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A SURVEY, CLASSIFICATION AND COMPARATIVE ANALYSIS OF MEDIUM ACCESS CONTROL PROTOCOLS FOR AD HOC NETWORKS

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ABSTRACT

Recent technological advances in wireless communications offer new opportunities and challenges for wireless ad hoc networking. In the absence of the fixed infrastructure that characterizes traditional wireless networks, control and management of wireless ad hoc networks must be distributed across the nodes, thus requiring carefully designed Medium Access Control (MAC) layer protocols. In this article we survey, classify, and analyze 34 MAC layer protocols for wireless ad hoc networks, ranging from industry standards to research proposals. Through this analysis, six key features emerge: (1) channel separation and access; (2) topology; (3) power; (4) transmission initiation; (5) traffic load and scalability; and (6) range. These features allow us to characterize and classify the protocols, to analyze the tradeoffs produced by different design decisions, and to assess the suitability of various design combinations for ad hoc network applications. The classification and the tradeoff analysis yield design guidelines for future wireless ad hoc network MAC layer protocols.

Many technological factors, such as cheaper hardware, smaller transceivers, and faster processors, are fueling the increased interest in wireless ad hoc networks. The main goal of wireless ad hoc networks is to allow a group of communication nodes to set up and maintain a network among themselves, without the support of a base station or a central controller. From the applications perspective, wireless ad hoc networks are useful for situations that require quick or infrastructureless local network deployment, such as crisis response, conference meetings, sensor networks, military applications, and possibly home and office networks. Ad hoc networks could, for instance, empower medical personnel and civil servants to better coordinate their efforts during large-scale emergencies that bring infrastructure networks down, such as the September 11 attacks or the 2003 blackout in the northeast section of the United States.

In the OSI reference model, medium access is a function of the layer 2 sub-layer called the Medium Access Control (MAC) layer. MAC protocols for wireless networks must address the hidden node problem and must exercise power control. Accessing the wireless medium thus requires a more elaborate mechanism than what is required by wired networks to regulate user access to the channel. Ad hoc wireless networks present even greater challenges than infrastructure wireless networks at the MAC layer. The absence of a centralized controller creates the need for distributed management protocols at the MAC layer, and possibly at higher layers of the network stack.

In this article we conduct a comprehensive survey of 34 MAC protocols for wireless ad hoc networks, ranging from industry standards (IEEE 802.11 [1], Hiperlan [2], and Bluetooth [3]) to research proposals. Table 1 shows the list of surveyed MAC protocols for wireless ad hoc networks in chronological order. The "Published" column in Table 1 confirms that research and development activity in this area has increased exponentially in recent years, with eight protocols published in the year 2002 alone.

PROTOCOL FEATURES

Designing improved protocols at the MAC layer requires an understanding of the features that characterize such protocols. Chandra *et al*. [35] provide a classification of wireless MAC

Protocol	Published	Channel	Topology	Trans. initiation	Power efficient	Traffic load and scalability	Range
1. CSMA [4]	1975	Single	Single/Flat	Sender	No	Wired networks	Medium
2. BTMA [5]	1975	1 control/1 data	Centralized	Sender	No	Hidden terminal	Long
3. PRMA [6]	1988	Hybrid	Centralized	Sender	No	Voice	V. short
4. MACA [7]	1990	Single	Single/Flat	Sender	No	Hidden terminal	N/A
5. MACAW [8]	1994	Single	Centralized	Sender	No	Delivery guarantee	Medium
6. FAMA [9]	1995	Single	Single/Flat	Sender	No	Delivery guarantee	Medium
7. IEEE 802.11 [1]	1996	Multiple (FHSS/DSSS)	Single/Flat	Sender	No	Access point	Medium
8. HIPERLAN [2]	1996	Multiple (hybrid)	Clustered	Sender	Yes	Data relay	Short
9. MACA-BI [10]	1997	Single	Multiple/Flat	Receiver	No	Predictable traffic	Long
10. FPRP [11]	1998	Multiple (time)	Multiple/Flat	Sender	No	Voice	N/A
11. PAMAS [12]	1998	1 control/1 data	Multiple/Flat	Sender	Yes	Dense low load	Medium
12. Bluetooth [3]	1999	Multiple (FHSS)	Clustered	Master	Yes	Low rate PAN	V. short
13. Markowski [13]	1999	Multiple (time)	Single/Flat	N/A	Yes	Voice	N/A
14. HRMA [14]	1999	Hybrid	Multiple/Flat	Sender	No	Large packets	N/A
15. MCSMA [15]	1999	Multiple (frequency)	Single/Flat	Sender	No	High density	Medium
16. PS-DCC [16]	1999	Single	Single/Flat	Sender	Yes	High load	Medium
17. RIMA-SP [17]	1999	Single	Single/Flat	Receiver	No	Predictable traffic	N/A
18. ADAPT [18]	1999	Multiple (time)	Multiple/Flat	Sender	No	High load	Medium
19. CATA [19]	1999	Multiple (time)	Multiple/Flat	Sender	No	Low load	Medium
20. Jin [20]	2000	Hybrid	Clustered	Sender	Yes	Heterogenous	N/A
21. MARCH [21]	2000	Single	Multiple/Flat	Sender	Implicit	Homogeneous	V. short
22. RICH-DP [22]	2000	Multiple (FHSS)	Multiple/Flat	Receiver	No	High load	Long
23. SRMA/PA [23]	2000	Multiple (time)	Multiple/Flat	Sender	Yes	Voice	N/A
24. DCA-PC [24]	2001	1 control/N data	Multiple/Flat	Sender	Yes	High density	Short
25. GPC [25]	2001	Single	Clustered	N/A	Yes	High density	N/A
26. VBS [26]	2001	N/A	Clustered	N/A	No	Voice	N/A
27. DPC/ALP [27]	2002	Single	Multiple/Flat	Sender	Yes	Heterogenous	Long
28. Lal [28]	2002	Multiple (space)	Multiple/Flat	Receiver	Implicit	High load/Density	Medium
29. GRID-B [29]	2002	1 control/N data	Multiple/Flat	Sender	No	High load/Density	Medium
30. MC MAC [30]	2002	Multiple (CDMA)	Multiple/Flat	Sender	No	High rate PAN	V. short
31. WCA [31]	2002	N/A	Clustered	N/A	Yes	Heterogeneous	N/A
32. DBTMA [32]	2002	2 control/1 data	Multiple/Flat	Sender	No	Hidden terminal	Short
33. MMAC [33]	2002	Multiple (space)	Multiple/Flat	Sender	Yes	High load	Medium
34. D-PRMA [34]	2002	Multiple (time)	Single/Flat	Sender	No	Voice	Medium

Table 1. *Chronological protocol classification.*

protocols through a joint analysis of both centralized (infrastructure) and distributed (ad hoc) protocols. Their work includes many wireless centralized MAC protocols, but unfortunately only two wireless ad hoc MAC protocols (IEEE 802.11 and HIPERLAN). As a result, their classification does not emphasize network topology but relies on the following six categories:

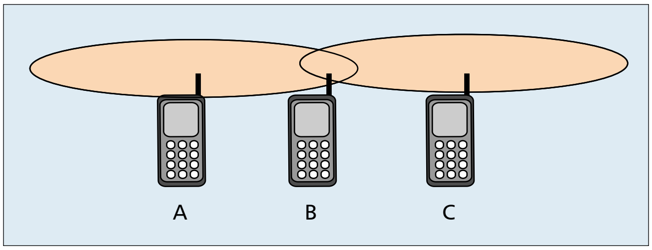
- Network architecture[1]
- Duplexity
- Collision resolution algorithm
- Robustness
- Stability
- Fairness
- Power efficiency
- Hidden node resolution
- Multimedia support

While we share the view that many of the features identified in [35] are important for ad hoc networks, we believe that such networks have characteristics that are distinct from centralized wireless networks. For that reason, we define a different classification that we believe is more appropriate for wireless ad hoc networks. From our survey of 34 available MAC protocols, six key features emerge:

- Channel separation and access
- Topology
- Power
- Transmission initiation
- Traffic load and scalability
- Range

In the context of ad hoc networking, Chandra's features b, c and h are highly correlated. For instance, the degree of multiplexing in a particular protocol is closely coupled with the collision resolution algorithm, which may be relaxed in the presence of many channels. Therefore, we integrate Chandra's b, c and h into one feature, "channel separation and access." Chandra's categories d, e, f, and i assess the performance of protocols. Our classification also discusses performance as a characterizing feature of a MAC protocol. However, our feature "traffic load and scalability" evaluates the performance of protocols by identifying their suitable network conditions, including traffic load and node density. In our classification, "topology" emerges as another key design feature in ad hoc networks, whereas this feature is absent from [35]. We attribute this difference to the fact that ad hoc network protocols consider a wide spectrum of topologies based on the applications for which they are designed, while the majority of protocols considered in [35] have a common centralized topology. Another added feature in our classification is "transmission initiation." The majority of protocols for centralized networks in [35] adopt a sender-initiated approach, since this approach is more intuitive for networks that typically serve end user needs. Ad hoc networks support an extended set of applications, and a receiver-initiated approach might be more suited for some ad hoc network applications. For that reason, we categorize ad hoc network MAC protocols according to their transmission initiation approach. Our final added fea-

[1] *In [35], network architecture refers to whether a network is centralized or distributed.*



■ FIGURE 1. *The Hidden Node Problem: Node A senses the medium as idle and initiates a transmission to node B. Node C also senses the medium as idle and initiates a transmission to node B. A collision occurs at node B, and both A and C are unaware of the collision since they are out of each other's range.*

ture, "range," is highly correlated with performance, flexibility, and mobility of ad hoc network MAC protocols. Since each of these protocols is designed for specific application scenarios, ranges of operation vary widely from one protocol to another. Many protocol design decisions also depend on the expected range of operation of a protocol. For example, a long-range protocol offers increased mobility support compared with short-range protocols, but it may also require tighter channel access mechanisms, for instance to handle longer latencies. Therefore, we also classify protocols based on their proposed ranges.

PROTOCOL OVERVIEW

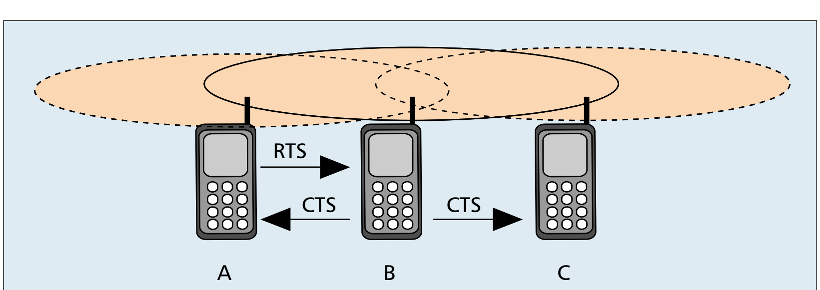
Table 1 classifies protocols according to each of the six features. We now examine Table 1 more closely. The first six protocols in this table were originally designed for packet radio networks, which are the predecessors of ad hoc networks. We include these protocols in our analysis because they provide the basis upon which more recent protocols, specifically designed for ad hoc networks, are built. Also, the protocols in rows 25, 26, and 31 in Table 1 describe enhancements of a generic wireless MAC protocol, rather than a fully specified MAC protocol. Consequently, we do not classify these algorithms for every feature. The "Implicit" entry in the "Power Efficient" column indicates that a protocol produces power savings, although its original design did not address power efficiency. For protocols that did not have relevant data on performance under different traffic loads or node density, the "Traffic Load and Scalability" column contains the protocol's suitable application or setting.

It is evident from the overview presented above that a variety of design choices can be made for each feature and application. Combining various design choices of features involves complex tradeoffs. In addition, most protocols in Table 1 were designed for a specific class of applications or physical-layer technologies, thus trading off generality for efficiency. In this article we analyze these generality tradeoffs for the 34 protocols, and we further assess the suitability of various combinations of features for ad hoc network applications. This tradeoff analysis and the classification presented here yield appropriate design guidelines for general wireless ad hoc network MAC protocols.

In the rest of the article each section focuses on categorizing protocols based on the manner in which they handle a specific feature in Table 1. Note that we drop the term "wireless" when referring to ad hoc wireless networks in these sections. First, we describe and classify protocols according to their channel separation and access techniques, which are the central mechanisms of MAC protocols. The subsequent sections discuss the additional features that characterize ad hoc network MAC protocols. Secondly, we examine the macro scale operation of these protocols by categorizing them into different topologies. Then, we assess available power management mechanisms and their suitability for particular channel access methods and topologies. Next, we classify protocols according to transmission initiation and discuss the effect that this feature has on a protocol's performance and applications. Then we evaluate and distinguish protocols according to their scalability and according to their performance for their intended traffic load. We discuss the proposed transmission ranges of different protocols, and their impact on the scale and applications of protocols. Finally, we offer a roundup of ad hoc network issues and derive guidelines for creating a more generalized protocol that is suitable for several physical-layer technologies and applications.

CHANNEL SEPARATION AND ACCESS

A key factor in the design of a MAC protocol for ad hoc networks is the way in which it utilizes the available medium. Earlier approaches assumed a common channel for all stations, while more recent approaches have used multiple channels for more efficient use of the medium. Most of the proposed protocols assume that the underlying physical channel employs radio frequency (RF) signals. Recently, other physical-layer technologies have been proposed for ad hoc networks: ultra wide band radio (UWB) [36] and acoustic communication [37]. UWB is a carrier-less transmission scheme that promises higher transmission rates [38, 39] and more sophisticated admission control mechanisms [40] than current RF technology. Acoustic technology [41] relies on communication through basic microphones and speakers that are already ubiquitous in many mobile devices. This technology has also been used in underwater communications for many years because acoustic signals propagate further than RF signals in water. The existence of multiple candidate transmission technologies gives rise to the concept of multi-modal nodes that can roam among networks with different physical channels to achieve some of the goals of ubiquitous computing [41, 42]. For example, a node may move from an RF network into an area where only UWB nodes exist. In order to maintain connectivity, the node has to be equipped for both communication technologies. Another example of multi-modal nodes is a surface buoy in an underwater sensor network. Such a node typically has an acoustic modem to communicate with underwater



■ FIGURE 2. *RTS/CTS handshake: Node A requests access of the channel through the RTS. Node B replies with a CTS indicating that it is ready to receive node A's transmission. Node C receives a CTS from node B and thus refrains from transmitting for the duration indicated in CTS. Even though A and C are hidden from each other, the handshake ensures that a collision at node B does not occur.*

nodes and a radio transceiver to communicate with a remote base station on shore. We note here that some proposed protocols have applied this multiple-mode concept in a limited scope by incorporating Global Positioning System (GPS) for positioning or synchronization purposes, while still using radio for data transmission.

In this section we classify protocols as either single-channel or multiple-channel protocols. Furthermore, we classify multiple-channel protocols based on their channel separation mechanism. Within each channel separation strategy, we describe the channel access method of particular protocols.

SINGLE CHANNEL

Considering the medium as a single channel was the most prominent approach in the earlier years of MAC design [4, 7–9, 43], primarily because mechanisms for channel separation had not yet been developed. In a common channel MAC protocol, all the nodes on the network share the medium for all their control and data transmissions. Collisions are an inherent attribute of such protocols. Two stations that transmit simultaneously will both fail, and a back-off mechanism is required by both stations.

The first proposed single-channel protocol is Carrier Sense Multiple Access (CSMA) [4]. In CSMA a node senses the common channel for ongoing transmissions. If the channel is idle, it begins its transmission. Otherwise, it sets a random timer before attempting to transmit again. CSMA does not address the handling of collisions on the channel. An improved variant of CSMA is CSMA/CD [43] (CSMA with collision detection). In CSMA/CD, if two or more transmissions collide, the sending nodes are notified and each chooses a random time before retransmitting. If a node detects a collision for the second time, it backs off for twice the time it backed off the last time. This mechanism is known as Binary Exponential Back-off (BEB). The performance of CSMA protocols degrades quickly with high load, due to the increased frequency of collisions and increased transmission latency.

When applying CSMA to networks where some nodes are not within range of each other, two or more nodes may have a common neighbor while they are out of range. If both nodes sense the channel and try to transmit to this common neighbor, then a collision occurs. Figure 1 illustrates this situation, which is called the hidden node problem. Multiple Access with Collision Avoidance (MACA) [7] was proposed for packet radio networks as an improvement over CSMA to eliminate the hidden terminal problem. The protocol introduces a handshake between a sender and receiver, shown in Fig. 2. This handshake ensures that neighboring nodes are aware of the upcoming transmission, and that they will refrain from sending for the duration of that transmission. The sender initiates the handshake by transmitting a Request to Send (RTS) signal to the receiver to indicate its request to access the medium. Nodes in the vicinity of the sender are notified of the upcoming transmission through this RTS message. Upon receiving an RTS, the receiver replies with a Clear to Send (CTS) message indicating its readiness for reception. Nodes that are in the vicinity of the receiver are also notified of the transmission through the CTS. Once the RTS/CTS handshake is complete, the transmission proceeds with no risk of collisions. If there is a collision of two RTS messages, then both stations back off for some time. By reducing the possibility of collisions and eliminating the hidden terminal problem for data transmissions, MACA offers an improvement over CSMA. MACA Wireless (MACAW) [8] was introduced to adapt MACA for the unreliability of the wireless medium, by making the receiver acknowledge successful data reception with an ACK message. This offers a delivery guarantee that is crucial in wireless networks. MACAW is based on a cellular structure in which a base station resides in each cell, and base stations are interconnected by a wired network. An additional modification in MACAW is replacing the BEB mechanism with a smaller back-off factor.[2] This modification is intended to reduce the latency caused by frequent collisions in loaded networks. Floor Acquisition Multiple Access (FAMA) [9] enhances MACAW by adding carrier sensing before sending an RTS. MACA-BI (By invitation) [10] takes a receiver-initiated approach, where a receiver indicates its readiness to receive by broadcasting a Ready to Receive (RTR) message. Any neighbor that hears a RTR can then send data to any destination. Therefore, MACA-BI does not prevent collisions in the vicinity of the receiver.

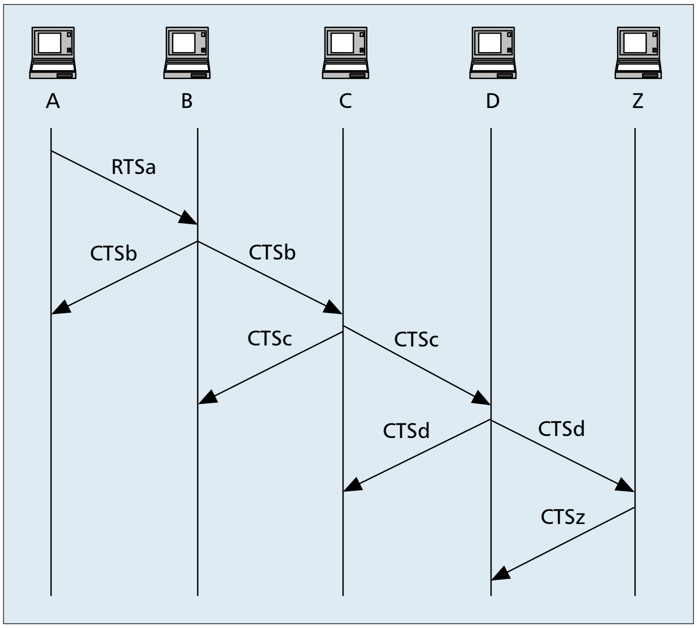


FIGURE 3. *Reduced handshaking in MARCH.*

Receiver Initiated Multiple Access with Simple Polling (RIMA-SP) [17] improves on MACA-BI by allowing polled neighbors to send only to the polling node. RIMA-SP also allows both nodes to send data after the handshake is complete. In both MACA-BI and RIMA-SP, the receiver takes a proactive role in initiating transmissions. Transmission initiation will be discussed in more detail in a later section.

Multiple Access with Reduced Handshake (MARCH) [21] attempts to reduce control signaling, while retaining the RTS and CTS framework. The handshaking involved in MARCH is shown in Fig. 3. Suppose a node A has data to send to node Z, using a path A,B,C,D,Z. A sends RTS_A to the next hop in the path B. When B replies to A with CTS_B, C hears that message. C now knows that B will send it data from A, so it will reply with CTS_C to B at the appropriate time. The same process is repeated at nodes D and Z. Using this mechanism, MARCH proposes a single RTS on the first hop of the path, while only CTS is required for every subsequent hop.

Distributed Power Control with Active Link Protection/Adaptive Probing (DPC/ALP) [27] also relies on the basic RTS/CTS handshake. In DPC/ALP, the sender issues an RTS

[2] *BEB was reduced to use a factor of 1.5 because of the high latency exhibited for a factor of 2. The optimal back-off factor could be obtained adaptively based on current channel utilization [16].*

at a power level that appears as noise, and keeps progressively increasing power and sending it again until the receiver replies with a CTS. If the transmit power for an RTS exceeds a threshold with no reply from the receiver, the sender backs off. This mechanism allows a RTS to interfere only minimally with other ongoing transmissions, since the signal will barely exceed the noise power.

Finally, Power Save with Distributed Contention Control (PS-DCC) [16] is designed as a probabilistic back-off mechanism for each channel in IEEE 802.11 [1] networks. In PS-DCC, nodes measure channel utilization constantly, and adaptively calculate a sending probability based on the current network load. PS-DCC offers better performance than a static back-off scheme, such as the scheme used in most deployed protocols.

Multiple Channels

Generalized Separation — Some protocols for ad hoc networks separate the control and data planes by assigning one channel for control signaling and one or more separate channels for data transmissions. A few of these protocols describe a generalized channel separation scheme, where they base an access scheme on having multiple channels, but they do not specify how to separate the channels. Busy Tone Multiple Access (BTMA) [5] suggests having a separate busy tone channel to solve the hidden terminal problem of CSMA. BTMA proposes that when a centralized base station senses a busy data channel, it places a sine wave on the busy tone channel to prevent any nodes from transmitting. Dual Busy Tone Multiple Access (DBTMA) [32] presented a recent extension of using busy tones, where two out-of-band busy tone channels are used to protect RTS transmissions, and to prevent nodes in the receiver's vicinity from transmitting. By offering a distributed approach instead of a base station, DBTMA presents a viable method of a busy tone solution to the hidden terminal problem in ad hoc networks. Power Aware Multiple Access with Signaling (PAMAS) [12] proposes using one control channel for sending RTS/CTS and a separate data channel. In terms of handshaking, PAMAS includes the length of the upcoming transmission in both RTS and CTS. Neighboring nodes that overhear RTS or CTS messages can therefore go into sleep mode for the duration of the transmission, thus reducing the probability of collisions.

Dynamic Channel Assignment with Power Control (DCAPC) [24] is another generalized channel separation protocol having one control and *N* data channels. In DCA-PC a sender checks if any of the data channels appear free. If so, it chooses one of the available channels and sends an RTS signal to the destination on the common control channel with maximum power. If the destination agrees with the sender's channel choice, it replies with CTS at a power level appropriate to reach the sender, and the sender subsequently reserves the channel. If the destination has a conflict with the sender's channel choice, the destination sends its free channel list to the sender so that the sender can choose a more appropriate channel.

Another generalized channel separation protocol is Grid with Channel Borrowing (GRID-B) [29], which proposes initially assigning data channels to each cell in a pre-defined geographic area. In this protocol, highly loaded cells borrow channels from neighboring lightly loaded cells if needed. Negotiations for channel borrowing occur on a common control channel. GRID-B proposes the use of Code Division Multiple Access (CDMA) or Frequency Division Multiple Access (FDMA) for channel allocation. In the case of CDMA, channel bandwidths are fixed and therefore increasing the number of channels up to a certain limit is beneficial. In FDMA, the total bandwidth is fixed, and therefore having additional users reduces the per user bandwidth.

Time Division Multiple Access — Time Division Multiple Access (TDMA) segments the medium by splitting it into several fixed time frames that are subdivided into slots. To ensure that nodes keep track of time frames and slots, TDMA protocols must maintain synchronization among the nodes. In these protocols, only one station may transmit during a particular time slot. Because of their periodic nature, TDMA protocols are most suitable for real-time and deadline-sensitive traffic.

The first proposed TDMA protocol for ad hoc networks is the Five Phase Reservation Protocol (FPRP) [11], in which each slot is split into an information slot and reservation slot. A sender that wants to reserve an information slot must contend for it during its reservation slot. The reservation slot consists of five phases that resolve conflicts among all nodes that are also contending for the information slot within a two-hop radius. A node that reserves an information slot can transmit with a low chance of collisions during that slot. In FPRP, nodes maintain perfect synchronization through GPS.

Collision Avoidance Time Allocation (CATA) [19] adopts almost the same concept as FPRP, with the only distinction being that it uses four reservation mini-slots to access a slot instead of five. Soft Reservation Multiple Access with Priority Assignment (SRMA/PA) [23] also resembles FPRP, since they both share the notion of having several mini-slots to reserve a data slot. The added feature in SRMA/PA is that it classifies nodes into high-priority and low-priority nodes, where high-priority nodes can grab reserved slots from low-priority nodes. Categorizing nodes in this manner gives better performance for voice nodes in the network. The protocol also suggests a new back-off mechanism, where access probability is based on packet laxity.

Markowski [13] proposed a window-splitting protocol based on TDMA. This protocol classifies nodes according to their traffic classes: Hard Real Time (HRT); Soft Real Time (SRT); and Non Real Time (NRT). Each class of nodes can preempt nodes in lower classes. Furthermore, nodes are only allowed to transmit at the beginning of a slot, while all nodes maintain perfect synchronization. Within each class, collisions are resolved through a window-splitting mechanism. If a collision occurs for two nodes of the same class, then half of the nodes of that class are placed in an active window for the current slot, while the other half are placed in an inactive window. Nodes in the active window contend for the next slot. If collisions occur again, the active window is further split into an active and an inactive window. Window splitting is done on a Node ID basis for HRT, on a packet laxity basis for SRT, and on an arrival time basis for NRT. There is no specification of how to handle synchronization in this protocol, nor is there any reference to the hidden node problem.

ADAPT [18] proposes assigning slots to nodes to cope with high-load and high-density networks. It also suggests using contention to manage the unused slots. Each active node owns one slot, and is given priority to send RTS in its slot while other nodes listen for the owner's transmission. If the owner does not send an RTS during its own slot, other nodes will contend for this slot by trying to send their own RTS. At that point, a node that receives a CTS message may use this slot only in the current frame.

In Distributed Packet Reservation Multiple Access (D-PRMA) [34], which is an adaptation of PRMA, nodes are designated as voice or data terminals. Only voice terminals can reserve the same slot for subsequent frames. This resembles slot ownership in ADAPT, with the difference that only voice terminals may temporarily own slots. A slot is split into *m* mini-slots, and contention in the first mini-slot determines the winner in the slot. If there are collisions in the first mini-slot, nodes contend again for the slot during the second mini-slot, and so on. Voice terminals are given priority over data terminals by always contending through the first mini-slots. Synchronization in D-PRMA is achieved through GPS.

Frequency Division Multiple Access — FDMA splits the available medium into several frequency channels to allow multiple nodes to transmit simultaneously. A proposed FDMA protocol uses CSMA on each of the frequency channels (MCSMA) [45]. Each node keeps a list of free channels, and when it has data to transmit, it tries to use the channel that it used during the last transmission. If that channel is busy, it selects one of the other free channels. Although MCSMA reduces overall collisions when compared to original CSMA, collisions and hidden terminal problems are still present on each channel.

Code Division Multiple Access — CDMA uses one of several orthogonal codes to spread each sender's signal. Through its use of orthogonal codes, CDMA allows concurrent multiple transmissions using all of the available spectrum. Multicode MAC (MC MAC) [30] uses CDMA by assigning *N* codes for data transmission and one common code for control signaling. A sending node in MC MAC issues an RTS to another node on the common control channel indicating the code(s) that it will use for transmission. If it gets a CTS, it assumes that there is no code conflict with the intended receiver and it subsequently sends data, after which it expects an ACK. If the receiver detects code conflicts, it exchanges its usable codes with the sender, so the sender chooses the appropriate codes for transmission.

IEEE 802.11 [1] Distributed Coordination Function (which is the specification for infrastructure-less mode in Wireless Ethernet) is almost identical to MACAW on each of its channels, except that it combines a CSMA mechanism with MACAW to lower the probability of RTS collisions. IEEE 802.11 splits the medium by using one of two forms of CDMA, either Frequency Hopping Spread Spectrum (FHSS) or Direct Sequence Spread Spectrum (DSSS). In FHSS, it allows up to 79 different hopping channels in North America and Europe, thus supporting up to 26 co-located networks. In DSSS, IEEE 802.11b uses 12 codes to allow concurrent transmissions of nodes. In IEEE 802.11, nodes that hear RTS or CTS set their network allocation vector (NAV), which indicates the remaining time until a current channel becomes free. The standard also provides a busy channel that nodes can sense to check if the medium is idle. To promote fairness among nodes and to prevent large transmission latencies, IEEE 802.11 introduces a contention window from which nodes waiting to transmit choose a random back-off time. The size of the contention window adapts to the number of collisions that occur. A node may transmit once its back-off timer expires. Whenever a node is forced to wait through another frame, it continues counting down from where it stopped instead of choosing a new random waiting time. This ensures that nodes that wait longer get priority to access the medium.

Receiver Initiated Channel Hopping with Dual Polling (RICH-DP) [22] combines the slow frequency hopping aspect of HRMA [14] and the receiver initiation aspect of RIMA/SP [17] to allow nodes to reserve hops and to send data both ways once a hop is reserved. A receiver that is ready to receive data sends an RTR message to its neighbors. If some neighbor has data to send, it responds with an RTS to reserve the hop for data exchange between the pair. Both nodes can send data after they complete this reservation.

Space Division Multiple Access — As in CDMA, Space Division Multiple Access (SDMA) aims at using the full spectrum all of the time to a certain degree. In SDMA, nodes use directional antennas, thus allowing a node to begin a transmission at any time as long as the transmission's direction does not interfere with an ongoing transmission. In Lal's [28] SDMA protocol, a node polls neighbors with an omni-directional RTR message that contains the node's training sequence. A training sequence indicates the directions in which a node accepts transmissions. Nodes that have data to send reply to the polling node using a directional RTS (DRTS) that contains each node's own training sequence. The polling node then replies to the accepted senders with a Directional CTS (DCTS) to complete the handshake. The use of directional antennas can therefore accommodate concurrent multiple senders to the polling node.

MMAC [33] proposes a technique of using smart antennas to establish a multi-hop link through the RTS/CTS handshake. In MMAC, nodes keep profiles of the neighboring transceiver directions. Whenever a new data request arrives at the MAC layer, the MAC initiates carrier sensing in the direction of the intended receiver. If the channel is idle in that direction, the MAC then issues a directional RTS to the next hop in the path to the destination. Nodes on the path to the destination forward this RTS message directionally until the RTS reaches its destination. The destination then replies with CTS directly to the sender, and the two establish data communication. Neighboring nodes that fall within the range of this new directed link set their directional network allocation vector (DNAV) for the duration of the transmission.

Hybrid Protocols — Hybrid protocols combine two or more of the above approaches. Packet Reservation Multiple Access (PRMA) [6], which was designed for an infrastructure network to enable voice nodes to communicate alongside data nodes, uses both TDMA and FDMA. PRMA divides time into frames that are further segmented into slots, and each slot may be either reserved or unreserved. There are also one upstream and one downstream frequency channels. A sender has to listen for an unreserved slot, to contend for it using ALOHA, and to await a base station's decision on the winner for this slot. PRMA also classifies nodes as periodic and non-periodic traffic nodes. If a periodic traffic node reserves a slot, that node can use the same slot in subsequent frames.

High Performance Local Area Network (HIPERLAN) [2], which is the European counterpart of IEEE 802.11, uses another hybrid FDMA/TDMA channel access scheme. It provides a maximum of five frequency channels, each with a rate of 23.5 Mb/s. Furthermore, nodes must contend for the channel in three phases prior to reserving it. The length and structure of these phases are based on fixed time slots and frames.

Hop Reservation Multiple Access (HRMA) [14] is another hybrid of TDMA and FDMA. In HRMA, nodes are all synchronized and hop to a common sequence (in each slot, all the nodes listen to the same frequency, and switch to another frequency during the next slot). If a node has data to send, it sends a Hop Reservation (HR) message using the current frequency hop, and it follows that with an RTS message to the intended receiver. If the receiver replies with CTS, then the pair has reserved the current frequency hop and they can send any amount of data using that frequency, while all other nodes are still following the common hopping sequence.

Jin [20] proposes a hybrid CDMA/TDMA protocol, in which nodes dynamically elect a pseudo base station (PBS) based on power considerations. The PBS maintains synchronization and assigns codes to nodes that it manages, using frames that have three mini-slots for synchronization, reservation, and scheduling, and a data slot.

Bluetooth [3] also combines CDMA and TDMA. A master node in Bluetooth assigns frequency hopping sequences a piconet, which allows simultaneous communication between the master and up to seven slaves. Bluetooth uses time division duplexity to separate the uplink and downlink. The master node manages medium access through a polling and reservation scheme, and it also assigns hopping sequences and maintains synchronization within the piconet.

Summary — Many medium access protocols for ad hoc networks use a variant of the RTS/CTS handshake. Protocols that do not use this handshake rely on carrier sensing, periodic exchanges of information among nodes, or reservations. Multiple-channel protocols, which use different techniques for channel separation, generally allow for more users than single channel protocols.

TOPOLOGY

Ad hoc networks typically include nodes with varying capabilities and resources. Nodes may also be mobile, so the topology of an active network could change frequently. Therefore, an efficient protocol is one that assumes a topology as generalized as possible. The network must also be able to adapt to heterogeneous node capabilities in a way that optimizes performance and minimizes energy consumption. Network topology can typically be described in terms of hierarchy and hops. A network could have a centralized, clustered, or flat topology. In the centralized case, a single node or base station controls and manages all other nodes in the network. Clustered topologies designate one node in each group of nodes to handle localized central control of the group. Flat topologies consider a fully distributed approach, where all nodes are both nodes and routers, and the notion of centralized control is absent.

We make a further characterization of protocol topologies by examining the hop nature of a network. Some protocols assume that nodes only need to communicate with reachable neighbors, and are referred to as single-hop protocols. Other protocols assume that nodes need to communicate beyond their reachable neighbors, and that sometimes a packet has to be relayed through many intermediate nodes to get to its destination. We refer to these protocols as multi-hop. Single-hop protocols are simple but restrictive since they offer limited support for larger networks. Multi-hop protocols are more general in scope and more scalable, although they introduce added complexity into channel access mechanisms.

There are several combinations of hierarchy and hops in proposed protocols:
- Single-hop flat topology
- Multiple hop flat topology
- Clustered topology
- Centralized topology

This section categorizes protocols according to their topology and explores how each topology choice impacts a network's performance.

SINGLE-HOP FLAT TOPOLOGY

Single-Hop Flat Topology protocols are not concerned with handling the relaying of data, and assume that all nodes are similar in capabilities. CSMA [4], MACA [7], FAMA [9], MACA-BI [10], RIMA-SP [17], IEEE 802.11 [1], Markowski [13], HRMA [14], RICH-DP [22], and DPRMA [34] are all examples of this category. The first six in the above list assume that a node has a global view of the network, or that higher-layer protocols can handle reaching distant nodes. Thus, each node only has to contend with its immediate neighbors in order to obtain access to a channel. As the node density and network load increase in a network, these protocols scale poorly since delay increases exponentially and throughput drops drastically. D-PRMA, IEEE 802.11, Markowski, and HRMA attempt to add scalability and adaptability to harsh network conditions to this topology class. D-PRMA and IEEE 802.11 provide multiple channels to support an increased number of users. Markowski, HRMA, and RICH-DP offer techniques such as window splitting and hop reservation to make better use of the common medium.

In dense or highly loaded networks, however, capacity and performance are limited in a single-hop topology, even when using optimization techniques. Other drawbacks of a single-hop topology are high power consumption and lack of flexibility. For instance, when two nodes move away from each other, both must increase their transmit power if they still need to communicate. Even if transmit power adaptation is ensured, the price for mobility is increased average power consumption, which could have been avoided in a multi-hop topology. Therefore, this topology is more suited for wired networks or smaller scale and lower throughput wireless networks, such as Personal Area Networks (PANs) or sparse Local Area Networks (LANs).

MULTIPLE-HOP FLAT TOPOLOGY

Multiple-Hop Flat Topology protocols offer a more scalable and general approach. Protocols that use this topology also assume that the network is homogeneous in terms of node capability and functionality. Ad hoc networks can benefit from a multi-hop topology mainly in power efficiency and correct channel reservation mechanisms beyond one-hop neighbors.

PAMAS [12] addresses the possibility of some nodes being out of range of the receiver or transmitter, and it allows nodes within range of an active transmission to turn off their radios for power efficiency.

MCSMA [15] also exploits a multi-hop flat topology to allow for frequency channel reuse within the network, thus increasing the total number of allowable hosts. Had it been implemented in a single-hop topology, this protocol would have only been able to support as many nodes as there are frequency channels. GRID-B [29] is also based on a multi-hop topology, where each cell in a pre-defined geographic area is a single-hop with its own set of channels.

FPRP [11], SRMA/PA [23], CATA [19], and ADAPT [18] use multi-hop in a similar way, where nodes can only reach their immediate neighbors, but they also have to establish reservations that do not conflict within their two-hop neighborhood. MC MAC [30] exploits the multiple-hop topology in a similar way by assigning codes that do not conflict within a two-hop radius. Given the limited number of available orthogonal codes, spatial reuse of these codes, which is possible through the multi-hop topology of the MC MAC protocol, is crucial for scalability. In a single-hop topology, channel reservation in these protocols would have to be unique among all nodes, thus preventing any channel reuse.

Other protocols such as DCA-PC [24] and DCP/ALP [27] also use this topology to model the network. These two protocols not only make use of multi-hop for channel access, but also for limiting the overall power consumption. Both protocols force nodes to transmit only with the power necessary to reach the receiver. Because of their multi-hop topology, nodes may choose to send data through a multi-hop path to a node that is within transmission range.[3] These protocols show how a multi-hop topology can reduce overall power consumption in the network. Lal [28] and MMAC [33] attempt to direct the emitted power toward the receiver. Using directional antennas, more active multi-hop links may co-exist on the same frequency channel.

MARCH [21] is one of the few single-channel RTS/CTS protocols that takes advantage of a multiple-hop topology. In MARCH, nodes on the next hop of the data path hear control signaling from the previous hop and prepare to receive a transmission.

DBTMA [32] is the only other protocol with a single data channel that uses this topology. It focuses on reducing situations that cause collisions and thus jam its single data channel. The two out-of-band busy signals are the main mechanism to tackle the exposed and hidden terminal problems, which occur with increased probability in multi-hop networks.

Clustered Topology

One major challenge in ad hoc networks is performing network initiation, management, and control. In infrastructure networks, a base station handles these functions. Researchers have found the idea of centralized control attractive, and have tried to emulate it in ad hoc networking models by designing protocols that use a clustered topology. In a clustered topology, one node among each group of nodes is selected to act as the cluster head. Clustered topology protocols attempt to reduce control overhead at individual nodes by placing much of this burden at the cluster head. There are several approaches to choosing the cluster head. The Virtual Base Station (VBS) [26] protocol focuses on a dynamic random selection of a virtual base station for clusters in mobile networks. In VBS, each node announces its IP address periodically by sending "hello" messages to its neighbors. Nodes listen to "hello" messages and join the cluster of the lowest IP address node in their vicinity. Adapting to changes in the network, such as nodes moving or dying, is accomplished through the periodicity of "hello" messages. Although the VBS protocol provides a simple mechanism for choosing a unique cluster head in a specific area in the network, the selection of a cluster head is totally random (since IP addresses do not hold any information relating to nodes). Furthermore, VBS has the undesirable feature that nodes with lower IP addresses suffer from resource overuse.

An approach that addresses some of the shortcomings of VBS is the Weighted Clustering Algorithm (WCA) [31]. WCA proposes electing cluster heads based on a weight function at each node that expresses a node's suitability for being a cluster head. In WCA, nodes first discover their neighbors, including node degrees, distances, and velocities. A node's degree is the number of neighbors that it has. After this initial discovery phase, each node calculates and announces its own weight value. The parameters that contribute to the weight function are: the distance from neighbors (for transmit power consideration); the time a node will spend as a cluster head (battery power available); mobility; and connectivity. The algorithm also proposes that cluster heads of different clusters maintain connections to each other using dual power radios. Finally, WCA supports mobile nodes by allowing handovers for nodes moving from one cluster to another.

[3] *[40] describes techniques for deciding on when to use a multi-hop path instead of a single-hop path through power considerations.*

Jin [20] and GPC [25] both propose electing a cluster head according to battery power only, which is a simpler but less generalized approach than WCA. Jin's protocol, however, specifies low-level details of how cluster heads manage their clusters through code assignment, synchronization, and scheduling.

Bluetooth [3] also has a clustered topology in the form of piconets of one master and up to seven active slaves. The master is not dynamically chosen; rather, it is always the initiator or founder of the piconet. Since Bluetooth was designed for PANs, which aim at achieving wireless connections within an office or home, such a selection of the master makes sense. A PC or another central device generally has to be powered on, and that device polls less intelligent devices to establish connections. For other ad hoc networks with more general applications, statically assigning a master is inefficient.

HIPERLAN [2] is another standardized protocol that adopts a clustered topology. In this protocol some nodes are designated as forwarders, which are responsible for relaying data to distant nodes. HIPERLAN designates other nodes as p-supporter nodes to keep track of the sleep schedule of neighboring nodes. Therefore, in HIPERLAN, forwarders and p-supporters share the duties of a cluster head.

Centralized Topology

BTMA [5], MACAW [8], and PRMA [6] are example protocols of a centralized topology. All three protocols require the presence of a central base station to coordinate medium access. In BTMA, all nodes communicate through the base station, which sends an out-of-band busy signal whenever the data channel is busy to prevent collisions. In PRMA, nodes contend for available time slots in the next frame. A central base station determines the status of each slot in the next frame and announces the successful reservations for the upcoming frame. Finally, MACAW assumes that there are several fixed base stations connected with a wired network.

Ad hoc networks generally do not adopt a centralized topology since, by definition, they are infrastructure-less. However, these protocols provide valuable concepts, such as a busy tone channel and time slot reservation that are extendable to ad hoc networks.

Summary

In short, a multi-hop flat topology or a clustered topology are more suitable to ensure scalability in ad hoc networks. Both of these topologies require more control messaging. In homogeneous networks, a multiple-hop flat topology is more appropriate. In heterogeneous networks, a clustered topology allows the high-power nodes to become cluster heads and handle most of the overhead control messaging. A single-hop topology requires fewer control messages but it is not scalable. A centralized topology is, by definition, an infrastructure network, and thus it is not an option for ad hoc networks.

Power

A major design consideration for ad hoc network MAC protocols is the power consumption of individual nodes, and the overall power consumption of the network. Power conservation is important for any type of mobile node, whether operating in an ad hoc or infrastructure network, because of its limited battery power. In infrastructure networks, a resourceful base station is responsible for managing channel access and allocation, while nodes consume most of their power for data transmissions. In ad hoc networks, however, the absence of a base station places the burden of control on one or more of the nodes. Furthermore, the absence of a centralized controller increases the chances of collisions and channel assignment conflicts that lead to higher power consumption in the form of control signaling and retransmissions. It is therefore clear that we can achieve much of the power optimization in these networks through careful design of the MAC protocol. In this section, we describe common mechanisms for power conservation, and we classify protocols based on the mechanisms they adopt.

TRANSMIT POWER CONTROL

The largest source of power consumption at a node is transmission power. Some protocols, such as GPC [25] and DCAPC [24], have proposed controlling the transmit power so that it is just enough to reach the intended receiver. GPC describes a high-level behavior of this mechanism. DCA-PC specifies a more detailed behavior of how each node continuously monitors, records, and updates the transmission power level it needs to reach each neighbor. In DCA-PC, a node is initially unaware of the appropriate power levels, so it transmits with maximum power. After it establishes contact with a neighbor, then both nodes learn the appropriate power levels they need to communicate. DPC/ALP [27] is another protocol that supports transmission power control. Recall that in DPC/ALP, a node sending its RTS progressively increases its transmit power until it exceeds a threshold of detection at the receiver. If the receiver replies, then a connection is established, otherwise the sender backs off. During data transmissions, a sender in DPC/ALP also transmits at the minimum power needed to overcome noise at the receiver. Lal [28] and MMAC [33] exercise another method of power control through directional antennas. Because nodes send messages in the direction of the intended receiver, the transmission requires less power than in the omni-directional case, where the signal is scattered in all directions.

Some protocols propose power control enhancements to the IEEE 802.11 MAC protocol [44, 45]. These protocols specify that a sender and receiver transmit RTS and CTS control messages at maximum power so that neighbors become aware of the upcoming transmission. The sender can subsequently transmit the data at a lower power level which is directly related to the distance between the pair of nodes, instead of the maximum power level. The work in [46] has shown that this approach may produce asynchronous links and that it may lead to collisions in the carrier sensing zone of the sender. In [46] it is proposed that the sender and receiver periodically raise the power level during the sending of data to keep neighbors within the carrier sensing zone aware of the ongoing transmission.

Transmission power control benefits dense or highly loaded networks, where a large number of nodes need to efficiently share the wireless medium with minimal interference. Protocols that support this mechanism must also use few data channels to avoid overuse of the common control channel.

SLEEP MODE

Some protocols acknowledge that in ad hoc networks a considerable portion of power consumption is wasted due to overhearing irrelevant transmission, or due to idle listening to the channel. PAMAS [12] takes advantage of the simple RTS/CTS handshake to avoid this problem. As mentioned earlier, PAMAS has a common control channel and a common data channel. Nodes that hear RTS or CTS on the control channel refrain from communicating since they are in the neighborhood of either the sender, receiver, or both. These neighboring nodes power off their transceivers for the duration of the transmission indicated in the handshake messages.

Therefore, PAMAS reduces battery power consumption in highly connected low-load networks, where at any time many idle nodes overhear other nodes' transmissions.

HIPERLAN [2] also allows nodes to go into sleep mode to conserve power. Such nodes are called p-savers, and must set up a specific wake-up pattern by notifying specialized neighboring nodes called p-supporters. P-supporters are responsible for keeping track of the sleep schedules of neighboring p-savers, for buffering data for these nodes, and for forwarding it to them when they are set to wake up. This mechanism obviously requires extra buffer space and battery resources at p-supporter nodes.

Bluetooth [3] supports three low-power states: park, hold, and sniff. Park state provides the lowest duty cycle and thus the lowest energy consumption. In this state a node releases its MAC address but remains synchronized with the piconet. The node wakes up occasionally to synchronize and listen for broadcast messages. Hold state is the next higher low-power state. In hold state a node keeps its MAC address and transmits immediately after waking up. Finally, in the sniff state a node listens to the piconet more often than in the hold state, but still at a lower rate than normal. The rate at which a node listens is programmable and application-dependant.

A potential drawback of supporting sleep mode is overhead power consumption for powering up a transceiver. In some cases this overhead may exceed the power savings of supporting sleep mode. Therefore, whether it is beneficial to support sleep mode depends on the specifications of particular transceivers.

BATTERY LEVEL AWARENESS

There are several protocols that are aware of battery power levels at nodes and adjust their behavior accordingly. For example, DPC/ALP, Jin, and GPC base their selection of a cluster head on battery levels. DPC/ALP and Jin also classify nodes into high power (HP) and low power (LP) according to remaining battery power. DPC/ALP gives LP nodes priority during transmissions, by allowing them to reserve slots sooner than HP nodes. All of these protocols produce power savings when they are used in a power-heterogeneous network. For example, a network may include laptops, palmtops, and pens equipped with transceivers. One of the laptops would generally be selected as a cluster head because of its relatively high power resources. For similar reasons electronic pens get priority for transmission in DPC/ALP due to their limited battery power. WCA [31] also considers battery power along with several other parameters to elect a cluster head. Because it combines the effects of several factors in electing a cluster head, WCA performs well in both power-homogeneous or power-heterogeneous networks.

REDUCED CONTROL OVERHEAD

The exchange of control messages prior to data transmission is also a source of power waste. Whereas control messages are necessary to avoid collisions, reducing these messages to the minimum is beneficial. MARCH [21] is one protocol that follows this reasoning. As described earlier, in a path where there are N hops, MARCH uses one RTS message and N CTS messages. When N is large, power savings from this approach are considerable. However, MARCH ignores the case of heterogeneous-power nodes. Referring to Fig. 3, when a node A has data to send to another node Z, using the path A-B-C-D-Z, A sends RTS_A to node B. Node B replies with CTS_B to indicate to A that it is ready to receive data. MARCH assumes that the next node in the path C hears CTS_B when it was sent to A. In this assumption, MARCH supposes that all nodes are equidistant in the network, and that nodes are always transmitting at a constant power level. If transmit power control was used in conjunction with MARCH, then the mechanism does not work. For example, C might be further away from B than A, in which case C does not hear CTS_B.

SAVINGS FOR PARTICULAR SETTINGS

Given that different networks have varying particularities when it comes to power, some protocols are focused on achieving power savings for specific settings. One of these protocols, SRMA/PA [23], is concerned with quality of service and assumes there are high-priority and low-priority traffic. It allows high-priority traffic to preempt the low-priority traffic when trying to grab slots for transmission. Markowski's [13] protocol follows a similar reasoning for three traffic classes. This technique improves performance for high-priority traffic, but it has the opposite effect for lower-priority traffic. In a network with many voice or real-time traffic nodes, both protocols reduce overall network power consumption by avoiding collisions and retransmissions for real-time traffic.

INCREASED CONTROL OVERHEAD

There are some protocols that are unaware of any power issues, and therefore do not incorporate power considerations into their behavior. A few of these protocols, however, contain power-wasting features. For example, RICH-DP's approach [22] is suitable for networks with predictable and periodic traffic. In networks that do not fit this description, many RTR messages are sent while no nodes have data to send. In such networks RTR messages present two sources of power waste. The first is the transmit power of the node sending a non-useful RTR. The second source of power waste is due to idle listening to RTR messages at neighboring nodes.

TDMA-based protocols also contain a regular source of power waste to maintain synchronization. Some of these protocols, such as FPRP [11] and D-PRMA [34], assume that nodes have a GPS radio to maintain synchronization. Although GPS is effective and reliable at keeping nodes synchronized, GPS radios consume valuable battery power resources at each node when periodically receiving synchronization messages. Nodes using a CSMA [4] protocol also waste power through idle listening to a busy channel.

In all multiple-channel protocols with a flat topology, channels are assigned dynamically at each node. This represents control overhead and therefore wasted power for performing channel assignments. In these protocols nodes typically need to monitor different channels for availability, or to adopt a greedy approach in grabbing channels. Monitoring channels dictates that the node's transceiver is frequently active, thus wasting more power. In a greedy approach the chance of conflicts and collisions is increased since a node tries to grab channels that may already be used. A clustered topology typically reduces the chance of conflicts by limiting the number of nodes contending for channels and by assigning a portion of the control tasks to a cluster head.

SUMMARY

The extent to which each of the different power-saving mechanisms in this section actually conserves power is dependent on the application type. A multi-purpose protocol should include as many of these mechanisms as possible to ensure its power efficiency in different application scenarios, without adding overhead that would counterbalance the benefits of having these features.

TRANSMISSION INITIATION

Some protocols adopt a sender-initiated approach to transmissions; others select a receiver-initiated approach. The choice of a transmission initiation strategy is dependent on the types of applications that a network is expected to support. Historically, sender-initiated protocols were most common until recently. In the rest of this section, we discuss each of the two approaches, and we categorize protocols based on their transmission-initiation strategy.

SENDER-INITIATED

CSMA [4] was the first sender-initiated protocol, with the sender sensing the channel before transmitting. Many protocols that followed, such as MACA [7], MACAW [8], IEEE 802.11 DCF [1], FAMA [9], PAMAS [12], and GRIDB [29], adopted the RTS/CTS mechanism to overcome the hidden node problem in CSMA. The RTS/CTS handshake became a basis for many proposed protocols to come. This handshake is based on the assumption that senders should be the proactive entity in establishing communication, by indicating their intent to transmit data. This handshake was also adopted in many multiple-channel protocols to contend for and reserve available channels. PRMA [6], FPRP [11], SRMA/PA [23], ADAPT [18], CATA [19], Jin [20], DPRMA [34], DCA-PC [24], MMAC [33], and MC MAC [30] all use a sender-initiated handshake on a common control channel to attempt to reserve a particular data channel. Finally, HRMA [14] proposes a similar sender-initiated protocol that adds a Hop Reservation message prior to RTS/CTS. Sender-initiated approaches are more intuitive and more suited to generalized networks with unpredictable traffic patterns.

RECEIVER-INITIATED

In this class of protocols receivers poll their neighbors with a RTR message that indicates a node's readiness to receive data. The first such protocol is MACA-BI [10], which was primitive in nature. In MACA-BI a node sends a RTR message to its neighbors whenever it is ready to receive data. A polled node that has data to send can subsequently transmit to any node, not necessarily the polling node. RIMA-SP [17] adds the restriction that nodes can only send to the polling node, and that both nodes can send data once the handshake is complete. In RICH-DP [22], receivers use RTR messages to poll neighbors, but they do so to reserve the current frequency hop. RICH-DP also adds an ACK message that is issued by the receiver when it successfully receives a portion of data. The final receiver-initiated protocol we discuss, Lal [28], combines SDMA with a receiver-initiated approach, in which a receiver sends a RTR message omni-directionally and awaits a directional RTS message by potential senders.

A receiver-initiated MAC protocol yields better network performance for a specific class of ad hoc networks. In sensor networks, for example, the goal is to get data to a certain data sink. The particular source node of the data may not be important, as long as the data is from a certain region of the network. In this case, having a receiver poll its nodes for any available data is desirable. In networks where nodes have data to send often, a receiver-initiated approach also performs well since most RTR messages serve a useful purpose. This approach also has its shortcomings. By merely announcing its readiness to receive data, a receiver does not ensure that exactly one of the neighboring nodes will attempt to send data. Therefore, more recent protocols propose additional mechanisms such as frequency hop reservation or directional RTS messages to mitigate this problem.

SUMMARY

The appropriate transmission-initiation strategy of a protocol is highly dependent on the potential application areas of that protocol. For generalized networks, a sender-initiated protocol is more suitable. For some specialized networks, such as sensor networks, receiver-initiated protocols are a better choice.

TRAFFIC LOAD AND SCALABILITY

A majority of the surveyed protocols perform well for their intended applications. In this section, we examine scenarios for which protocols are optimized:
- High load
- High density
- Real-time traffic
- More selective scenarios

For each traffic load or type, we assess the scalability and adaptability of protocols to dynamic network conditions. Our discussion of performance is qualitative, based on parameters such as channel utilization, throughput, and delay.

HIGHLY LOADED NETWORKS

Receiver-initiated approaches operate well in networks where channel utilization is high. RICH-DP [22] and Lal's SDMA protocol [28] both achieve improved performance under high load. Since nodes send RTR messages whenever they are ready to receive data, there is a high probability that whenever a sender has data, it can find an appropriate receiver to relay its data. Since both of these protocols reserve channels (one does so in space and the other does so in frequency) for data transmission once the handshake is complete, they exhibit reduced collisions and increased efficiency. Both of these protocols are highly adaptive to varying network conditions, and both offer mobility support. The SDMA approach in Lal's protocol is especially effective at bottleneck nodes, where support for simultaneous multiple transmissions is desirable. Another SDMA protocol, MMAC [33], achieves higher throughput than IEEE 802.11 and is thus better suited for high-load networks. MMAC also has a lower end-to-end delay than IEEE 802.11. However, the performance of MMAC is topology-dependent, and more-aligned networks tend to degrade the performance of this protocol.

PS-DCC [16] also adapts well to high network load. Because it always calculates the sending probability based on current channel utilization, PS-DCC reduces collisions in the network when utilization is high by forcing individual nodes to wait for longer durations before transmitting. This technique clearly introduces increased transmission latency. If it is used with other channel separation mechanisms, this scheme becomes attractive in its simplicity and effectiveness. PS-DCC is also adaptive to the general network case, where nodes are moving around and topology changes are frequent.

GRID-B [29] is designed to manage areas in the network where the load is high, which are referred to as hot spots. By adaptively borrowing channels from a neighboring area, a hot spot can support the required load. ADAPT [18] is another protocol designed to handle high-load networks, since it allocates slots to each node statically. Borrowing unused slots allows nodes with a high traffic rate to have increased access to the channel. Neither GRID-B nor ADAPT are adaptive to a rapidly changing network topology or highly mobile nodes, due to their static assignments of resources. In GRID-B, high mobility might bring nodes out of the predefined geographic area for which the channels were initially assigned. Similarly in ADAPT, each slot has a pre-defined owner. New nodes that enter the network do not own any slot and thus have reduced priority, since they are only allowed to contend for other nodes' slots.

TDMA protocols are generally adaptive to highly loaded networks with periodic traffic, such as a voice-dominated network. These protocols, however, do not cope well with random data traffic, and are not scalable, since increased network size requires more nodes to contend for a fixed number of slots.

DENSE NETWORKS

Protocols that perform best for dense networks base their behavior on power considerations. Through transmission power control, GPC [25] and DCA-PC [24] limit the possibility of collisions among nodes. DCA-PC performs well in high mobility situations, as well as for larger networks. The only constraint on DCA-PC is to use few data channels in each vicinity and few power levels to avoid control channel overuse. As for GPC, it dynamically chooses forwarding agents based on battery power level, which avoids overusing the resources of a single node and thus promotes fairness in a dense network. Lal's protocol [28] and MMAC [33] also perform well in dense networks, through their use of directional antennas. Although these protocol are appropriate for both high-load and dense networks, which seems attractive, some issues relating to the economic feasibility of SDMA remain unresolved. GRID-B handles dense networks through its hot-spot mechanism in the same way it adapts to high-load situations. MCSMA [15] also offers a solution for dense but lightly loaded networks through its use of several frequency channels that are spatially reused within small distances. In a dense MCSMA network, the per-node bandwidth is reduced but the overall channel utilization of the network is increased.

VOICE AND REAL-TIME TRAFFIC

Some protocols are more suited for voice and real-time traffic. These protocols typically have two common attributes: priorities and reservations. To support priorities, a protocol must classify nodes or traffic into two or more classes. Each class typically has a certain priority level based on node features and the nature of the traffic. Reservations are usually allowed for higher priority traffic. PRMA [6] was designed to support voice communication in a data network over wireless. By allowing voice nodes to reserve slots for subsequent frames, PRMA ensures that once a voice node reserves a slot, it is guaranteed the needed bandwidth to maintain an acceptable quality of service. This protocol offers improved performance over pure TDMA, but it assumes there is a base station to maintain synchronization and resolve contentions. An improved adaptation of PRMA for ad hoc networks could be achieved by implementing it within a clustered topology, where a cluster head performs most base station functions. D-PRMA [34] adds a fully distributed flavor to the original PRMA by having nodes resolve contention for slots among themselves. D-PRMA performs well for periodic traffic networks. SRMA/PA [23] follows a similar approach to PRMA by designating nodes as voice and data terminals. Since it allows voice nodes to preempt data nodes, SRMA/PA favors voice nodes even more than PRMA. SRMA/PA also performs well in a network with many voice terminals.

The virtual based station (VBS) [26] is another protocol designed for voice and real-time traffic. After it is elected in a cluster, VBS allocates virtual circuits to nodes that request connections. Virtual circuits ensure a certain bandwidth allocation, which makes them suitable for supporting real-time traffic. The VBS protocol exhibits stable performance when it comes to VBS changes and cluster memberships, and it provides a mechanism for handovers between neighboring clusters, which supports mobility. However, this protocol focuses mainly on managing topology and clusters, and does not elaborate sufficiently on data transmission and related issues.

Markowski's window-splitting protocol [13] is also favorable toward real-time traffic by allowing hard real-time nodes to preempt soft real-time nodes that also preempt non real-time nodes. Because of its fully distributed nature, the window-splitting scheme can theoretically handle a large number of nodes of each traffic class. An increased number of senders, however, causes the active window to become too small, and that in turn causes increased transmission latency for many nodes. Thus, this protocol performs well in real-time traffic networks that are sparse and limited in size. It can also enforce a firm real-time traffic class, where a node attempts to send a packet for a few times as soft real-time, and if those attempts are unsuccessful, then it sends the packet as hard real-time.

More Selective Scenarios

There is a group of protocols that performs best when used in more specific situations, other than traffic deadline restrictions. For example, HRMA [14] performs well when packet sizes are large. Its performance degrades, however, when node density increases. In Jin's proposed protocol [20], low-power nodes get priority over high-power nodes. In a dense network with a large percentage of low-power nodes, high-power nodes may experience large transmission delays. However, if a network only has a few low-power nodes, high-power nodes experience tolerable transmission delays.

MC MAC [30] also has specific constraints for adequate performance. Although the number of usable codes is approximately 30, MC MAC proposes an optimal performance for a seven-code network to avoid overusing the control channel. The protocol also performs best for short-range applications. In MC MAC, a highly loaded network also causes a high access delay.

Protocols that perform well for more selective scenarios are unattractive for use in general ad hoc networks, which must support a wide set of applications

Summary

In short, multiple-channel protocols and power-efficient protocols exhibit better performance for high-load and high-density networks. TDMA and reservation-based protocols perform best for networks dominated by voice and real-time traffic. Protocols that perform well for selective scenarios are not suitable for a general ad hoc network.

Range

Some measures of a protocol's scale include transmission range, bandwidth, and spatial capacity. Transmission range is simply the radio coverage distance of a single node. Bandwidth is the channel rate upon which the protocol is implemented or simulated. Spatial capacity [47], also referred to as spatial efficiency, is a measure of the rate of information per square meter, and can be perceived as a density measure for a protocol. In this section, we classify protocols based on their proposed range of operation, and the implications that the range has for the applications of each protocol.

Table 2 shows a comparison of the scale of some of the surveyed protocols. The first six protocols from Table 1 are absent from this comparison since they were designed for wired or infrastructure networks. We also excluded other protocols from Table 1 from the range analysis because the related publications performed their simulation on logical network topologies with no specifications of distances. The remaining set of protocols contains currently implemented protocols and simulated protocols. For simulated protocols, the values are in direct relation to the simulation parameters. For example, in many of the simulated protocols, the channel bandwidth is 1 Mb/s, which directly affects spatial capacity. A lower underlying channel bandwidth places proposed protocols at a disadvantage relative to implemented protocols that typically use a higher channel rate. We obtained the spatial capacity for each protocol using the expression:

$$S = B/A \tag{1}$$

where A is the transmission coverage area and B is the aggregate throughput of all coexisting transmissions in A.

Some protocols specified the simulation coverage area. For protocols that did not specify this value, we used:

$$A = \Pi \times r^2 \tag{2}$$

where r is the transmission range of a single node. In Eq 2, A denotes the area of a circle around a particular node. For single-channel protocols, B is simply the maximum achievable throughput. For multiple-channel protocols of N channels, the expression for B is:

$$B = \sum_{i=1}^{N} b_i \tag{3}$$

where b_i is the throughput of the ith communicating node within the area A. Foerster [47] compares Bluetooth, 802.11a, IEEE 802.11b, and UWB radio according to spatial capacity and range. Here we compare additional MAC protocols along the same parameters. From Table 2 we observe a wide spectrum of different ranges and spatial capacities. While the range of MC MAC [30] is 4m, MACA-BI [10] deals with a range of 10 miles. The spatial capacity, from its expression in Eq. 1, is inversely proportional to the square range. The difference in spatial capacities of MC MAC and MACA-BI or RICH-DP [22] clearly displays this effect. There is a tradeoff between achieving high spatial capacity and radio coverage. High spatial capacity allows multiple nodes in spatial proximity to communicate with high throughput, whereas long-range protocols provide better mobility support.

Very Short-Range Protocols

MC MAC has the highest spatial capacity of the considered protocols, which is an efficient spatial use of the medium. Its range of 4m, however, limits its scope of applications to PANs or networks within a room. MC MAC achieves high spatial capacity through the use of multiple (seven) codes that can be reused even within the same room thanks to the limited radio coverage. In MC MAC, each node within a seven-node set has a unique channel, with a theoretical maximum of 2 Mb/s. MC MAC is therefore suitable for concurrent transmission of multiple multimedia streams in a PAN, such as in a wireless network of PCs and several multimedia devices.

Protocol name	Range (*m*)	Spatial capacity (*bits/sec/m²*)	Bandwidth (Mb/s)	Maximum neighbors
MC MAC	4	280000	2	7
Bluetooth	10	30000	1	70
MARCH	10	1600	1	5
MCSMA	10	637	1	13
DCA-PC	30	2500	1	6
DBTMA	35	260	1	20
IEEE 802.11a	50	83000	54	12
HIPERLAN	50	15000	23	5
IEEE 802.11b	100	1000	11	3
PS-DCC	100	151	2	200
D-PRMA	100	21	1	24
GRID-B	200	1000	1	50
MMAC	212	70	2	9
DPC/ALP	1000	11	11	20
RICH-DP	1600	1	1	8
MACA-BI	16000	1	1	9

Table 2. *Protocol scales.*

Another PAN protocol, Bluetooth [3], more than doubles the range of MC MAC, but its spatial capacity is almost one tenth. A piconet in Bluetooth supports one master and up to seven slaves, and 10 piconets can co-exist within a range of 10m for the low-power mode of Bluetooth [3, 47]. Each piconet achieves a rate of 1 Mb/s, which limits the applications of Bluetooth technology to connecting peripherals to a PC in a wireless fashion, streaming of voice or low-quality video, or transferring small files.

MARCH [21] is also simulated for a radio range of 10m, which makes it another candidate for PANs. The maximum number of allowable neighbors has not been explored for this protocol, but the topology used for simulation assumed a maximum of five neighbors. As expected, given that all the nodes share one medium, the spatial efficiency is low, almost 20 times less than Bluetooth. Applications for the MARCH protocol include relatively low-rate transmissions within a room. MCSMA [15] has an even lower spatial capacity than MARCH, thus limiting its potential application scope even more.

Short-Range Protocols

Short-range protocols extend the range of protocols in the previous section to cover a building-wide, or possibly a campus-wide, network. IEEE 802.11a provides the best spatial capacity in this category. It achieves a channel bandwidth of 54 Mb/s through its use of Orthogonal Frequency Division Multiplexing, which allows 12 stations to operate within a 50m circle with minimal degradation [47]. This high throughput makes IEEE 802.11a suitable for high-density networks and high-rate traffic such as multimedia and large file transfers.

HIPERLAN's [2] spatial capacity is approximately six times lower than IEEE 802.11a, due to the lower rate underlying channels and the fewer number of available channels. The spatial capacity in HIPERLAN is still suitable for dense high-rate, short-range network applications.

DCA-PC [24] achieves a lower spatial capacity than 802.11a, although it has a smaller range. The spatial capacity achieved is still at an acceptable level, making it suitable for average load and density networks in building-wide or campus-wide environments.

In the short-range category, DBTMA has the lowest spatial capacity among the surveyed protocols, since it uses only one channel for data transmission. DBTMA is therefore not suited for supporting many users in a small geographic area, because at any time, only one user gets access to the data channel.

These protocols support mobility to a certain extent. People walking around with their laptops or PDAs can remain on the network as long as they stay within a certain distance of an active node.

Medium-Range Protocols

Medium-range MAC protocols for ad hoc networks provide radio coverage on the order of 100m. Application scenarios for medium-range protocols are similar to those for short-range protocols, except that the medium-range class supports higher mobility. The extended range also decreases routing overhead by reducing the average number of hops in a path. On the other hand, it also reduces the ability to spatially reuse channels within the network.

Three of the five surveyed protocols in this category provide a 100m range for a single node. Among them, IEEE 802.11b [1] offers the best spatial capacity. One key factor in this protocol's superiority is the high-rate channel that it uses, since all other protocols in this class use a lower-rate medium. Given PS-DCC's [16] lower channel rate, it appears to offer an improved spatial capacity over IEEE802.11b, if we consider that spatial capacity and network behavior vary linearly with medium bandwidth.

GRID-B [29] doubles the range of IEEE 802.11b and has the same spatial capacity, although it also considers a channel rate of 1Mb/s. This is an indication that GRID-B is better suited for hot spots than IEEE 802.11b. Application of GRID-B is limited to known geographic areas, such as a conference in a hotel, where a heavy load is expected at different conference rooms at different times.

MMAC [33] has a slightly wider range than GRID-B. Because of the smaller number of nodes within a single hop, MMAC has a lower spatial capacity than GRID-B, PS-DCC, and IEEE 802.11b. We attribute the lower spatial capacity of MMAC to the fact that it depends solely on directional antennas for channel separation in its simulations. This channel-separation technique limits the number of coexisting channels within one hop and thus yields a lower spatial capacity.

The longer range of this class of protocols achieves more mobility support since nodes can better maintain connectivity to the network. Medium-range protocols offer limited support for inter-vehicular communications on a freeway, for example, with certain assumptions concerning vehicle traffic density and spacing.

Long-Range Protocols

Although not typical for ad hoc networks, there are some protocols that propose a range on the order of kilometers. The obvious leap in range results in lower spatial capacity than the previous classes. RICH-DP proposes a node range of one mile, and achieves a spatial capacity of one, while MACA-BI extends that range by 10 times and achieves the same spatial capacity.

Long-range protocols relax some of the mobility constraints that apply for short-range and medium-range protocols. Moving vehicles can set up and maintain an ad hoc network even when they are separated by a distance of one mile, or in MACA-BI's case, 10 miles. Control and management of the network, however, becomes more difficult in a wider coverage area, due to increased propagation delays and potential near-far problems that could arise when inter-node distances vary widely.

Summary

In this section we observed the tradeoffs required when increasing the range versus achieving a high spatial capacity. Protocols that manage to increase the transmission range while maintaining a high spatial capacity provide the highest utilization of the available medium.

CONCLUSION AND DISCUSSION

Ad hoc networks provide a distributed communications paradigm that can be extended to fit into the "anytime anywhere" concept of ubiquitous computing [41]. One major obstacle that impedes the proliferation of such networks is the tight regulation exercised on unlicensed communications, restricting frequency bands and bandwidth where ad hoc networks may be used. Whether this distributed model will be applied to a broader range of networks and become dominant in the coming years remains to be seen. This will also depend in part on regulatory issues. The other challenge toward the development of ad hoc networks is the design of efficient self-management protocols. In our survey of ad hoc network MAC protocols, it has become evident that the overwhelming majority of these protocols were derived heuristically and were aimed at optimizing a particular set of measures under a particular set of operating conditions. However, most of these heuristics lacked generality and were not tested in a deployed network. Establishing a principled framework for optimizing ad hoc network behavior is challenging since there is clearly a wide range of applications and potential physical-layer technologies that have different considerations. To address both of these issues, we propose integrating a flexible high-level cost function [40] into the MAC layer. This will allow the network to optimize cost based on the requirements of various settings. The cost function equips the MAC protocol with the means to exercise admission control and coordinate effectively between the physical layer and higher layers. A promising direction for future work would be to integrate the cost function into an ad hoc network MAC protocol that follows suitable guidelines. We derive these guidelines in the following, based on the classification presented in this work.

From our earlier discussion we conclude that a general-purpose MAC protocol must support multiple channels in order to separate control from data and reduce the probability of collisions. The need for multiple channels and the highest possible throughput implies that CDMA is the optimal choice for a channel-separation method, since it uses all of the medium all of the time. The protocol must use a limited number of codes, because too many data channels typically result in an overused control channel. Note that in a technology such as UWB, multiple channels are implicitly present thanks to time-hopping codes. We suggest that a suitable general protocol should adopt a multi-hop topology to ensure scalability. The protocol should also support a flat mode and a clustered mode depending on application requirements. From our earlier discussion we learn that a power-efficient ad hoc network MAC protocol requires that nodes be power-aware, control transmission power, and support sleep mode only when they are in a sufficiently dense area of the network. Based on discussion of transmission initiation, a sender-initiated approach ensures maximum flexibility for this MAC protocol. Finally, we propose that the optimal range for our generalized protocol should be in the short to medium range, so that it can support a wide scope of applications. The reason for not recommending a long-range network is that in a long-range network control becomes more difficult and collisions more frequent. This set of design choices provides a basis for a protocol that is sufficiently flexible and scalable and performs well for high-load and high-density situations.

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