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Ad Hoc and Mesh Network Protocols and Their Integration with the Internet

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Abstract

Ad hoc and multihop wireless networks are becoming increasingly important for a variety of applications ranging from tactical military networks, to metro area WiFi networks, to sensor applications. Multihop wireless is motivated by the fact that many embedded wireless devices are power-limited and cannot communicate directly with a distant base station or access point. In addition, ad hoc network formation is motivated by mobile service scenarios, such as tactical or vehicular. Protocol design considerations are given for both mobile ad hoc network (MANET) and static (planned) mesh network scenarios. These include self-organization, resource discovery, medium access control, and routing. Existing routing protocols for MANETs, including Destination Sequenced Distance Vector (DSDV), Dynamic Source Routing (DSR), and Ad hoc On-demand Distance Vector (AODV), are described and performance comparisons are given. More recent work on cross-layer mesh-routing protocols is introduced, including cross-layer metrics such as Airtime or PHY/MAC Awate Routing Metric for Ad hoc networks (PARMA), as well as Integrated Routing and Medium Access (IRMA) control. The chapter concludes with implications for future IP protocols that would allow for seamless integration of multihop wired and wireless networks.

3.1 Introduction and Motivation

Wireless ad hoc and mesh networks have been an important research area for about two decades. Research topics like the network architecture and design, integration with TCP/IP, routing, and medium access control in the shared wireless medium have been discussed at length. However, the mobile and dynamic nature of the network introduces new challenges in self-organization, including

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neighbor and topology discovery, network management, and disconnected operation. Unlike wired communication, wireless channels suffer from intermittent losses due to various environmental effects like multipath fading and shadowing. Therefore, the lossless assumptions on which protocol layers are designed had to be abandoned and a new research topic in cross-layer protocol design emerged to design better wireless communication protocols. This chapter studies the interesting roadmap of research in wireless ad hoc and mesh networks covering topics in network architecture, protocol design, self-organization, and cross-layer adaptation mechanisms. The integration of ad hoc and mesh networks with the Internet is briefly discussed.

3.2 Network Architecture

Ad hoc network is a completely unplanned deployment of mobile wireless nodes whereas a mesh network is a semiplanned deployment of fixed wireless routers that provide Internet connectivity to mobile wireless devices. We describe the two architectures and point out some subtle distinctions in terms of the challenges faced by each.

3.2.1 Mobile Ad Hoc Networks and Mesh Networks

A mobile ad hoc network (MANET) is a self-configuring wireless network of mobile devices connected by wireless links. Each radio device in a MANET can move independently and therefore change its link to other devices. Each device can work as a router to help forward traffic for other nodes. Ad hoc networks may operate by themselves or may be connected to the Internet. The primary challenge in a MANET is to maintain network topology and provide multihop routing in spite of physical connectivity changes and without a centralized controller.

Mesh network 802 (2006) is an example of wireless ad hoc networks. Many mesh networks consist of static devices and can be connected to the Internet. Mesh networks are being deployed in cities to provide ubiquitous wireless coverage for general population or, in many instances, as a network for common use by different first-responder agencies such as the police, firefighters, or emergency medical services (ACG and Meshdynamics; PacketHop). The challenge in the mesh network is due to its dense deployment and integration with the Internet.

3.2.2 Flat Ad Hoc Networks

A traditional ad hoc network has a flat structure in which all nodes in the network have identical functionalities. The control functions, such as routing, are performed on the flat network without any central controller. This flat structure

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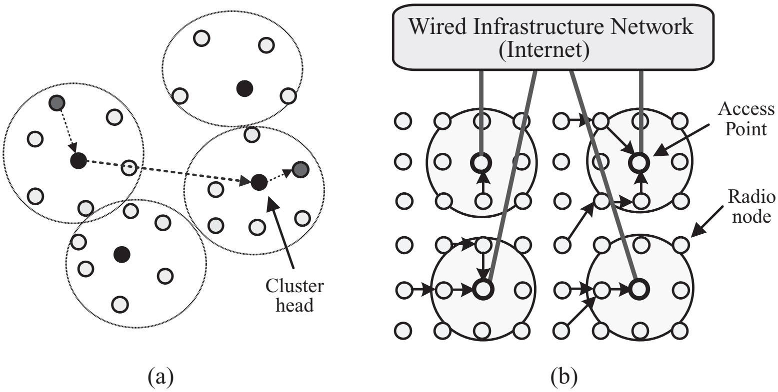

Figure 3.1. (a) Cluster-based network (b) Infrastructure-aided network.

has potential problems, such as poor scalability as network size is getting bigger; Gupta and Kumar's well-known theoretical result (Gupta and Kumar 2000) for multihop wireless networks indicates that achievable end-to-end per-node throughput decreases in proportion to the square root of the number of radio devices.

3.2.3 Cluster-Based Network Structure

A natural approach to facilitate network control functions is to self-organize ad hoc nodes into cluster-based hierarchical structures (shown in Figure 3.1[a]). This is especially motivated by the properties of ad hoc wireless networks: changing topology and shared wireless links, which can be managed effectively by cluster-heads by applying distributed link cluster algorithms (Baker and Ephremides 1981). Previous work (Perkins 2001) also demonstrates that clustering increases network availability and reduces delay in response to network state changes because it reduces sensitivity to small network-state changes and localizes control in response to significant changes. In Lin and Gerla (1997), Gerla proposes a MAC-layer "clustering" that provides a framework for code separation, channel access, and bandwidth allocation, and improves system performance.

3.2.4 Infrastructure-Aided Network Structure

Introducing infrastructure to ad hoc mesh networks further overcomes the problem of scalability bottleneck of flat ad hoc networks. The infrastructure-aided network structure is also motivated by the fact that realistic mesh network scenarios involve predominant traffic flows from mobile or sensor devices to and from the wired Internet, thus requiring effective integration of wired "access points" with the ad hoc wireless network. By introducing some proportion of wired "infrastructure" nodes, the network can be organized into a hierarchy with "shortcut" paths for traffic that would have required larger numbers of hops in a flat ad hoc network (see Figure 3.1[b]). Results of Liu et al. (2003), Kozat and Tassiulas (2003b), and Zemlianov and de Veciana (2005) have shown that adding infrastructure nodes to ad hoc networks can effectively reduce the average number of end-to-end hops and ultimately help achieve better performance relative to flat ad hoc networks.

3.2.5 Hierarchical Hybrid Wireless Network Structure

As described earlier, ad hoc mesh networks benefit from a hierarchical "hybrid" wired or wireless architecture both in terms of scalability and effective integration with the Internet. However, with two-tier architecture, wired infrastructure costs can be high, especially for dense usage scenarios. In Liu et al. (2003), Liu and Towsley proved that linear scaling of throughput can be approached in a two-tier hybrid network as long as the number of access points grows asymptotically faster than the square root of the number of radio nodes.

A network with more than one tier of ad hoc radio nodes is motivated by the previously described considerations. Lower tiers in the network aggregate traffic up to intermediate radio relays, while continuing to use robust ad hoc self-organization and routing protocols as in flat ad hoc networks. A general K-level hierarchy with $(K - 1)$ tiers of radio nodes and a top tier of access points (see Figure 3.2) is presented in Zhao et al. (2003), Ganu et al. (2004), and Zhao and Raychaudhuri (2009). The access points at the top tier provide access to infrastructure and interconnections with the Internet. A key technology enabler for the generalized hierarchical wireless network is the so-called "radio forwarding node" or "radio router," equipped with two or more radio interfaces to

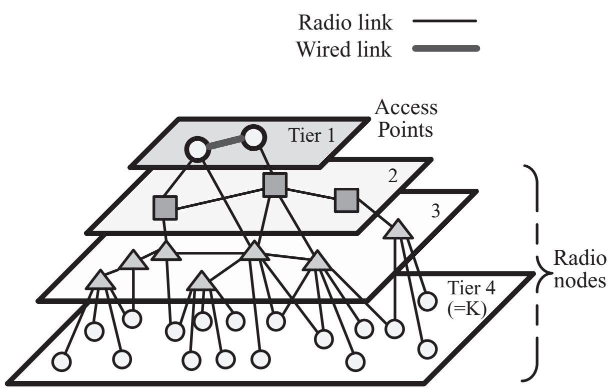

Figure 3.2. Concept of multitier hierarchical hybrid network.

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permit it to handle packets going to or from one layer of the hierarchy to another. The end-user devices at the lowest tier of the network, owing to typical energy constraints, have limited routing capability, which helps reduce processing and transmission power.

Multiple tiers of radio-forwarding nodes can provide performance improvements by facilitating shorter routes between distant nodes, improving MAC efficiency via traffic aggregation and less stringent transmit power constraints. Meanwhile, multiple tiers of radio-forwarding nodes potentially reduce the required number of wired access relative to the two-tier network case (Zhao et al. 2004; Zhao and Raychaudhuri 2006b, 2007).

3.3 Protocol Design

Large-scale deployment of ad hoc and wireless networks calls for a protocol design that is both adaptive and robust to changes in the environment as well as to hardware failures. Some challenges that a protocol designer should consider are medium access control, self-organization and automatic resource discovery, routing, and transport control. The protocol stack is shown in Figure 3.3.

3.3.1 Medium Access Control

Medium access control (MAC) layer is responsible for brokering channel access between contending devices. A good design would minimize collisions, provide a reasonable guarantee of reliable transmission across the link, and ensure fair medium sharing between contending devices. In ad hoc and mesh networks, MAC layer needs to perform these functions in the presence of rapidly varying channel conditions owing to multipath fading, interference, hidden and exposed terminals, and multihop topology. In addition, ad hoc networks pose the challenge of dynamic changes in the topology due to mobility. MAC layer on each

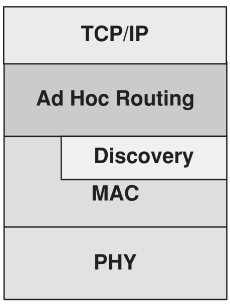

Figure 3.3. Protocol stack of an ad hoc node.

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node must also support quality-of-service (QoS) requirements set by the upper layers without the knowledge of QoS requirements of traffic carried by the contending nodes. Due to the absence of infrastructure in ad hoc networks, carrier-sensing-based distributed MAC protocol design has been adopted, and IEEE 802.11, popularly known as WiFi, has been enhanced with an ad hoc mode for this purpose. Mesh networks, on the other hand, may have a planned deployment with some infrastructure support. Therefore, hierarchical or centrally controlled medium access is possible. 802.16, popularly known as WiMAX, is the upcoming standard for mesh networks.

In this section, we will discuss the basic access mechanism in the IEEE 802.11 standard and the fundamental problems with the 802.11 MAC scheme. We will also present an overview of the WiMAX protocol and provide a discussion of some scheduling algorithms proposed for WiMAX.

3.3.1.1 802.11 Standard

The 802.11 standard is the most widely used medium access technique in wireless multihop and access point controlled networks. After the first published IEEE 802.11 standard in 1999, a variety of extensions have been studied to support higher data rate (802.11b, g), mesh and ad hoc architecture (802.11a, b, g, s), mobility (802.11r), vehicular communication (802.11p), cross-layer design (802.11k), multimedia communication (802.11aa), higher throughput (802.11b, g, n, ad, ac), and quality of service (802.11e). The 802.11-2007 revision 802 (2007) combines several amendments including 802.11 a, b, g, d, h, i, j, e providing a single document specifying one medium access and several physical layer specifications for fixed wireless LANs, mesh and mobile ad hoc networks. The most popular versions of the standard is 802.11b/g whereas the 802.11n standard, providing higher throughput, is the next upcoming standard.

Basic Access Mechanism

The basic access mechanism in the 802.11 standard is called the distributed coordination function (DCF), which is based on carrier-sensing multiple access with collision avoidance (CSMA/CA). DCF specifies that every transmitting station must sense the medium for a random duration before initiating a transmission. The station deems it safe to start a transmission if the medium remains idle for the entire random duration. All stations that overhear a transmission must refrain from initiating their own transmissions and continue sensing the medium.

Hidden Terminal Problem

The random backoff mechanism may reduce the probability of collision but does not eliminate it completely. For example, consider Figure 3.4 where station

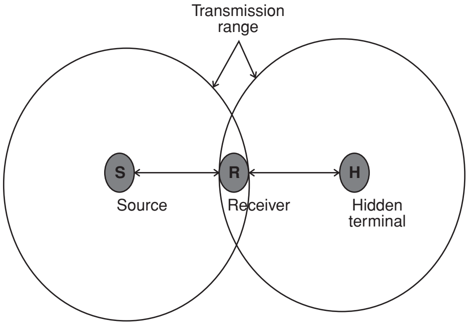

Figure 3.4. Hidden terminal problem in multihop wireless networks.

'H' is beyond the receiving range of the transmitter 'S,' therefore when 'S' transmits, 'H' does not sense the medium as busy. However, the receiver 'R' is within the receiving range of both 'S and 'H'. If 'S' and 'H' simultaneously start transmissions, the data may not be received correctly at 'B'. Retransmission will be required if either data was intended for B. This is known as the hidden terminal problem in multihop literature, and 'H' is known as the hidden node.

Virtual Carrier Sensing and RTS/CTS

802.11 introduces the concept of virtual carrier sensing and short-control message exchange to alleviate the hidden terminal problem. First, all transmitted packets contain a time duration that specifies the duration for which the medium must be occupied by the packet and any subsequent control packet exchange required for successful completion of the transmission. All overhearing stations set a network allocation vector (NAV) to the specified transmission duration and refrain from any transmission even if the medium is sensed as idle. Second, the transmitter must first send a Request to Send (RTS) frame before transmitting the data. The intended receiver must respond to the transmission with a Clear to Send (CTS) frame. The RTS and CTS frames notify all overhearing nodes about the duration of the impending transmission. The hidden terminal 'H' in our example in Figure 3.4 overhears the CTS and holds all transmissions for the entire duration specified in the RTS or CTS frame. This mechanism was designed to solve the hidden terminal problem.

The RTS/CTS mechanism also provides a fast collision detection by inferring lack of reception of CTS within the expected RTS/CTS exchange time as a collision or a busy medium at the receiver. If a larger data packet was sent without the RTS/CTS exchange, a collision would be detected after a longer time duration, wasting more bandwidth and energy. However, the overhead of RTS/CTS is not justified in short message transmissions, and therefore this is an optional feature. We present this control overhead with respect to transmitted data size in Figure 3.5.

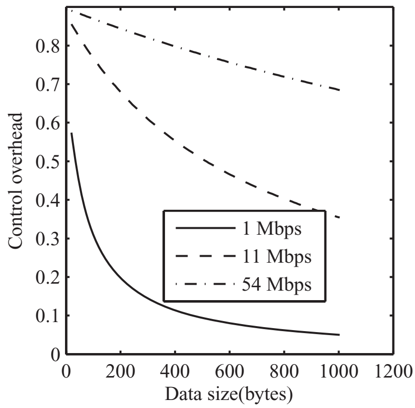

Figure 3.5. Control overhead when using RTS and CTS to protect data packets.

Contention Window

The random backoff duration in 802.11 is selected as a number between 1 to $2^{cw} - 1$, where cw is known as the contention window. The minimum size of the contention window is set to 32 in 802.11b and the maximum size is 1024. Different versions of the standard adjust the backoff window size to support priority channel access for real-time data packets. 802.11 follows a binary exponential backoff (BEB), which essentially means that after each collision, the size of the contention window is doubled, and after a successful data transmission, the window size is reset to the minimum value. The BEB method of setting the window size is sometimes very inefficient as shown in the analytical results from G. Bianchi (2000). In Figure 3.6, we recreate the analytical results from this

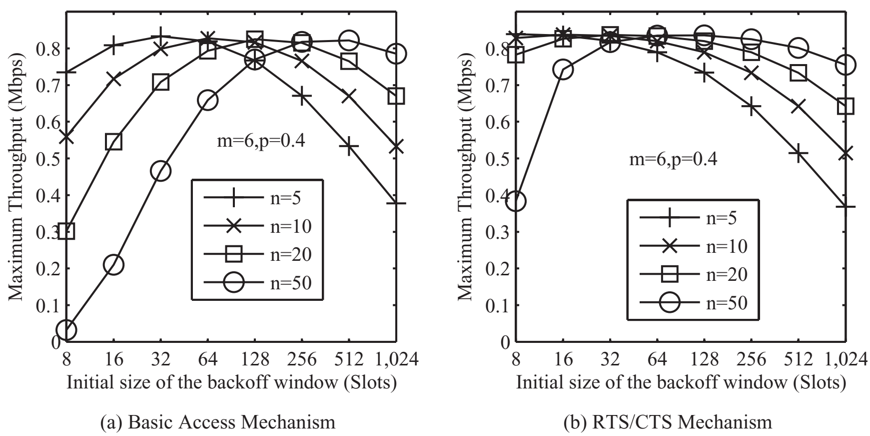

Figure 3.6. Saturation throughput versus initial size of backoff window.
Note: p: conditional collision probability at each time slot, m: number of backoff stages, n: number of contending stations

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work to show the maximum achievable throughput with respect to the initial window size. The result shows that for the best throughput performance, the initial window size must be adapted based on the number of contending stations. However, 802.11 does not have any provision to adapt the window size. Therefore, contention is subjective to traffic arrival patterns, which, being a function of user behavior, changes dynamically. An adaptive contention window protocol would thus require a mechanism to continuously sense the environment through passive listening or through the exchange of protocol messages to detect the number of active stations in the network. For example, stations can maintain a moving average of the size of their network allocation vector (Wang and Song 2007), which symbolizes the "busy period" in the neighborhood. With this knowledge, stations may be able to make an approximate "guess" of the contention level and adjust the contention window size accordingly. As an alternative, stations may use the RTS/CTS packets exchange to announce their queue sizes in the neighborhood, thus providing explicit information about future contention levels around their broadcast range. Finally, the beacons used in the ad hoc mode in 802.11 may be enhanced to include fields like "intent to contend" and number of contenders in the neighborhood to exchange the learned expected contention levels (Kim 2005).

Reliable Broadcast and Multicast

The RTS/CTS and ACK mechanism ensures reliable unicast transmission in 802.11, but there is no provision in the standard to ensure reliable multicast and broadcast messages. Several research efforts have suggested extending the RTS/CTS exchange to improve broadcast/multicast reliability. Some suggest protocols in which a leader is selected to transmit CTS on behalf of all receivers (Tourrilhes 1998). Another reliable broadcast mechanism, Broadcast Medium Window (BMW) (Tang and Gerla 2001), maintains neighbor lists and the sequence numbers of missing broadcast data packets. An RTS message is transmitted to each neighbor to inquire of the next missing broadcast sequence number. The CTS returned by the neighbor indicates the requested information. When the requested data is sent, all overhearing neighbors take advantage of the broadcast nature of the medium and update their received sequence numbers. Finally, BMMM (Min-Te, Lifei, Arora, and Ten-Hwang 2002) suggests exchanging RTS/CTS with each next hop receivers, and once all receivers have responded, the sender commences the data transmission. Such simple modifications of 802.11 provide compliance with the standard but may not be always effective. For example, in Tourrilhes (1998), the choice of the leader may not be representative of all receivers. The schemes that request multiple CTS may incur substantial delay depending upon the number of receivers and contention level.

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3.3.1.2 802.16 WiMAX Standard

The IEEE 802.16 standard, popularly known as WiMAX, specifies physical and medium access control layers of fixed broadband wireless access systems. Unlike 802.11, which is based purely on contention, 802.16 subscribers initially compete for transmission and then are assigned fixed time slots. The standard specifies the provision for implementing scheduling algorithms that assign collision-free time slots to contending subscriber stations while leaving the design of any particular algorithm to the vendor. Each frame in the IEEE 802.16 standard is divided into two parts: a control subframe to transmit all packets necessary for establishing schedules, and a time division multiplexing based data subframe in which specific time frames are assigned to and reserved for each station enabling collision-free data transmission.

The standard defines two modes of operation: Point to Multipoint (PMP) and Mesh. In the PMP mode, like single-hop wireless LANs, traffic flows only between the base station and the subscriber stations. In the Mesh mode, which is of more interest in this chapter, stations may communicate directly with one another as well as with base station. Moreover, in the Mesh mode, the base station may not be reachable from all subscriber stations, in which case, communication to the base station is through multihop traffic forwarded by other subscriber stations. There are three different scheduling mechanisms defined for the Mesh mode:

- Centralized Scheduling (CS): The base station assigns schedules to all subscriber stations, including those that are not directly connected, through resource request and grant messages transmitted in a collision-free manner during a control subframe.
- Coordinated Distributed Scheduling (CDS): Stations collectively agree upon coordinated transmission schedules in their two hop neighborhood.
- Uncoordinated Distributed Scheduling (UDS): Schedules are established by direct request and grants between two stations.

Both CDS and UDS exchange their schedules through a three-way handshake in which requests are sent indicating potential slots for replies and schedules, grants are sent indicating a subset of suggested available slots that suit the stations, and a grant from the original requestor indicating the final schedule, if any. All overhearing stations must accept and work within the agreed schedule. The only difference is that the three-way handshake occurs in a collision-free manner in CDS whereas in UDS, the handshake messages can collide. Nodes replying to the Request message in UDS must take care to give priority to those that are listed earlier in the Request to avoid collision.

3.3.1.3 WiMAX Scheduling Algorithms

The 802.16-2004 of the WiMAX standard defines four scheduling classes to differentiate traffic based on QoS requirements. First, the Unsolicited Grant Service (UGS) class designed to support real-time traffics that generate fixed-size periodic packets. Second, the real-time Polling Service (rtPS) designed for real-time applications that generate variable-size packets periodically. The rtPS traffic class requires a minimum traffic rate guarantee and latency bounds. Third, Non-Real-time Polling Service (nrtPS) that supports non-real-time, delay-insensitive traffic classes with a minimum bandwidth requirement. Fourth, the besteffort (BE) traffic class that is delay- and bandwidth-insensitive. The 802.16e revision adds an Extended real-time Polling Service (ertPS) that provides more bandwidth to real-time applications.

Scheduling for Real-time Polling Service

The rtPS scheduler at the subscriber station that has real-time traffic to send must send demands for time slots for data transmission. The base station then grants the requested number of slots. There is generally a time lag between the request/grant process and when the data is actually sent. If more data arrives at the subscriber station during this interval, additional slots need to be requested through another request/grant process. The total delay that the application traffic may incur depends on the traffic arrival pattern as well as the number of contending stations. To reduce this delay, an adaptive rtPS scheduler is proposed (Mukul et al. 2006). The subscriber station performs a stochastic prediction of data that may arrive before the requested time slots become available. This calculation is based on the average arrival rate and the time lag between request and the grant process for the transmission slot.

Scheduling for Best Effort Traffic Class

Wireless transmission rates and success probability largely depend on the SNR experienced at the receiver. WiMAX scheduling algorithms for best-effort service class can prioritize transmissions that traverse higher data rate links in order to improve the overall system efficiency. Therefore, many scheduling algorithms suggest the use of SNR to assign transmission scheduling priorities to links with high signal-to-noise ratio. Care should be taken to prevent starvation of links and to avoid violating packet delivery deadlines, fairness policies and bandwidth guarantees. Several scheduling strategies described further in this chapter have been suggested to achieve the efficiency objectives while staying within the constraints. Based on the assumptions made, these scheduling strategies may be suitable for either uplink or downlink transmissions only.

Temporary-removal scheduling (TRS) (Ball, Treml, Gaube, and Klein 2005) policy, as the name suggests, removes packets for low-rate links from the transmission queues. If the link does not improve after a fixed maximum number of removals, the packet must be scheduled anyway. In the worst case, a packet under TRS may be delayed by an additional amount. However, if the link conditions improve, the overall system throughput would benefit from this scheme. Opportunistic Deficit Round Robin (ODRR) scheduling (Rath, Bhorkar, and Vishal Sharma 2006) policy is a polling-based uplink-scheduling policy. Like TRS, ODRR prefers links with higher SNR as it transmits packets if they pass certain eligibility criteria, one of the criteria being SNR, while a packet of a slow SNR link is considered ineligible for transmission. The base station periodically determines an eligible set of subscriber stations. Results show that the polling interval k affects the delay, efficiency, and fairness of the system. When k increases, the system becomes more efficient but less fair. The choice for k is left to the WiMAX service provider.

Scheduling for All Traffic Classes

Due to different requirements of traffic classes, most algorithms concentrate on a single class. However, Wongthavarawat and Ganz (2003) presented a framework for QoS scheduling for all traffic classes in WiMAX using a combination of strict priority services. The UGS connection uses a fixed bandwidth, rtPS uses earliest deadline first (EDF), and weighted fair queuing (WFQ) is used for nrtPS traffic, whereas equal bandwidth distribution is applied to best-effort traffic class. However, in strict priority assignments, it is possible that high-priority traffic may starve the low-priority one. To circumvent this problem, a traffic policing module is introduced, which ensures that a subscriber station does not exceed its total bandwidth allocation. The overall contribution in this work is that it uses well-known scheduling policies applicable to different traffic classes and applies them to each traffic class in WiMAX with appropriate scheduling to prevent starvation.

3.3.2 Self-Organization and Discovery

Because there is no central controller in the ad hoc wireless network, it is required that ad hoc nodes be capable of self-organizing to perform desired tasks. Examples of self-organization include neighbor discovery, construction of connectivity, clustering, and formation of hierarchical structures. A basic discovery protocol is used for the radio nodes to discover each other and organize themselves into a topology in a distributed manner.

In an ad hoc network where there are no explicit discovery mechanisms, the routing protocol is responsible for building the topology by exchanging

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and disseminating neighboring information. Although this may be sufficient for small networks, it results in excessively high routing overhead as the network size increases. This problem becomes more severe in a multichannel network because the routing messages have to be propagated across all channels. Meanwhile, forming any kind of structure, such as clusters or hierarchy, requires a suitable control function. With the discovery protocol designed particularly for topology control, the control overhead, including routing overhead, can be greatly reduced.

The design of discovery protocol is also motivated by the heterogeneous network scenario. Note that topology formation based on routing protocols assumes the radio nodes to be homogeneous with the same capabilities. A heterogeneous network consists of different types of devices, for example, the end-user devices at the lowest tier of the hierarchical network in Figure 3.2 that do not have the full routing capability.

A very important characteristic of a mobile ad hoc wireless network is its changing topology (Baker and Ephremides 1981; Ephremides 2002). In particular, the network connectivity is affected by the nodes when they join, leave, and move in the network. The topological changes may also be caused by fluctuating wireless link quality and physical bit-rate adaptation (Holland et al. 2001; Kamerman and Monteban 1997). Under these circumstances, whether a node is a “neighbor” or not depends on a set of physical layer parameters instead of fixed connections as in wired networks. The topological changes may be frequent and/or unpredictable, which makes protocol design of ad hoc wireless networks an important challenge. Therefore, the protocol stack must include management functions that discover and maintain the network topology in spite of physical connectivity changes.

3.3.2.1 Neighbor Discovery

Neighbor discovery (ND) is the determination of what nodes are neighbors when a wireless network is initially deployed. If the network topology is changed during network operation, the ND algorithm could be rerun. The neighbor discovery is an important enabler of network connectivity. In neighbor discovery phase, nodes are required to discover their neighbors quickly and efficiently in order to feed topology information to routing protocols and other topology-control algorithms while conserving energy.

A node A detects the presence of its neighbor B upon successful reception of B’s packet when the received signal-to-noise ratio is greater than a defined threshold. Due to asynchronous transmitting and sensing behavior of the nodes in the ad hoc network, some packets may be dropped if the receiver does not listen to the channel while the sender is transmitting or the packet collides with others.

To improve the possibility of successful packet reception during the ND phase, several ND algorithms have been proposed (Borbash et al. 2007;

McGlynn and Borbash 2001; Vasudevan et al. 2005). Those ND algorithms run on top of a broadcast-based physical layer and a random-access MAC protocol to handle the medium contention. To further improve the efficiency of neighbor discovery, some contention-free mechanisms have been proposed; for example, the multiuser detection approach avoids collisions at modulation level (Angelosante et al. 2007).

3.3.2.2 Topology Control and Self-Organization

Through neighbor discovery, radio nodes become aware of each other's presence. Furthermore, ad hoc nodes can execute a suitable distributed control function to create a wireless network via selection of appropriate radio frequencies and nodes to associate with. In particular, the discovery protocol can determine the logical topology based on the physical topology detected by the MAC protocol. By making a subset of wireless links available to routing, the discovery protocol creates an efficient topology and reduces burden on routing and routing overhead.

The discovery protocol may also provide a metric that can be used by the routing protocol for path selection based on some performance objective. The objective function aims to optimize a target performance metric such as maximum throughput, minimum delay, energy efficiency, link fairness, or load balance.

The BEacon Assisted Discovery (BEAD) protocol (Raju et al. 2004) is proposed for the hierarchical ad hoc networks in Figure 3.2. The radio nodes use MAC beacons to identify themselves and exchange information such as node type and link quality. Different metrics are used for different types of associations: The received beacon signal-to-noise ratio is used for the energy-constrained mobile nodes (MNs) to select the association with either a forwarding node (FN) or AP; the hop count is used for the FN to choose its association with another FN or an AP. As a result, the logical topology of the network is formed by taking into account connectivity, throughput, delay, and energy requirements or constraints. Simulation results demonstrate that the BEAD protocol provides the flexibility of topology control, reduces the routing overhead, and achieves the desired performance based on the objective function.

There are other discovery issues under investigation, for example, resource or service discovery. In a heterogeneous network, some nodes may choose to provide a service to other nodes. This requires a resource or service discovery mechanism to locate the resource (Dekar and Kheddouci 2009; Kozat and Tassiulas 2003b).

3.3.3 Routing

Throughout the history of wireless protocol research, several routing protocols have been discussed. These protocols may be broadly classified as on-demand

and link-state. We will discuss various routing protocols in this section, including CNF/DTN routing protocols.

3.3.3.1 *Distance Vector and Link State Routing*

A routing algorithm is used to generate a decision-making procedure for each node to select one or more of its neighbors to forward a packet on its way to the correct destination. Most ad hoc routing protocols are based on ideas from routing methods in conventional wired computer networks. Two of the most popular routing algorithms in computer networks are *distance vector* and *link state* routing (Tanenbaum 1996).

Distance vector routing algorithms maintain a table in each router, which gives the best known distance to each destination and the link to use to get there. Pure distance vector algorithms such as distributed Bellman-Ford (Bertsekas and Gallager 1992) do not perform well in mobile networks because of slow convergence and count-to-infinity problem. Therefore, these algorithms need to be modified and enhanced when used in ad hoc network scenarios. Examples are Destination Sequenced Distance Vector (DSDV) (Perkins and Bhagwat 1994) and Ad hoc On-demand Distance Vector (AODV) (Perkins and Royer, 1999).

In link-state routing algorithms, each router discovers its neighbors and measures the link cost to each of them, then distributes the link-state information to all other routers and finally computes the shortest path to every other router. Optimized Link State Routing (OLSR) (Jacquet et al. 2000) falls into this category. Compared to link-state routing, distance vector routing is easier to implement and requires less storage space because of its computation efficiency. But link-state routing records the entire path and enables nodes to gather more link-state information, which facilitates route selection corresponding to different criteria.

3.3.3.2 *Proactive and Reactive Routing*

Ad hoc routing protocols may also be categorized as *proactive* (or *table-driven* e.g., DSDV) and *reactive* (or *on-demand*, e.g., AODV and Dynamic Source Routing [DSR] [Johnson and Maltz 1996]) routing protocols, and combinations thereof (e.g., Zone Routing Protocol [ZRP] [Haas and Pearlman 1997]). Proactive routing protocols continuously compute routes to all nodes so that a route is readily available when a packet needs to be sent to a particular node. On the other hand, on-demand routing protocols start a route computation process only when a packet needs to be sent to some other node. Therefore, on-demand routing protocols save bandwidth and reduce power consumption in mobile environments

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without periodic route advertisements, but data packets may experience larger delay than using proactive routing protocols (Lee et al. 2000).

3.3.3.3 Location-Aided, Directed Diffusion, and Geographic Routing

Location information may improve routing performance. For example, as an extension of DSR, Location-Aided Routing (LAR) (Ko and Vaidya 1998) sends location information in all packets to decrease the overhead of a future route discovery.

In addition to the ad hoc routing protocols extended from wired networks, presented here, there are some other routing approaches specifically designed for dense sensor networks. *Directed diffusion* (Estrin et al. 1999) is an example of such. Directed diffusion incorporates attribute-based naming, data-centric routing, and application-specific processing inside the network. In particular, each node in the sensor network names data that it generates with one or more attributes, and other nodes may disseminate interests based on these attributes. The propagation path of interest then sets up a reverse data path for data that matches the interest.

Another routing approach designed for ad hoc networks is geographic routing. Geographic routing identifies nodes by their locations and uses these coordinates to forward packets (if possible) toward the destination in a greedy manner. This type of routing scales well because it only keeps local information. The challenge of geographic routing is how to get through dead ends when greedy routing fails. Greedy Perimeter Stateless Routing (GPSR) (Karp and Kung 2000) solves this problem by routing around the perimeter of such regions.

3.3.3.4 Adaptive Routing and Adaptive Routing Framework

There are many studies on specific classes of ad hoc routing protocols, but no single routing protocol performs well across the full range of parameters associated with a complex real-world environment. For example, previous work (Broch et al. 1998) shows that DSDV, as a proactive routing protocol, is preferable for latency-sensitive traffic; but DSR, as an on-demand routing protocol, outperforms DSDV in high-mobility environment.

Adaptive routing has been proposed to dynamically adapt routing to changing network topology and external service needs. For example, the Sharp Hybrid Adaptive Routing Protocol (SHARP) (Ramasubramanian et al. 2003) automatically finds the balance point between proactive dissemination and reactive discovery of routing information and dynamically adapts to changing network characteristics and traffic behavior. Another example that dynamically combines

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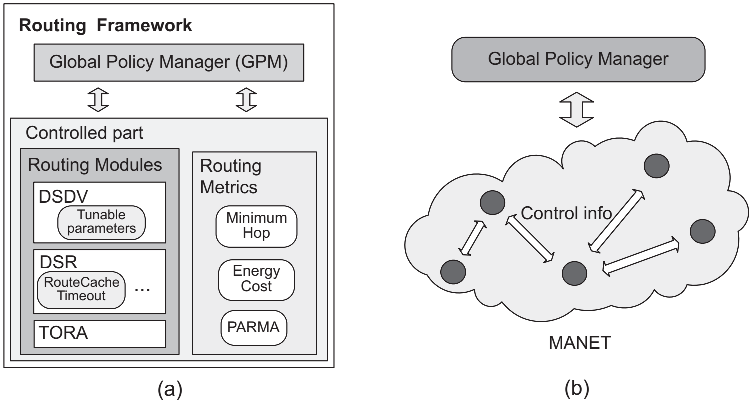

Figure 3.7. (a) Adaptive routing framework (b) Distributed global policy manager.

table-driven and on-demand routing is the strategy presented in McDonald and Znati (2000). It is adaptive to node mobility by balancing the tradeoff between path optimality and routing overhead. Tuning routing algorithm parameters can also help achieve adaptive behavior. Such an example is Adaptive Zone Routing Protocol (AZRP) (Giannoulis et al. 2004) that uses variable zone radius and controllable route update interval.

Adaptive routing framework proposed in Zhao and Raychaudhuri (2006a) is another step further. This unified adaptive framework aims to solve the routing efficiency problem in a systematic approach, and various adaptive mechanisms can be deployed in it. The architecture of the adaptive routing framework is shown in Figure 3.7(a). It implements self-adaptation by a control loop, which collects the information about routing states from the system, makes decisions, and adjusts the system as necessary. The control loop consists of two parts: the controlling part and the controlled part. The Global Policy Manager (GPM) is the controlling part that implements particular adaptation operations such as selecting the routing module, tuning the routing algorithm parameters, and adjusting the routing metric variables. The routing modules and routing metrics are the controlled elements.

Several routing modules are available in the framework. The routing module that would produce the best desired performance is selected by the GPM. The parameters of the selected routing module can also be tuned by the GPM. According to service requirements and traffic behavior, the GPM decides a routing metric and its variables. To achieve global optimization, the GPM, when making decisions, needs not only local information but also information from other nodes of the network. The control information, including state variables and management information, is disseminated through the network. Thus the

GPM entities of all the nodes in the network construct a distributed system and perform the global controlling functionalities, instead of being isolated, as shown in Figure 3.7(b).

According to the implementation of adaptation operations, the adaptive mechanisms can be classified into two types: One is switching between available routing modules or routing metrics, and the other is implementing an integrated adaptive algorithm to control a particular routing element, such as a routing metric or a routing algorithm parameter. The integrated adaptive approach is more interesting because it implements the controlled and controlling parts of the self-adaptation function in a distributed algorithm. The control information including time-varying state variables can be propagated over the network by routing messages, and each node makes decisions based on its local information without a consensus protocol. Therefore, the integrated adaptive algorithms are practically flexible to implement with reduced adaptation overhead and do not involve service interruptions.

Integrated adaptive algorithms include adaptive routing protocols (e.g., SHARP described earlier), adaptive routing parameters (e.g., the cache timeout of DSR [Johnson and Maltz 1996]), or adaptive routing metrics. In addition, cross-layer adaption is achieved when cross-layer information such as physical data rate and wireless medium busy level is incorporated into routing decision. Cross-layer adaptive mechanisms are discussed in details in Section 3.4.

3.3.3.5 DTN Routing

The routing protocols that we discussed so far work on the underlying assumption that there is always an end-to-end path in the ad hoc network. Delay/Disruption Tolerant Networks (DNTs) relax this assumption and propose partially, intermittently connected networks where an end-to-end path between two parts of the network may not always exist. Figure 3.8 shows a typical DTN network where regions A and B are never connected. However, low-earth orbiting relay satellite or a motorbike/bus might be available to make the necessary connections periodically. DTN routing has been classified based on complete, partial, and zero knowledge of periodic connectivity through mobile message carriers (Fall 2003). When mobility models of such entities are perfectly known, a message ferry may be used to carry data to a designated server, as illustrated in Figure 3.8.

Vahdat and Becker (2000) propose epidemic routing for DTN networks when no knowledge regarding mobility behavior is known. Each node maintains a list of all the messages in its buffer, called summary vector. This contains both the messages it has initiated and the messages in transit. When two nodes come in communication range of each other, an antientropy session is initialized in

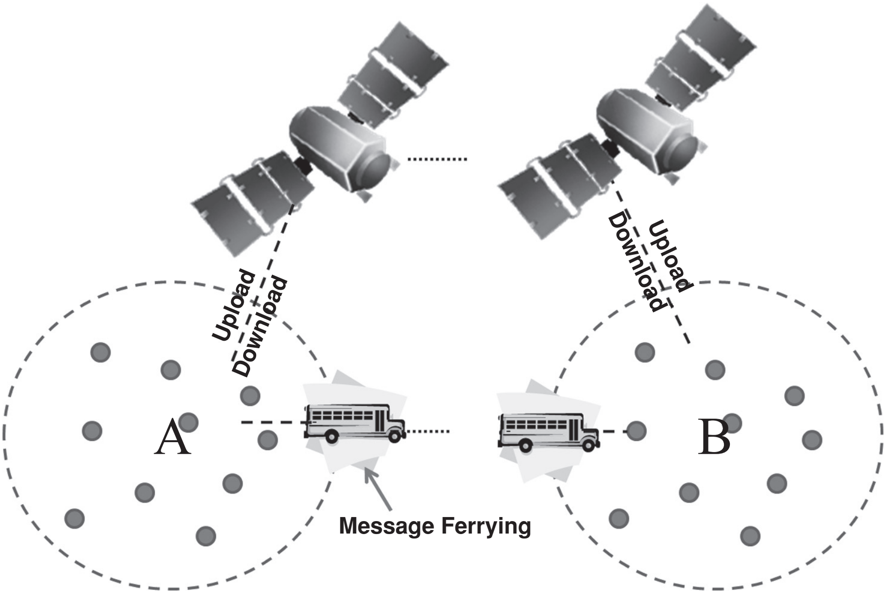

Figure 3.8. Example of a delay-tolerant network scenario.

which the nodes exchange their summary vectors. Based on the vectors, each node in the communication pair may decide to "download" messages that it has not encountered yet. By spreading messages in such an "epidemic" manner, the probability that a message reaches its destination increases with the number of replications. However, this scheme is resource-intensive, and buffer management techniques must be employed to manage the large number of messages in the network.

The MaxProp (Burgess, Gallagher, Jensen, and Levine 2006) routing protocol provides an improvement over the epidemic routing protocol by reducing the amount of storage space used. Like in epidemic routing, messages are replicated to improve the likelihood of delivery; however, a cost metric called "estimated delivery likelihood" is used to "contain" the epidemic instead of disseminating messages to all nodes encountered. Each node in the network keeps an account of its probability of meeting its peers. This probability is estimated by averaging the number of contacts between nodes over time. Nodes that were in contact further in the past have a lower likelihood of delivery compared to those encountered recently. The cost for a path is the sum of the probabilities that each connection on the path does not occur, estimated as one minus the likelihood of delivery. The cost for a destination is the lowest path cost among all possible paths.

When peers meet, the following information is exchanged. First, all messages from the peer are transmitted. Second, routing information, that is, a vector listing estimations of the probability of meeting every other node, is exchanged. Third, acknowledgments for all delivered packets are exchanged so that peers can delete delivered packets from their buffers. Fourth, new packets, that is, those that have not traversed too far in the network, are given priority when selecting packets from the set of packet to forward. These strategies have been shown to reduce delivery latency.

3.3.4 Transport Control Protocol

End-to-end protocols such as TCP developed on wired networks perform poorly over ad hoc and mesh networks. This section discusses the transport control protocol design considerations for ad hoc and mesh networks.

TCP is the most widely used transport protocol in the Internet today. In the early 1980s, when connection to the Internet was over slow dial-up links, a set of thinwire protocols (Farber, Delp, and Conte 1984) were suggested for computers connecting to the ARPA-Internet over a data path of 9,600 baud or less. Wired broadband at home and office has replaced the slow wired dial-up access to the Internet; however, the demand for mobile wireless broadband brings the same challenge with an order-of-magnitude data rate difference between wired, wireless, and cellular networks. Therefore, cross-layer transport layer design is still required to efficiently navigate bottleneck wireless links. Header compression and transport proxy are two different optimizations often suggested to improve the network performance when the rate information is available. Mowgli data channel protocol (MDCP) (Alanko, Kojo, Liljeberg, and Raatikainen 1997) employs header compression, reduced control overhead, use of transmission rates based on the speed of the transmission link, and transport proxy nodes to improve the transport performance. Proxy nodes act as the mobile user and receive data from the network on behalf of the mobile. The mobile may then retrieve the requested content from the proxy at a later time. Indirect TCP (I-TCP) uses the same proxy concept for the wireless endpoint connection. Several optimizations over TCP have been suggested to improve transport layer performance in wireless multihop networks. We will discuss some of these protocols in this section.

3.3.4.1 Cross Layer Aware Protocol (CLAP)

The Cross Layer Aware Protocol (CLAP) was designed for wireless networks with link rates that fluctuate with time in response to changes in signal-to-noise ratio in the link. The main objectives of CLAP is to adapt the transport layer flow rate with the current detected physical layer data rate, reduce self-interference by minimizing control transmissions in the opposite direction, and decouple flow control from error control by removing the dependence of flow

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control on roundtrip time. The transport layer flow control depends solely on the transmission rate to the destination. Before initiating a transmission, the transport layer observes the data rate to the next hop and the length of the link layer queue. The number of packets to be transmitted during the next fixed interval is computed based on the two parameters. Per-hop per-packet reliability is considered redundant at the transport layer, and the existing MAC layer per-hop reliability in wireless networks is leveraged. The transport layer only sends an aggregate list of packets that were not received successfully. These design choices improve the transport layer performance for wireless networks, and simulation results show significant improvement when compared to TCP Selective Acknowledgment Protocol (TCP-SACK).

3.3.4.2 Freeze TCP

Freeze TCP was proposed for last-hop wireless links and when the destination is mobile. The destination is responsible to measure signal strengths received from the access point to detect an impending disconnection. In case the signal strength weakens and the mobile determines that a disconnection or handoff is about to happen, it sends an advertisement of zero window size to the source, forcing the source into the ZWP mode and preventing the dropping of packets from the congestion window. When the connection is reestablished, the mobile may send back three acknowledgments of the last received packets. This scheme prevents the TCP session from breaking when the mobile node is disconnected for a short time duration. Simulation results show performance gain of about 38 percent when disconnections last for ten seconds.

3.3.4.3 Hop-by-Hop Transport

Cache and Forward architecture suggests a novel hop-by-hop transport protocol where large files traverse the network as single transport layer entity. At each network hop, the file is transferred in its entirety to the next hop router before being forwarded further downstream, as shown for the media file C1 moving from router A to destination M1 in Figure 3.9.

While the file is transferred through the cache and forward (CNF) network, an en-route router may decide to cache it. The caching decision may be based on popularity, availability of the file in caches nearby, and the access frequency in the local network. In Figure 3.9, router B caches the file C1 while forwarding it to C. Similarly requests to retrieve a file also result in hop-by-hop transport from the end-user to the file's location. Every en-route router checks its cache to locate the requested file. If an intermediate router finds the file in its cache, it sends a cache hit response to the requestor followed by the requested file. In

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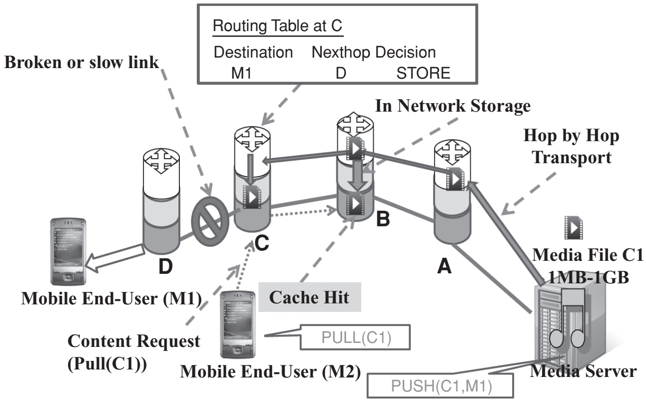

Figure 3.9. Conceptual diagram of CNF.

our example (Figure 3.9), router B responds to the mobile M2 with a cache hit message and serves the request (Pull[C1]) from its local cache.

There is a large improvement in file delay performance shown in comparison to end-to-end streaming concept of TCP under simulation scenarios where wireless endpoints communicate with one another through a wired backbone.

3.4 Cross-Layer Adaptive Mechanisms

Wireless medium access control layers are designed to shield physical layer variations from the upper layers in the protocol stack. The intention is to present to the upper layer an illusion of error-free physical medium so that the wireline protocol stacks may function in wireless access networks without any modification. Over the years, research has shown that this design choice is inhibitive to efficient wireless communication. Today wireless consumers of the Internet outnumber wired clients, and research interest is highly skewed in favor of cross layer designs that expose the properties of layers to one another. Distance or hop-based routing cost computation do not work well in practice in wireless networks (De Couto, Aguayo, Bicket, and Morris 2005). Instead, physical data rate, congestion, collision, and retransmissions are conveyed by the medium access control layer to the network layer to facilitate expected transmission count (De Couto, Aguayo, Bicket, and Morris 2005), transmission time (Draves et al. 2004) and data rate (Park and Kasera 2005) routing costs. Similarly, TCP being designed for wired networks considers any packet loss to be a sign of congestion. This assumption is not valid in the error-prone wireless medium (Shen and Zhao 2006), and therefore variations have been suggested to improve TCP performance in wireless networks (Gerla et al. 1999). In some cases, new transport protocols suitable for both wired and wireless networks have been suggested (Paul, Yates, Raychaudhuri, and Kurose; Jain et al. 2009).

3.4.1 Cross-Layer Routing Metric

Most conventional ad hoc routing protocols, including DSDV, AODV, and DSR, use the minimum hop (MH) as the metric to make routing decisions. This is primarily a carry-over from wired networks where the transmission rate of a link does not dynamically change and the link rate is independent of the physical transmission range. However, in case of wireless networks, the MH metric tends to choose paths with fewer hops, and each hop in paths tends to have a longer physical span and also is associated with a lower bit rate than an alternative path with more hops. Meanwhile, note that rate control has been implemented readily, such as auto-rate feedback (ARF) (Kamerman and Monteban 1997) and receiver-based auto-rate (RBAR) (Holland et al. 2001) schemes proposed for the IEEE 802.11 devices 802 (1999). Therefore, to take advantage of the wireless multirate capability and make better use of available network capacity, transmission rate needs to be incorporated into the routing metric.

Some examples of routing metrics that incorporate the physical layer parameters include the Medium Time Metric (MTM) (Awerbuch et al. 2004), the expected transmission count metric (ETX) (De Couto et al. 2003), the Expected Transmission Time (ETT) (Draves et al. 2004), and airtime link 802 (2006). The MTM aims to find a path with the minimum total transmission time. It is a static solution that only handles the multirate capability. Upon observing that using the shortest path would result in poor throughput, De Couto et al. (2002) propose the ETX to incorporate the effects of link loss ratios. The ETX introduces extra routing overhead of the dedicated link probe packets to measure the delivery ratio. Like the MTM, the ETX is independent of network load and does not attempt to route around congested links. The ETT incorporates both the link loss rate and the link speed, and is used as the weight associated to each link. The individual link weights are combined into a path metric called Weighted Cumulative ETT (WCETT) that explicitly accounts for the interference among links that use the same channel. The WCETT metric tends to choose channel-diverse paths to improve throughput in multiradio multihop wireless networks. The airtime link metric is specified in the IEEE 802.11s draft 802 (2006) and is in fact equivalent to the ETT.

In addition to the physical layer parameters, it is also possible to provide an awareness of congestion at each node in order to avoid bottleneck regions with high link utilizations. The wireless link is usually shared with other links in the same neighborhood, whereas in a wired network, links operate independently of each other, and channel access on one link has no effect on any of the adjacent links. Thus it makes sense to devise metrics that account for both congestion and transmission rate in a combined manner. For example, a link may provide for a high transmission rate but could appear congested because neighboring links have a high link utilization. Thus, if we account for only the link rate, this link would show up as a "good" link, but when combined with a congestion metric, it may turn out to be just the opposite, which is a more accurate reflection of the PHY/MAC layer. The next section introduces a PHY/MAC-aware routing metric and discusses techniques needed to handle different variations of changes of different layers in cross-layer design.

3.4.1.1 PARMA: A PHY/MAC-aware Routing Metric for Ad Hoc Wireless Networks with Multi-Rate Radios

The PHY/MAC-aware routing metric for ad hoc networks (PARMA) (Zhao et al. 2005) incorporates both the PHY bit-rate and MAC congestion information.

Rate-Adaptive PHY and Auto Multirate Mechanism

The widely used IEEE 802.11x standard uses adaptive selection of physical layer bit rate as a function of observed channel quality. 802.11b radios can choose different physical rate (1, 2, 5.5, 11 Mbps) whereas 802.11a/g radios select between 6, 9, 12, 18, 24, 36, 48, or 54 Mbps as the physical channel rate. This automatic PHY bit-rate adaptation feature is considered to be useful in most systems because it permits end-users to take advantage of good-quality short-range links when available. When such multirate radios are used to build ad hoc networks, the network topology and link speed change more dynamically than in radio networks with a single mode radio with fixed bit rate and range.

Figure 3.10 depicts the way in which an 802.11b radio device experiences different bit rates when connecting to its neighbors at various distances. As

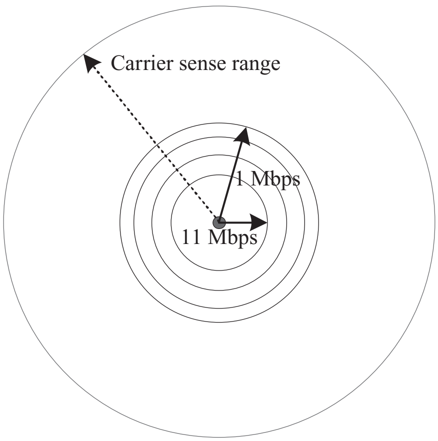

Figure 3.10. Transmission range of a multirate radio.

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shown in the figure, if a node wants to use the 11 Mbps rate, only nodes in the innermost circle can decode its frame correctly with sufficient signal-to-noise ratio (SNR). However, if it chooses to use the lower 1 Mbps rate, the transmission range would be much larger. The outermost circle indicates the threshold of carrier sense in 802.11 MAC. If there is a radio outside this circle, then the signal level of this radio's transmission received at the central node is not large enough, so the central node would sense the channel as "idle." Note that in the above description, a two-ray path loss channel model (Goldsmith 2005) is assumed and the received signal strength is simply compared to a series of fixed thresholds.

Two popular auto-rate schemes are the auto-rate feedback (ARF) (Kamerman and Monteban 1997) and receiver-based auto-rate (RBAR) (Holland et al. 2001) proposed for the IEEE 802.11 devices 802 (1999). A multirate device working with ARF scheme adjusts the rate according to the positive or negative feedback. For the RBAR scheme, the receiver decides the rate based on the measured signal strength and piggybacks the rate information to the sender via RTS/CTS exchanges. Another auto-rate scheme eliminates the extra overhead by choosing the rate for each outgoing packet based on the SNR measurements of the packets received on the reversed link (Zhao et al. 2005). This SNR-based auto-rate scheme can be easily incorporated with periodic routing updates.

MAC Channel Congestion

The MAC channel congestion can be measured by the channel access delay. The channel access delay correlates to the traffic at the MAC layer by taking into account both the locally offered traffic and that forwarded by neighboring nodes. Because the wireless medium is shared, whether a packet can access the channel immediately is determined by not only the states of the two end-nodes of the link, but also those of all neighboring nodes.

To measure this effect, a "virtual access delay" estimation based on physical layer information is introduced. To avoid unnecessary overhead introduced by periodic probes, a passive estimation method is employed. Every node records every channel event (i.e., transmission) sensed from the physical channel and makes an estimation of the "expected delay if a packet has to be sent." Suppose an M/M/1 queueing system (Bertsekas and Gallager 1992) with the common channel as the server, where packets arrive from the nodes in the neighborhood of the channel to obtain service (i.e., access the channel and get transmitted). According to the results of queueing theory, the average waiting time in queue, i.e., the *channel access delay*, is given by

$$T_W = T_S \frac{\rho}{1-\rho}, \tag{3.1}$$

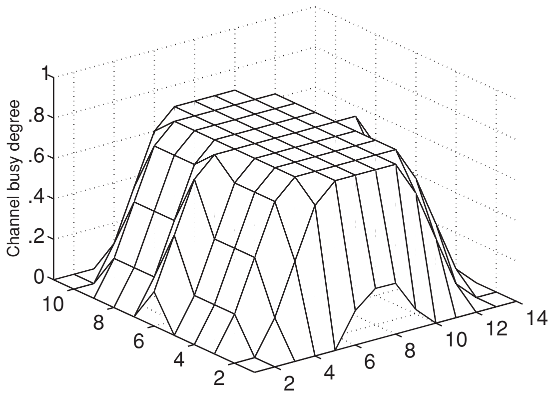

Figure 3.11. Channel busy degree around a flow with saturated load.

where ρ represents the utilization factor of server (i.e., the *channel busy degree*), and T_S is the service time for the channel event, corresponding to the packet transmission time. The estimated T_W is given to the routing protocol for use in the routing metric.

Each node can estimate ρ by sensing the occupancy of the channel. Figure 3.11 illustrates the channel busy degree ρ around a flow with saturated load. Note that the region with high busy degree ($\rho \simeq 0.75$) actually lose the ability to support any flows further.

PHY/MAC-aware Route Selection

PARMA aims to optimize the packet end-to-end delay. The end-to-end delay of a packet of size L_{pkt} transversing a path p_i is calculated as

$$Delay_{\ p_i} = \sum_{\forall links \in p_i} (T_{transmit} + T_{access} + T_{queuing}), \tag{3.2}$$

where $T_{transmit}$ denotes the packet transmission time in the link, T_{access} the medium access time spent by the packet getting access to the link, and $T_{queuing}$ the queueing time required for the packet waiting before trying to access the channel.

The packet transmission time can be calculated as

$$T_{transmit} = N_{transmit} \times \frac{L_{pkt}}{R_s}, \tag{3.3}$$

where R_s is the link speed, which would be one of the rates the multirate devices provide, and $N_{transmit}$ is the number of transmissions, including retransmissions, needed for the packet to be received correctly. When the link quality is poor, packet retransmissions will be carried out by the MAC protocol. With adaptive multirate PHY, around 90 percent of packets get transmitted successfully in

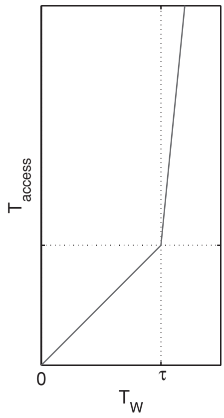

Figure 3.12. A nonlinear mapping from T_W to T_{access}.

the first attempt (Gopalakrishnan 2004). Hence $N_{transmit}$ can be set to 1 as an approximation.

The medium access time, T_{access}, is used to indicate the medium busy level around the sending node of the link. When the medium is busy, it takes a relatively long time for a packet to get the chance to transmit. Incorporating the medium access time into the routing metric, the routing algorithm can choose a route with light traffic load in addition to high-speed links, and thus spread the traffic over the network to achieve load balance, avoid congestion, and increase effective bandwidth. Notice that the highly busy region loses the ability to support any flows (see Figure 3.11). A nonlinear mapping from T_W, the access delay estimated by the MAC layer, to T_{access}, as shown in Figure 3.12, is applied. It is one of the techniques introduced to smooth the link layer change effect on routing and also to improve route convergence.

A large access delay reflects a growing interface queue length when the network is congested. When a system below saturation is considered, $T_{queueing}$ can be omitted.

With the above assumptions and simplifications, the routing metric computation can be summarized as

$$Delay_{\,p_i} = \sum_{\forall links \in p_i} \left(\frac{L_{pkt}}{R_s} + T_{access} \right). \tag{3.4}$$

The system performance with the PARMA metric is compared with the MH and MTM (Awerbuch et al. 2004) metrics using the *ns*-2 network simulator (Fall and Varadhan 2002). Those routing metrics are plugged into DSDV. To make DSDV work well with the PHY/MAC-aware routing metric, specific enhancements to the routing protocol are required, such as maintaining two routing tables to avoid missing the best route when it arrives later than the first route of the next new sequence number. In addition, smoothing techniques for the link portion of the proposed metric are introduced to adjust the different variations of changes between the PHY/MAC layer and the network layer, and also to improve route convergence. The simulation results indicate that, with both the PHY rate and the MAC occupancy level taken into account in the routing metric, packets can choose high-rate links while avoiding congested areas in the network, thus improving system throughput and reducing average end-to-end delay.

3.4.2 Integrated Routing and MAC Scheduling

The PHY/MAC-aware routing metric optimizes the routing function by incorporating MAC contention and interference effects. It belongs to the layered implementation of multihop 802.11 MAC and routing protocol. However, the performance achieved by optimizing an individual layer such as routing or MAC in multihop wireless environment is limited by a certain point (Barrett et al. 2002). Meanwhile, the fundamental inefficiency caused by CSMA/CA MAC (Bertsekas and Gallager 1992; 802 [1999]) in multihop scenarios need to be solved. Therefore, it makes good sense to treat MAC and routing jointly to improve MAC efficiency and further improve system performance.

Several studies on joint optimization of routing and link scheduling provide performance bounds (Jain et al. 2003; Kodialam and Nandagopal 2003; Tassiulas and Ephremides 1992). A recent work proposes IRMA (Integrated Routing and MAC Scheduling Algorithm) to integrate routing and MAC as a single algorithmic framework (Wu et al. 2006; Wu and Raychaudhuri 2008). The IRMA uses joint optimization techniques to establish end-to-end path and TDMA schedules for flows across the network.

3.4.2.1 IRMA: Integrated Routing and MAC Scheduling for Single-Channel Wireless Mesh Networks

The IRMA approach is proposed to overcome the problems presented in multihop wireless networks, for example, hidden nodes contending for channel (Xu and Saadawi 2001), poor spatial reuse due to channel sensing-based backoffs in the extended neighborhood of an ongoing transmission (Li et al. 2001), and self-interference among packets of the same flow transmitted at each hop along the path (Gerla et al. 1999).

The nodes in a traditional 802.11-based mesh network randomly access the shared medium based on the locally observed information. The IRMA algorithm attempts to solve the fundamental inefficiency caused by the CSMA/CA mechanism by creating conflict-free TDMA link schedules based on traffic demand across all end-to-end routed paths.

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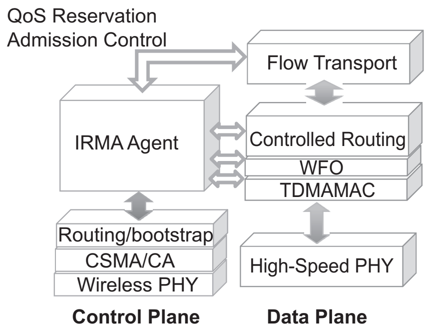

Figure 3.13. IRMA protocol architecture.

Control Plane

Because of lack of coordinations, the neighboring nodes using CSMA/CA contend to access the medium in a distributed manner. To improve the efficiency of medium access, the IRMA uses a centralized algorithm to allocate schedules and paths simultaneously for each source-destination pair of traffic in the network. In particular, the network entities execute online control procedures to collect necessary information, run optimization, and distribute the MAC and routing parameters. The IRMA framework places the control processes in a *control plane*, separated from the *data plane* over which packet data are transferred. The protocol architecture consisting of control plane and data plane is shown in Figure 3.13.

The control plane may be implemented using either a dedicated portion of TDMA slot or a separate channel or frequency to exchange the control information including topology, bandwidth, and traffic flow specifications. Based on the information, the centralized control algorithm determines the route and TDMA slot assigned for each source-determination pair.

The medium contention is eliminated by arranging conflicting transmissions in different TDMA slots. Spatial reuse is maximized by scheduling a maximum number of interference-free transmissions simultaneously in the same time slot.

Traffic Aware Scheduling

Link scheduling in a single-channel packet radio network has been formulated as a vertex-coloring or edge-coloring problem (Cidon and Sidi 1989; Ramaswami and Parhi 1989; Ephremides and Truong 1990; Gandham et al. 2005). Meanwhile, several distributed MAC schemes (Zhu and Corson 1998; Bao and Garcia-Luna-Aceves 2001) have been proposed to create interference-free TDMA schedules. However, these approaches are based on oversimplified interference models and are per-packet scheduling approaches. Relying on the control plane to collect and disseminate the topology information and traffic

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specifications, the IRMA assigns traffic flows to alternative paths based on actual end-to-end traffic demand.

Joint MAC and Routing Algorithms: IRMA-MH and IRMA-BR

The IRMA establishes nonconflicting radio resources by considering all relevant traffic in the interference neighborhood collectively. The routing table and link access schedules for each involving node are solved jointly in one algorithm.

Two alternative joint MAC and routing algorithms are designed. Link scheduling with minimum hop count (IRMA-MH) algorithm solves min-hop routing and optimizes link scheduling based on routing results and real-time flow demands. Link scheduling with bandwidth-aware routing (IRMA-BR) algorithm optimizes routing and scheduling decisions simultaneously by using available MAC bandwidth information to route around congested areas.

It is worth mentioning that the IRMA-BA algorithm conducts bandwidth-aware path selection to route around medium busy areas. As illustrated in Figure 3.14, node A will choose node B as the next hop and its packets will enter a highly interfered region (shown as the shaded region in the figure), when the min-hop routing is applied. The IRMA-BA takes into account the available bandwidth and chooses a link (from node A to C) with light interference while still leading to the destination.

To provide upper and lower bounds, the integrated routing and MAC optimization is formulated as a linear programming (LP) problem. The objective function maximizes the aggregate throughput of all end-to-end traffic. After conducting a certain large number of iterations, if the upper and lower bound converge, the converged value is used as the analytical throughput of the LP solution as a reference to compare with the simulation results.

Both IRMA-MH and IRMA-BR with centralized and distributed algorithm variations are evaluated using *ns*-2 simulations (Fall and Varadhan 2002) and

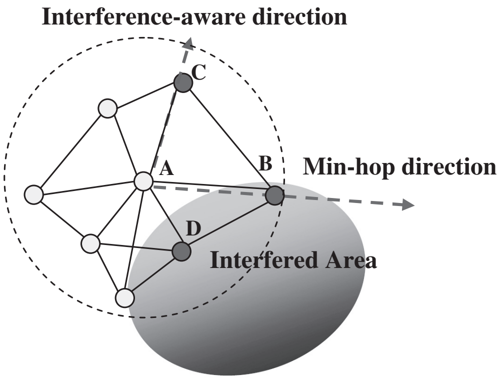

Figure 3.14. IRMA protocol architecture.

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compared with two baseline schemes (DSDV and AODV). The results show significant two-to-three times improvements in network throughput over baseline 802.11-based mesh networks with independent routing protocols such as DSDV and AODV. The control overhead is also much lower than baseline schemes.

3.5 Integration with the Internet

It is noted that most applications involve traffic flows to and from the Internet in addition to peer-to-peer communication between ad hoc nodes. As the Internet users turn toward mobile Internet access using mobile broadband, 3G, and WiFi, there are worldwide initiatives to rethink the Internet architecture, layering and services (FIND; Lemke 2007; FP7 2007). The focus is on designing solutions that provide seamless integration of wired Internet with wireless, ad hoc, sensor, mesh, and cellular networks. Having studied the nature of different types of wireless deployments earlier in this chapter, we know that they are very different from the traditional fixed infrastructure. Therefore, we need to answer several questions while looking for an interface that integrates them into one network. Can the IP-based addressing be used to identify each device in the Internet? How far should information like changes in the network organization and mobility-based disconnections be propagated into the core network? Should BGP be extended for wireless networks, disseminating summary information across all connected networks? Should the architecture be designed for end-to-end connectivity, or is the hop-by-hop protocol a better option?

An easy approach is to make minimal changes and preserve the existing protocol stack, then simply provide a Proxy server to glue together these different types of networks to the wired core. A second approach would be to allow more awareness across the networks and let BGP like gateway routing disseminate long-term events, like a mobile end-user disappearing from the network, while hiding the short-lived changes like transient link variations. A third approach is for seamless integration, where a control plane in which any router can query the routing information for any end-point across the network, regardless of the wired or wireless nature of the links that constitute the path. These ideas are elaborated in the following paragraphs.

3.5.1 Glue Network

A glue network requires minimal changes to the current state of the art. It is based on the idea that simple interfaces may be designed to translate data at the boundaries so that it can be represented in the format suitable for the destination network type. Thus, simple "Proxy Gateway" nodes can be designed with multiple communication interfaces. To the wired network, all data coming from or going to the wireless end nodes appears to originate/terminate at the Proxy Gateway

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and vice versa, just as transport models like I-TCP and CLAP described earlier. Concerns for cross-layer design, self-organization, addressing, routing, and so on become local to the individual networks and the wired Internet is oblivious to all the idiosyncracies of the wireless networks. However, this creates a narrow waist of congestion and excessive delays at the entry and exit point to the wireless "cloud." Perhaps local in-network caching of popular content may be used to reduce the amount of traffic that must cross the network boundaries.

3.5.2 Extended Glue Network

The glue network described earlier has several performance issues in terms of localized congestions both in the wired and wireless end of the glue/proxy gateway. Another design may solve this problem by allowing some summarized routing information to percolate into the wired core. For example, a Border Gateway Protocol-like method may be used to exchange summarized longer-term variations and local congestion information in wireless routes so that TCP-like flow control may be used at further upstream points rather than closer to the wireless gateway.

However, by design, ad hoc networks are expected to appear and tear down dynamically at any place in the world. Therefore, the nodes sending these summary information may also appear at random places in the network. Moreover, these ad hoc gateways may appear via cellular, satellite, or multihop mesh networks and even through a combination of multiple heterogeneous network hops. It is unclear if the summarized information regarding such a network should reach all the way to the wired core, or should the information be further summarized each time it traverses a different network type. Therefore, this approach calls for at least a redesign of the BGP protocol to handle these points.

3.5.3 Seamless Integration

Perhaps the answer for a seamlessly and fully integrated Internet lies in the cross-layer design philosophy that has been so popular in wireless network designs. The protocol stack may be redesigned so that the upper layer can implement optimizations depending on the link-layer technology used for communication. Perhaps a control plane may be developed to make information like routing, location, sessions, and so on available on an on-demand basis so that protocols can opportunistically select the best mode of operation. For example, if an application server notices a slow-end link to the destination, it may change the format of the data being delivered. Thus, high-definition video transmission may be scaled down so that the content is delivered but at a lower rate. The transport protocol may dynamically switch to I-TCP/CLAP/Hop-by-Hop transport when a weak wireless link is encountered and revert back to normal TCP when a series of good wired links are being traversed. Network layer may temporarily store instead of forwarding over slow links, especially if it is possible to judge through past observations that the link may improve soon.

Similarly, self-organization tactics can be used for dynamic connection with the control plane for information dissemination. When a new ad hoc network appears and needs to connect to the Internet, it may perform a resource discovery to select the best set of gateway nodes for this connection. The gateway nodes may then announce their presence to the control plane and start feeding relevant local state information to the Internet. Mobile devices that can have several heterogeneous interfaces may be able to dynamically select the best network for communication. Similarly naming, addressing, authentication, and dynamic entry and exit to and from the broader Internet should be resolved in terms of physical location coordinates of devices rather than network-level IP addresses.

This design requires a complete overhaul of the network architecture and therefore seems like a daunting task. But a seamless redesign will perhaps be the most sustainable way into the future. It is also the first opportunity for researchers to design the Internet based on experiences from the past, rather than from making good guesses and imaginations regarding how the network to be used in the future.

3.6 Conclusion

The research in wireless ad hoc and mesh networks has come a long way. It is a maturing field where several important topics are now understood quite well. However, several areas are still lightly explored and therefore important for current and future works. Some important current research topics include integration of various wireless technologies and architectures, as well as improvement in communication capacity using MIMO techniques and multichannel operation. Opportunistic channel access using cognitive radios and integration with the Internet will form the major research effort in the coming years.

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