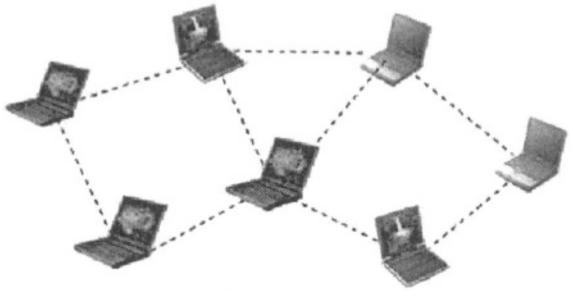

Figure 8.2. Ad-hoc Network

The rest of the chapter is organized as follows. Section 8.2 provides a definition of QoS and a discussion on QoS metrics. Section 8.3 presents QoS issues in the design of the physical layer. Section 8.4 discusses QoS support at the MAC layer in WLANs and ad-hoc networks. Section 8.5 describes various solutions for QoS routing in ad-hoc networks. Section 8.6 discusses other QoS approaches at transport and higher layers. Frameworks that span more than one networking layers are discussed in Section 8.7. Section 9 presents some future challenges in the design of QoS enabled Ad-hoc Networks and concludes the chapter.

8.2 Definition of QoS

So far we have been discussing about QoS in an abstract sense. But, what is QoS? What are the QoS metrics?

Quality of service refers to different notions at different networking layers. At the physical layer, QoS refers to the data rate and packet loss rate on wireless links, which is a function of the channel quality. With continuously varying channel quality, it is impossible to maintain constant data rate and low packet loss rate. At the MAC layer, QoS is related to the fraction of time a node is able to successfully access and transmit a packet. At the routing layer, end-to-end QoS metrics would depend on the metrics at each hop of a multi-hop route. The routing layer must try to compute and maintain routes that satisfy the QoS requirement for the lifetime of a connection. The transport and upper layers could include support for QoS if the routing layer is not able to meet the QoS requirements.

Bandwidth, delay and jitter are the three commonly studied QoS metrics. However, the problem of QoS in ad-hoc networks is more challenging than in wired networks as described in Section 8.1. As a result there has been little work on supporting delay and jitter; and most of the focus has been on providing bandwidth assurances. Various mechanisms have been proposed to estimate the amount of bandwidth in CSMA/CA (Carrier Sense Multiple Access) networks [8] and TDMA networks [12].

For ad-hoc networks, it is difficult to provide hard QoS guarantees due to fluctuations in the wireless channel and interference from non-neighboring nodes. It is therefore easier to design solutions where QoS support from the network is in the form of soft-assurances [18] rather than hard guarantees. For the same reasons, relative assurances are more common than absolute assurances. Most of this chapter refers to soft-assurances for QoS metrics, unless stated otherwise.

8.3 Physical Layer

One of the fundamental challenges in wireless networks is the continuously changing physical layer properties of the channel. The physical layers of 802.11a and 802.11b can support multiple data rates. Depending on the channel quality the data rate can be altered to keep the bit error rate acceptable, as high data rates are also prone to high bit error rates.

The 802.11a standard operates in the 5.7 GHz band and supports data rates of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. The 802.11b standard operates in the 2.4 GHz band and supports 1, 2, 5.5 and 11 Mbps. However, the standards do not specify any mechanisms to discover the highest possible rate on a link.

The data rate switching policy has a direct impact on the QoS metrics of the channel. For example, the most conservative switching policy of always staying at the lowest channel rate will guarantee equal physical layer data rate on all links in ad-hoc networks. If an application requires all links to have the same data rate, a policy of using the lowest data rate may work. However, this leads to severe under-utilization of resources as the links with good channel quality do not send at the highest possible rates.

For efficient use of a multi-rate physical layer, there has been several algorithms proposed at the physical layer. Some of these algorithms are closely tied to the MAC layer as well. They impact the observed throughput on a link and the end-to-end throughput of a multi-hop connection. The QoS requirements of upper layers may effect the design of this algorithm. However, the current proposals are all based only on improving the link utilization, although they may be modified to implement QoS requirements of higher layers.

8.3.1 Auto Rate Fallback (ARF)

[9] presents an algorithm called Auto Rate Fallback (ARF) for finding the highest possible data-rate on a wireless link. It was designed for Lucent's WaveIan II devices based on the IEEE 802.11b standard. The default operation is at the highest data-rate. When a MAC layer ACK is missed after successful transmissions, the first retransmission is done at the same rate. If the ACK is missed again, the rate is lowered to the next data-rate for subsequent transmissions and re-transmissions. If ten ACKs are received correctly or if a timer expires, then the device attempts to upgrade the data-rate. If the first transmission at the higher data rate fails, it immediately drops to the lower data-rate.

8.3.2 Receiver-Based Auto Rate (RBAR)

[7] observed that the data rate of a 802.11 link can fluctuate very frequently (on the order of 50 times per second) and the ARF algorithm is not capable of altering the data-rate according to the changing channel conditions. They propose a rate adaptive MAC protocol called RBAR (Receiver-Based Auto Rate). The algorithm makes use of the RTS-CTS exchange in 802.11 DCF mode to learn about the current condition of the channel. The SNR (Signal to Noise Ratio) of the RTS is used to determine the highest possible data-rate that can be used for DATA packets. The maximum allowed data rate is informed to the sender using the CTS. Since the channel estimation is done at the receiver just before the data transmission, the data-rate estimation is very accurate.

8.3.3 Opportunistic Auto Rate (OAR)

[15] proposes a mechanism called Opportunistic Auto Rate (OAR) for improving throughput in the presence of multi-rate links in ad-hoc networks. The key idea is to send multiple packets when the channel rate is higher. The RBAR protocol can be used to compute the channel rate that can be supported. Similarly, OAR can also be used with sender based rate adaptation protocols such as ARF. However, it has been shown that RBAR outperforms ARF [7]. The algorithm ensures that all nodes are granted channel access for the same time-shares as achieved by single rate IEEE 802.11. This opportunistic mechanism is similar in principal to the design of proportional-fair scheduling algorithm [4] for 3G networks such as HDR (High Data Rate standard from Qualcomm).

8.4 Medium Access Layer

The original IEEE 802.11 [1] standard specifies the physical layer and the medium access layer mechanisms and provides a data rate up to 2 Mbps. The later standards IEEE 802.11b and IEEE 802.11a modifies the physical layer part of the standard and increases the maximum data rates to 11 Mbps and 54 Mbps respectively.

In this section, we first discuss the basic 802.11 MAC layer functionality called Distributed Coordination Function (DCF) for distributed access to the shared medium. We then discuss the Point Coordination Function (PCF) which provides a mechanism for centralized control of channel access. DCF is a natural choice for ad-hoc networks, as there is no centralized controller such as an access-point. However, PCF can support QoS metrics in single-hop wireless networks due to its centralized design. Both DCF and PCF are enhanced in the upcoming standard 802.11e [13] that is designed for supporting QoS in WLANs. We also present key features of the 802.11e protocol and discuss some service differentiation schemes that have been proposed for extending DCF.

8.4.1 802.11 Distributed Coordination Function (DCF)

The DCF protocol attempts to provide equal access (in terms of number of packets) to all backlogged nodes that share a channel. For example, in the Infrastructure mode if all nodes in a cell are in the transmission range of each other and there are no other sources of noise or interference, all users nodes and the AP get to send the same number of packets, assuming they all are backlogged.

In an ad-hoc network the throughput that a node obtains using DCF is a function of the number of neighbors that it has and the state of their queues (backlogged or not). Since the throughput of the neighbors depend on *their* neighbors, throughput determination becomes a global problem rather than a local problem. So, in general in an ad-hoc network using DCF the throughput received by a node depends on the whole topology. Note that the DCF mechanism attempts to provide access per-node and not per-link.

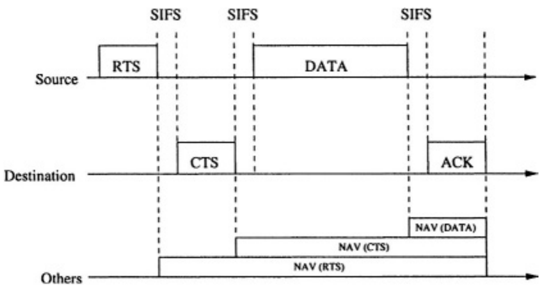

Figure 8.3. IEEE 802.11 DCF

We now describe the DCF mechanism is detail. Each node that has a packet to send picks a random slot for transmission in $[0, cw]$, where cw is the contention window used for backoffs. Initially cw is set to cw_{min}. In the chosen slot, the node sends a MAC layer control packet called RTS (request-to-send), to the receiver. If the receiver correctly receives the RTS and is not deferring transmission, it responds with a CTS (clear-to-send). This is followed by transmission of the data packet by the sender, and a subsequent acknowledgment from the receiver. The transmissions of these four packets are separated by short durations called SIFS (Short Inter-Frame Space). The SIFS allows time for switching the transceiver between sending and receiving modes. The sequence of transmission of these four packets is shown in Figure 8.3. The MAC header of all these packets (see the packet structures in Figure 8.4) contains a "duration" field indicating the remaining time till the end of the reception of the ACK packet. Based on this advertisement, the neighboring nodes update a data structure called NAV (Network Allocation Vector). This structure maintains the remaining time for which the node has to defer all transmissions.

If the packet transmission fails, the sender doubles its contention window $(cw \leftarrow [2 \times cw - 1])$ and backs off before attempting a retransmission. The number of retransmissions is limited to 4 for small packets (including RTS packets) and 7 for larger (typically DATA) packets. If these counts are exceeded, the data packet is dropped and cw is reset to cw_{min}. If the data packet is successfully delivered, both the sender and the receiver reset cw to cw_{min}.

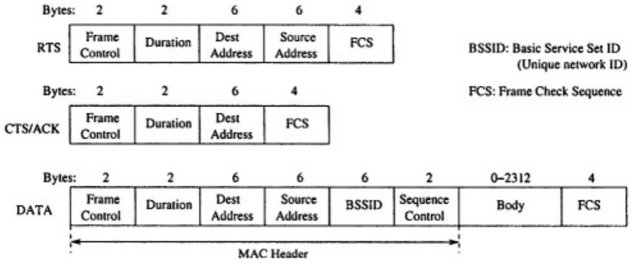

Figure 8.4. Packet formats for basic 802.11

8.4.2 802.11 Point Coordination Function (PCF)

PCF operates in the Infrastructure mode of 802.11. The standard requires that an AP implementing the PCF mode (contention-free period) must alternate it with the DCF mode (contention period). In the PCF mode, the point-coordinator (AP) sends packets to other nodes and polls a list of nodes giving them an opportunity to transmit. Unlike the DCF mode, in the PCF mode nodes can transmit only if they are polled by the AP. The beginning of the contention-free period (the period in which PCF operates), is marked by a beacon from the AP which also advertises the length of the contention-free period. During this period, the transmission schedule is completely determined by the AP. The contention-free period could be foreshortened by the AP by transmitting a special packet called the CF-End packet. The polls and the acknowledgments are piggybacked on the data packets as shown in Figure 8.5. Note that before sending the beacon, the AP waits for a period called the PIFS (PCF Inter Frame Space) which is larger than SIFS. This ensures that all communication related to the contention period has ceased. The PIFS interval is also used to wait for a response to a poll by the AP. After this interval elapses, the AP concludes that the node being polled either does not have packets to send or did not receive the poll. It then moves ahead by polling the next node after a PIFS period.

8.4.3 The QoS Extension: 802.11e

The IEEE 802.11e extension provides mechanisms for supporting different priorities in WLAN networks. Being a distributed protocol, it is hard to ensure strict priorities. Hence, the priorities are probabilistic in nature. Such priorities can be viewed as a form of QoS metric.

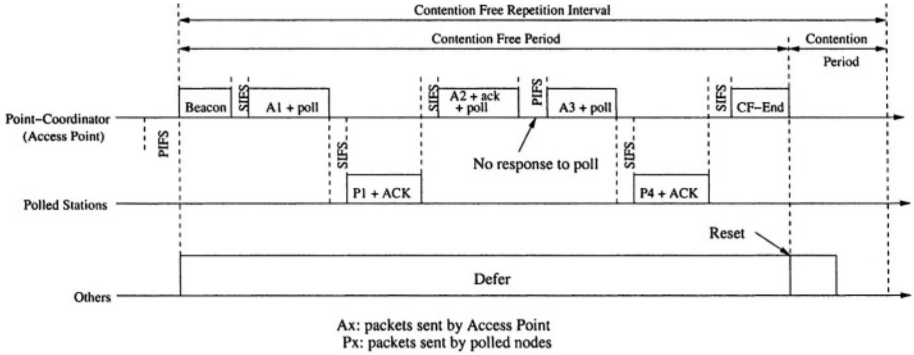

Figure 8.5. Point Coordination Function (PCF)

The DCF and PCF functionalities of 802.11 have been extended, and these extensions form the 802.11e standard[2]. The Enhanced DCF (EDCF) extends the functionality of DCF by providing the notion of priorities. The enhancement of PCF is called HCF (Hybrid Coordination Function) in 802.11e. Some of the mechanisms of 802.11e are similar to the service differentiation mechanisms to be discussed in Section 8.4.4.

Figure 8.6 shows the 802.11e functionality in detail.

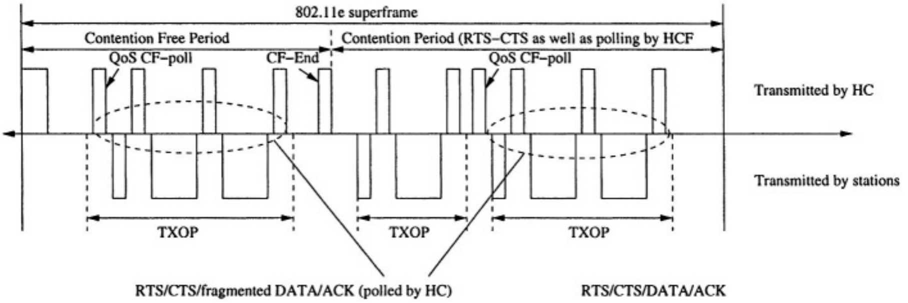

Figure 8.6. Example of a 802.11 super-frame. It relies on TXOPs (Transmission opportunities). Polled TXOP may be located in Contention Period or Contention-Free Period.

In EDCF, the frames entering the MAC layer can request 8 different service priorities. These priorities are mapped to different access categories (ACs). Each AC may have a distinct value for the DIFS period (now called AIFS), cw_{min} and cw_{max}. Figure 8.7 shows an example illustrating different class of

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[2] The standardization is not yet complete

traffic with different AIFS values. These values can be dynamically determined by the access point. The nodes are informed of these values by using the beacon. The AIFS is at least as large as the DIFS in 802.11. Different priority levels will correspond to different values of AIFS.

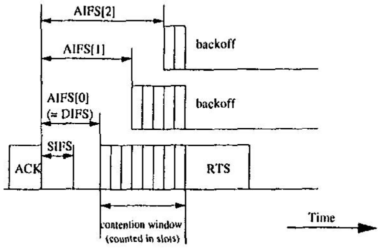

Figure 8.7. Multiple backoff of streams with different priorities

HCF allows the hybrid coordinator to maintain state for nodes and allocate contention free transmit opportunities (TXOP) in a smart way. The offered load per traffic class at each node is used by the hybrid coordinator for scheduling. Unlike in the case of the PCF mode of 802.11, the hybrid coordinator may poll user nodes in the contention-free period as well as in the contention-period.

Like the PCF in 802.11, this protocol requires centralized operation. To achieve the QoS requirements, the AP coordinates the transmissions in its cell. This protocol needs to be extended for ad-hoc networks where there is no centralized coordinator.

8.4.4 QoS Support using DCF based Service Differentiation

As it is difficult to provide absolute QoS guarantees, relative QoS assurance can be provided by service differentiation. This helps in designing systems which can support multiple classes of users.

As discussed in Section 8.4.1, in 802.11 all backlogged nodes contend for the channel using the same protocol with the same set of parameters. As a result, if all the contending nodes are in range of each other, 802.11 will provide long term fair share to each node. However, to provide differentiated services, the 802.11 protocol needs to be modified. [2] proposes three ways to modify the DCF functionality of 802.11 to support service differentiation. The parameters that need to be modified to achieve service differentiation are described below.

1 *Backoff increase function:* Upon an unsuccessful attempt to send an RTS or a data packet, the maximum backoff time is doubled. More specifically the backoff time is calculated as follows:

$$Backoff_{time} = \lfloor 2^{(2+i)} \times rand() \rfloor \times Slot_{time} \qquad (4.1)$$

where i is the number of consecutive backoffs experienced for the packet to be transmitted. To support different priorities, the backoff computation can be changed as follows

$$Backoff_{time} = \lfloor {P_j}^{(2+i)} \times rand() \rfloor \times Slot_{time} \qquad (4.2)$$

where P_j is the priority of node j.

2 *DIFS:* As shown in Figure 8.3, this is the minimum interval of time required before initiating a new packet transmission after the channel has been busy. To lower the priority of a flow we can increase the DIFS period for packets of that flow. However, it is difficult to find an exact relation between the DIFS period for a flow and its throughput. Figure 8.8 shows the different DIFS values and the corresponding relative priorities. This idea is similar to the concept of AIFS in 802.11e, as described in Section 8.4.3.

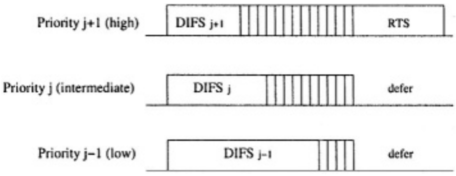

Figure 8.8. Service Differentiation using different DIFS values

3 *Maximum Frame Length:* Channel contention using the DCF functionality is typically used to send a single frame. By using longer frames, higher throughput can be provided to high-priority flows.

8.5 QoS Routing

The QoS metrics of an end-to-end route depends on the links of the computed route. There are three main challenges in computing a route satisfying QoS requirements. First, the QoS metric on each link must be either computed continuously or discovered on demand, when the route request packet is being forwarded. Second, broadcast based routing algorithms do not explore all possible routes. Third, mechanisms to compute the available bandwidth on a link are coarse and are based on observing other parameters such as queue length and channel access history.

Multi-hop networks are dynamic in nature, and transmissions are susceptible to fades, interference, and collisions from hidden/exposed stations. These characteristics make it a challenging task to design a QoS routing algorithm for multi-hop networks. Following are the main design goals for such an algorithm:

- The algorithm should be highly robust and should degrade gracefully with increasing mobility.
- Route computation should not require maintenance of global information.
- The computed route should be highly likely to sustain the requested bandwidth for the flow.
- The route computation should involve only a few hosts, as broadcast in the whole network is expensive.
- Hosts should have quick access to routes when connections need to be established.

AODV (Ad-hoc On-demand Distance Vector) and DSR (Dynamic Source Routing) are the first two routing protocols proposed for ad-hoc networks. Both the protocols are on-demand. AODV uses next-hop routing, whereas DSR uses source routing. More information on AODV and DSR can be found in [14]. A QoS routing protocol based on AODV for TDMA networks is proposed in [22]. An extension for DSR to support QoS is proposed in [11].

Rather than trying to fit QoS into the protocol, some routing protocols have been designed specifically for QoS routing. We describe two such protocols, namely CEDAR [16] and Ticket Based Routing [6, 20] in the remaining section.

8.5.1 Core Extraction based Distributed Ad-hoc Routing (CEDAR)

CEDAR achieves the above design goals for small to medium size ad-hoc networks consisting of tens to hundreds of nodes. The following is a brief description of the three key components of CEDAR.

- *Core Extraction:* A set of hosts is distributedly and dynamically elected to form the *core* of the network by approximating a minimum dominating set of the ad hoc network using only local computation and local state. Figure 8.9 shows an example network with four core nodes. Each core node maintains the local topology of the nodes in its domain, and also performs route computation on behalf of these nodes.

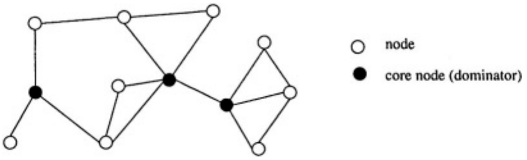

Figure 8.9. CEDAR: Core nodes in a network

- *Link state propagation:* QoS routing in CEDAR is achieved by propagating the bandwidth availability information of stable links in the core graph. The basic idea is that the information about stable high-bandwidth links can be made known to nodes far away in the network, while information about dynamic links or low bandwidth links should remain local.

- *Route Computation:* Route computation first establishes a core path from the dominator of the source to that of the destination. The core path provides the directionality of the route from the source to the destination. Using this directional information, CEDAR computes a route adjacent to the core path that satisfies the QoS requirements.

8.5.2 Ticket based routing

Ticket based routing [6] is based on the idea of limiting the broadcast messages and directing them toward the *right direction.* The goal of this approach is to select routes from the ones that are probed for route computation. The source has a certain number of tickets. Tickets are of two kinds: yellow and green. Each probe carries a certain number of tickets. The purpose of the yellow tickets is to maximize the probability of finding a feasible path. Hence probes carrying yellow tickets prefer paths with smaller delays. The purpose of the green tickets is to maximize the probability of finding a low-cost path, where each link is associated with a certain cost. Green tickets prefer paths with smaller costs, which may however have larger delay and hence have less chance to satisfy the delay requirement.

The source initiates the probing with a certain number of tickets of each color. At each intermediate node a decision is made as to how many tickets would be forwarded on each of the new probes. This decision is based on the observed QoS metrics of the link. For example, a link with lower delay gets higher number of yellow tickets compared to another link with higher delay.

The “Enhanced Ticket Based Routing Algorithm” approach [20] eliminates redundant probing and further optimizes ticket probing.

8.6 QoS at other Networking Layers

The need for QoS arises at the application layer. The application layer requests the transport layer to provide QoS services. The transport layer must request the routing layer to compute routes satisfying the QoS requirements. This request may need to travel down to the physical layer. Each layer receiving a QoS request from the above layer needs to take the following actions:

- *Check if it can be supported:* Each layer needs to see if the QoS requirements are within the limits of what it can support. It needs to notify the higher layer, if it can not support the QoS request.

- *Request the lower layer for supporting it:* The current layer processing the QoS request may be able to support it with the help of the lower layers. It needs to map the QoS requirement to the QoS services provided by the lower layer and then send the request to the lower layer. For example, for supporting a QoS route with a certain minimum bandwidth, the routing layer may inform the MAC layer to increase the priority of channel access.

- *Negotiate with the lower/upper layer:* When a QoS request is received from the upper layer, it should be checked if the network can support that request. If the QoS demands can not be met, a different QoS requirement may be negotiated by suggesting alternate values of the relevant QoS metrics.

- *Report the application layer on failure to support QoS:* After establishing a QoS connection, in case the network fails to support the QoS metrics, the application layer needs to be notified so that it can take appropriate actions. For example, if the network can not find routes requiring a certain minimum bandwidth for supporting real time communication, the application layer can change the encoding or resolution of the multimedia data. The networking layer noticing a change in observed QoS must report it up the layers to the application layer.

8.7 Inter-Layer Design Approaches

The previous sections discussed mechanisms at individual networking layers for providing QoS support in ad-hoc networks. The QoS support provided by a layer is dependent on the support from the lower layers as well. INSIGNIA [10] and Cross-Layer Design [5] are two efforts directed toward design and implementation of inter-layer QoS solutions. The rest of the section describes these two frameworks in detail.

8.7.1 INSIGNIA

In this framework the applications specify their minimum and maximum bandwidth needs. INSIGNIA is responsible for resource allocation, restoration control, and session adaptation between communicating mobile hosts. The design of the QoS routing protocol is independent of this framework.

This framework uses in-band signaling. There are two mechanisms that may be used for QoS related signaling: out-of-band and in-band. Out-of-band signaling refers to sending explicit control messages. In-band signaling refers to carrying control information as part of packet headers. Using in-band signaling flows/sessions can be rapidly established, restored, adapted, and released in response to wireless impairments and topology changes.

Various components of the architecture are shown in Figure 8.10. *Admission control* is responsible for allocating bandwidth to flows based on the maximum/minimum bandwidth requested. *Packet forwarding* classifies incoming packets and forwards them to the appropriate module (viz. routing, signaling, local applications, packet scheduling modules). *Routing* dynamically tracks changes in ad-hoc network topology, making the routing table visible to the node's packet forwarding engine. *Packet Scheduling* responds to location-dependent channel conditions when scheduling packets in wireless networks. *Medium Access Control (MAC)* provides quality of service driven access to the shared wireless media for adaptive and best effort services.

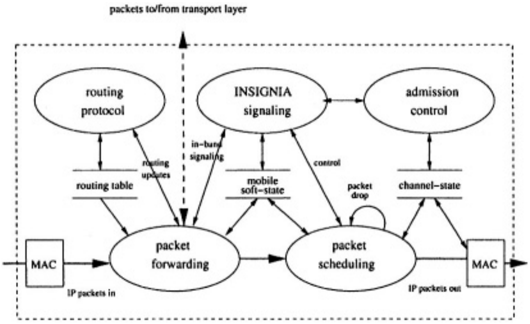

Figure 8.10. INSIGNIA QoS Framework

8.7.2 Cross-Layer Design for Data Accessibility

The architecture of the Cross-Layer Design [5] is shown in Figure 8.11. The application, middleware and the routing layers share information to achieve a higher quality in accessing data. The system relies on data replication to avoid the problem of missing data when network partitioning occurs. Map viewing and messaging are two examples shown in the figure.

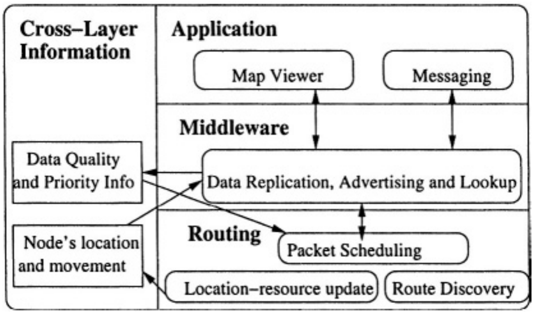

Figure 8.11. Cross-Layer Design for Data Accessibility

The routing layer uses a *predictive location-based routing protocol.* It uses each node's geometric coordinates and movement pattern information for the purpose of route discovery and maintenance. The *location-resource update* module periodically broadcasts messages containing the node's location and resource information to other nodes in the network. The routing layer reacts to route performance deterioration by route re-computation.

The middleware layer implements a *data accessibility service* that assists applications to advertise and share data with other users in the network. Data is accessed in two steps. In the first step, data availability information is obtained and presented to the application level. The QoS parameter of interest is the *success rate* in accessing data. In the second step the middleware layer retrieves the data from a remote host with certain application level requirements, such as data access deadline and data quality. The middleware layer translates the application level requirements into network level QoS parameters such as bandwidth and delay. It then sets up a route with these parameters. For sustaining QoS violations, the middleware layer is notified as the routing protocol will not be able to handle it. The middleware layer may adapt to the available QoS values.

8.8 Conclusion

In this chapter we studied QoS issues at various networking layers for ad-hoc networks. The physical layer and the MAC layers are primarily responsible for QoS on a single link. The DCF and PCF functionality of 802.11 is being extended into the QoS extension called 802.11e. The PCF and 802.11e protocols are specifically designed for QoS support in single-hop networks. These algorithms need to be adapted for use in multi-hop ad-hoc networks. The routing layer is responsible for computing and maintaining end-to-end multi-hop QoS routes. CEDAR [16] and Ticket Based Routing [20] protocols are two QoS routing protocols proposed for ad-hoc networks. Since the QoS needs arise at the application layer, the QoS requirements in the form of acceptable values for QoS metrics are specified by the application. The QoS request may have to travel down the network layers up to the physical layer. Applications would typically like to be notified in case the QoS requirements can not be met due to changes in the network conditions. The application may be able to (re)negotiate a different QoS requirement and adapt to it.

QoS is currently an active research area in ad-hoc networks. This chapter has covered some of the main research topics related to QoS in ad-hoc networks. However, there are several avenues that require further exploration for designing a QoS enabled ad-hoc network. We briefly outline some of these issues:

- *Energy efficient QoS architecture:* Ad-hoc networks are energy constrained as they are composed of hand-held devices with limited battery. Supporting QoS may require addition of extra in-band or out-of-band signaling messages, or other changes to protocols that increase the total energy needs. Hence, the QoS components of ad-hoc networks must be designed keeping energy efficiency as one of the key goals.

- *QoS metrics with level of tolerance:* The routing approaches such as CEDAR and the ticket based routing protocols attempt to compute QoS routes. These approaches do not provide hard guarantees on any QoS metric. The source can specify the amount of tolerance for each QoS metric and the network would then support the request based on the tolerance levels.

- *Multi-hop synchronized MAC Layer:* For packets that traverse multiple hops, the end-to-end QoS is a function of the QoS metrics at each intermediate link. End-to-end QoS properties can be improved by designing a MAC layer that coordinates with other intermediate nodes on a multi-hop path.

- *Extending PCF and 802.11e for Ad-hoc Networks:* Both the PCF and 802.11e solutions require the point coordinator (or the access point) to decide the transmission schedule. As there is no centralized control in an ad-hoc network, either this functionality needs to be performed distributedly or other changes need to be made to these protocols to use them in ad-hoc networks.

We find that QoS is an inherent component of ad-hoc networking and that there are several unsolved challenges that need to be addressed to design QoS enabled ad-hoc networks.

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