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Energy-efficient MAC layer protocols in ad hoc networks

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Contents

1 Introduction

A mobile ad hoc network (MANET) is defined as an autonomous system of mobile routers (and their associated hosts) connected by wireless links - the union of which forms an arbitrary graph. It is characterized by fast deployment, dynamic multi-hop topology, self-organization without typical infrastructure support, etc. These properties are desirable in situations such as battlefields, where network connectivity is temporarily needed, or fixed infrastructures are unavailable, expensive, or infeasible to deploy. However, wide deployment of MANET has not come yet due to many technical challenges, among which energy issue is a fundamental one. Typical wireless devices are powered by small-sized batteries, whose replacement is very difficult or even impossible in some applications (e.g. disaster relief operation). Therefore, power conservation is one of the most important design considerations for MANET. It has attracted a large number of researchers in recent years [3].

Power conservation in an ad hoc network is the procedure of determining the transmit power of each communication terminal such that a design objective (e.g. network lifetime, throughput, etc.) can be satisfied. There are two major reasons for transmit power control. First, transmitting at a high power may increase the interference to co-existing users and therefore degrade network throughput. Power saving mechanisms have been shown to be able to decrease multi-user interference, and hence increase spatial channel reuse and the number of simultaneous single-hop transmissions. One direct benefit of this increase is the enlarged overall traffic carrying capacity of the network [27]. Second, energy-efficient schemes can impact battery life, consequently prolonging the lifetime of the network. Current power control mechanisms include low-power wireless access protocols, power-aware routing for ad hoc and sensor networks [60] [51], and node-level energy-efficient information processing [16]. In this paper, we will focus on energy aware MAC (Media Access Control) layer protocols for ad hoc networks.

MAC layer is the sublayer of the data link layer that is responsible for coordinating and scheduling of transmissions among competing nodes. As claimed by [63], MAC protocols could significantly reduce the power consumption of mobile terminals in MANETs. The energy-aware MAC protocols in a multi-hop self-organizing mobile ad hoc network must simultaneously satisfy the following three objectives. First, MAC protocols should facilitate the creation of the network infrastructure. Second, MAC protocols are in charge of fairly and efficiently sharing the wireless channels among a number of mobile terminals. In MAC layer channel scheduling, packet collision among different users should be reduced or even completely avoided, and the bandwidth should be fully-utilized. These two goals are conflicting with each other. Therefore MAC protocols should be carefully designed to balance them based on network requirements. Third, MAC protocols should be energy-aware for extending battery lifetime. Supporting power management to save energy is required for battery-powered mobile nodes in MANETs. Actually, this is the motivation of our paper. The power conservation mechanisms for MANETs also must support multi-hop forwarding. They should be distributed, as there is no centralized control to rely on.

The remainder of this paper is organized as follows. In Section 2, we identify major sources of energy waste in MANETs and discuss low-power MAC design principles. From Section 3 to section 8, we survey and analyze different energy-aware mechanisms together with their applications in energy-aware MAC protocols. The techniques covered include channel reuse, power controlled scheme, power off mechanism, dual channels, and antenna-based power efficient schemes. Detailed analysis and comparison will also be given. We conclude this paper in Section 9.

2 Sources of power waste and low-power MAC design principles

2.1 Major sources of energy waste

The major sources of power waste in mobile computing devices include radio communication and data processing, with radio communication often being the dominate source of energy consumption. Data processing involves the usage of CPU, memory, hard drive, etc. Its energy consumption is relatively negligible compared with that of the radios. The energy expenditure in radio communication includes the power consumed by transmitting and receiving devices of all nodes along the path from source to destination, together with their neighbors that can overhear the transmission. Actually, there is a tradeoff on energy consumption between data processing and radio communication, the two energy consuming factors [33]. For example, data compression techniques are introduced in [13] to reduce packet length and therefore achieve energy saving in radio communication, but the cost of computation is increased.

Let's first take a look at the characteristics of energy consumption in a radio interface so that we can easily understand the motivations of the energy efficient mechanisms discussed in the following sections. In mobile ad hoc networks, communication related energy consumption includes the power consumed by the radios at the sender, receiver and intermediate nodes in the route from the source to the destination. Actually, at any time a mobile node in MANETs must be in one of the following four modes: transmit, receive, idle listening, and sleep. When a node is in transmit or receive mode, it is transmitting or receiving a packet. Idle listening mode means the node is neither transmitting nor receiving a packet, but is doing channel monitoring. This mode consumes power because the node has to listen to the wireless medium continuously in order to detect the arrival of the packet that

Table 1: LUCENT IEEE 802.11 WAVELAN PC CARD (2Mbps) CHARACTERISTICS

Modes	Energy Consumption
Sleep Mode	14 mA
Idle Mode	178 mA
Receive Mode	204 mA
Transmit Mode	280 mA

it should receive, so that the node can switch to receive mode [45]. When in the sleep mode, nodes do not communicate at all. Receive and idle mode consume similar amount of power, while transmit mode requires slightly larger amount. Nodes in sleep mode consume extremely low power. As an example, we illustrate the energy consumption of different modes for the 2.4GHz DSSS Lucent IEEE 802.11 WaveLAN PC "Bronze" (2Mbps) wireless network interface card [21] in Table 1. Note that mobile ad hoc nodes must keep on monitoring the media for possible data transmission. Thus most of the time nodes must be in idle listening mode instead of sleeping. Actually, a network interface operating in ad hoc status has a constant idle power consumption, which reflects the cost of listening to the wireless channel. Many measured results have shown that the energy spent by idle listening is 50$\sim$100% of that by receiving. In other words, idle listening consumes only slightly less energy than actually receiving traffic. Thus, significant energy is consumed even when there is no traffic in the MANETs. Further, the energy expenditure for the radio interface to transit from one mode to anther is not negligible because the transition time can not be infinitesimally short. For example, the transition between transmit and receive modes typically takes 6 to 30 μs, while the transition from sleep to transmit or receive generally takes even more time (250 μs) [29]. Mode transitions have significant impact on energy consumption of wireless nodes.

Besides the power consumption in transmit, receive and idle listening, there exists other significant energy expenditure in packet retransmission, node overhearing and protocol overhead [62]. Retransmission is caused by collision. When a packet is corrupted, it must be discarded and transmitted again. Retransmission increases energy consumption. In fact, due to the lack of a centralized authority in mobile ad hoc networks, transmissions of packets from distinct mobile terminals are more prone to overlap, resulting in more serious packet collisions and energy loss. Overhearing means a node picks up packets that are destined for other nodes. Wireless nodes will consume power unnecessarily due to overhearing transmissions of their neighboring nodes. Protocol overhead is generated by packets dedicated for network control and header bits of data packets. It should be reduced as much as possible because transmitting data packet headers or control packets also consumes energy, which results in the transmission of less amount of useful data packets.

2.2 Low-power MAC design guidelines

As stated in Subsection 2.1, the major energy waste comes from idle listening, retransmission, overhearing and protocol overhead [62]. Thus there is no wonder why all power-aware MAC protocols try hard to reduce energy waste from one or all of the above sources. To make a MAC protocol energy efficient, at least one of the following design guidelines must be obeyed:

- **Minimize random access collision and the consequent retransmission**

Collisions should be avoided as far as possible since otherwise the followed retransmission will lead to unnecessary energy consumption and longer time delay. Actually, one of the fundamental tasks of any MAC protocol is to avoid collisions so that two interfering nodes do not transmit at the same time. The simplest ways for collision avoidance in a general network include code division multiple access (CDMA), time division multiple access (TDMA), and frequency division multiple access (FDMA). However, for mobile ad hoc networks there exist many special issues that need to be addressed for a MAC protocol design. For example, because of the nonexistence of fixed base stations in MANETs, mechanisms to avoid collision among mobile nodes must be distributed. Since collision avoidance may result in substantial overhead, which will burn more energy, tradeoffs must be explored to achieve reasonable solution. Further analysis on channel reuse mechanisms based on scheduling will be given in Section 3. Such schemes are designed to increase the channel utility and at the same time to avoid collisions.

- **Minimize idle listening**

In typical MANET systems, receivers have to be powered on all the time. This results in serious energy waste. Since the power consumed in idle listening is significant, as indicated in Subsection 2.1, we should pay attention to the energy conservation in nodes other than the source and destination. Ideally the radio should be powered on only when it needs to transmit or receive packets, thus remove the unnecessary monitoring of the media. Recently, energy-aware MAC protocols that require nodes be in sleep mode periodically for energy conservation have been proposed. When in sleep mode, nodes neither transmit nor receive packets; but they must be woken up to idle mode first for attending traffic relay. Sleep mode requires more than an order of magnitude less power than idle mode. Hence, intelligently switching to sleep mode whenever possible will generally lead to significant energy saving. This topic will be addressed in detail in Section 5.

- **Minimize overhearing**

Wireless nodes consume power unnecessarily due to overhearing the transmissions of their neighbors. This is often the case in a typical broadcast environment. For example, as the IEEE 802.11 wireless protocol defines, receivers remain on and monitor the common channel all the time. Thus the mobile nodes receive all packets that hit their receiver antennae. Such scheme results in significant power consumption because only a small number of the received packets are destined to the receiver or needed to be forwarded by the receiver. One solution to this problem is the introduction of a control channel for the transmission of control signals that will wake up the nodes only when needed. Such dual channel mechanism will be discussed in Section 6. Another solution for overhearing avoidance is to power off interfering nodes after they hear an RTS or CTS packet [62]. [54] proposes to broadcast a schedule that contains the data transmission starting times for each mobile nodes.

- **Minimize control overhead**

Protocol overhead should be reduced as much as possible, especially for transmitting short packets [62]. Due to the large channel acquisition overhead, small packets have disproportionately high energy costs. Header compression can be used to reduce packet length, thus achieving energy savings. Since significant energy is consumed by the mobile radio when switching between transmit and receive modes, packet aggregation for header overhead reduction will be useful. When mobile nodes request multiple transmission slots with a single reservation packet, the control overhead for reservation can be reduced. Allocating contiguous slots for transmission or reception to reduce the turnaround also helps to achieve low power consumption [11].

- **Explore the tradeoff between bandwidth utilization and energy consumption**

As stated by [21], energy consumption and bandwidth utilization are substantively different metrics. But they are strongly related to each other. To conserve power, its radio must be turned off if the node does not participate in the traffic dissemination, as the energy spent in receiving and discarding packets (this happens when overhearing and idle listening) is significant. Further, to shun the energy consumption resulted from packet retransmission, a node need to be powered off if the media is busy. This greatly decreases the channel utilization, thus decreases network throughput. Therefore, the tradeoff between the bandwidth utilization and energy consumption must be exploited for throughput improvement. Scheduling the channel efficiently among neighboring nodes is a challenging problem.

To design a good MAC protocol for MANETs, designers must take into account energy, bandwidth, delay, channel quality, etc.. Other factors that play important roles in power-aware MAC protocol design include network-wide traffic pattern (broadcast versus point to point traffic, short packet vs. long packet, etc) and per node operation mode (promiscuous mode vs. non-promiscuous mode). Different tradeoffs must be explored based on application requirement (operation time, availability of infinite power supply, etc.) such that multiple factors can be considered together. We can simplify the design goal of power-controlled MAC protocols as follows: to increase the overall network throughput while maintain low energy consumption for packet processing and radio communication. We will discuss different mechanisms for power-controlled MAC protocols in detail in the following sections. All of them are trying to achieve the above goal.

3 Scheduling-based mechanism

From the above analysis, we know that collisions occurred in MAC layer is one of the major sources of energy waste in mobile ad hoc networks. Therefore, reducing or avoiding the data link layer collision is the first issue we should consider in power-controlled MAC protocol design. This is the motivation of the scheduling-based mechanism for low power MAC. The simplest techniques in this category include frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA). Such classification is based on the domain in which the channel resources are shared by multiple simultaneous transmissions, as shown in Figure 1. FDMA divides the available frequency band into multiple non-overlapping channels. Nodes access the media at the same time but operate on different frequency channel. On the other hand, TDMA allocates

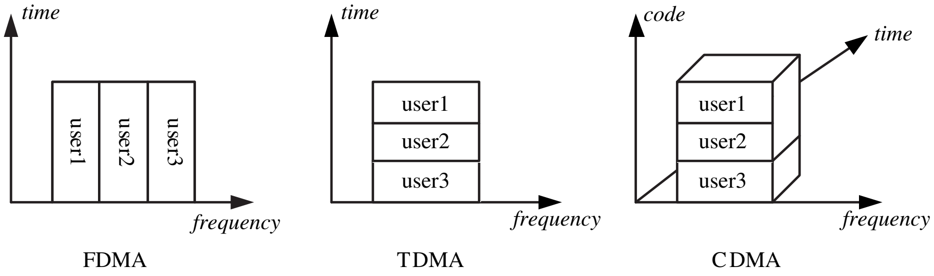

Figure 1: FDMA/TDMA/CDMA

different time slot to each user. Nodes share the same frequency band but access the media at different time slot. CDMA relies on orthogonal codes. Simultaneous transmissions can coexist on the same frequency channel at the same time if each is assigned a unique code. These three techniques have been well studied in literature. FDMA is applied to the first-generation mobile system, while TDMA and CDMA are widely used as the multi-access scheme for the second-generation system. Now, CDMA seems to attract the most attention in research. Actually, it has been shown that the capacity provided by CDMA is up to six times of that by TDMA/FDMA-based solutions [23]. Thus in this paper, we will put more effort on CDMA ad hoc networks. We will talk about the motivation of scheduling-based MAC protocols in Subsection 3.1. Then we will discuss the three techniques together with their applications in mobile ad hoc networks in Subsections 3.2– 3.4. Example scheduling-based low power MAC protocols for ad hoc networks will be examined in Subsection 3.5.

3.1 Motivation

With the introduction of FDMA, TDMA, and CDMA, wireless links occupied by different transmissions can be maintained active at the same time without collision. The scheduling in frequency, time, or code domain, is essential to coordinate the transmissions of independent users. This mechanism assigns each user a predetermined and fixed portion of the wireless bandwidth resource. Such scheduling-based assignment can eliminate the interference among different users. With scheduled access, each node can only transmit with the pre-assigned frequency or code, or at the pre-assigned set of slots. Therefore no collision in the MAC layer can occur. In this way, energy waste due to packet retransmission can be avoided. Another direct benefit of collision avoidance is the improvement of network throughput and effective channel utilization. Further, in TDMA, since nodes know their schedules ahead of time, they can simply turn off their radios to save energy if it is not the time for them to grep the channel. Thus the chance of overhearing and idle listening can greatly decreased, and the corresponding energy expenditure can be reduced too.

Compared with random access MAC protocols, in which nodes contend for the channel resource whenever they have packets to send, scheduling-based MAC protocols can achieve better energy conservation due to collision avoidance. However, the complicated control involved in the setup and maintenance of a schedule may compensate the saved energy obtained from collision avoidance, if it does not exacerbate the energy consumption. On the other hand, scheduling-based MAC protocols may not work well for bursty traffic, as the schedules are fixed, regardless of the user's real need. Another restriction on the application of these techniques is the topology dynamism. Scheduling-based protocols require that the network topology remains stable or changes slowly such that a schedule can effect for longer time to compensate the high setup overhead. Thus, they cannot be applied to highly mobile or other dynamic environments directly [25].

3.2 CDMA ad hoc networks

3.2.1 CDMA

CDMA is based on direct sequence spread spectrum (DSSS) encoding technique. In a typical CDMA system, all users share the same frequency, but each sender-receiver pair is assigned a unique pseudo-random noise (PN) code [48]. Data packets are *xor*-ed with the PN code before transmission and then *xor*-ed again with the same PN code at the intended receiver to ensure the correct decoding. When each signal is assigned a distinct PN code, several coded messages can simultaneously occupy the same channel.

CDMA improves the overall system capacity by making it possible for several independently coded signals to occupy the same channel. Thus multiple users can "coexist" and transmit simultaneously with minimal interference. This feature is crucial for networks with bursty traffic, high node density, and asymmetric transmission ranges. CDMA can effectively average the interference across transmissions at different spatial scales, hence enhance capacity and relax power control requirements. For example, by using CDMA, the channel efficiency has been improved by a factor of 4 with respect to TDMA in the Qualcomm cell phone. And as mentioned earlier, CDMA has been shown to provide up to six times as large as the capacity of TDMA or FDMA based solutions [23]. CDMA can also protect users from outside interference and jamming. Some other desirable features of CDMA include signal degradation, multi-path fading resistance, and frequency diversity [41].

However, there are also some deficiencies. First, CDMA degrades network throughput for bursty traffic. Orthogonal codes may be wasted when users have no data to send. Second, CDMA can not avoid idle listening. Nodes must keep on sensing the channel to receive possible traffic. As mentioned earlier, such idle listening consumes a large amount of energy. Third, data transmission rate is limited.

3.2.2 CDMA ad hoc networks

In a CDMA ad hoc network, mobile nodes serve as CDMA transceivers. This topic has been extensively studied in recent years. As claimed by [56], analysis of a CDMA ad hoc system is quite difficult due to the uncoordinated behavior of nodes. In [6], the performance comparison between centrally-controlled and ad hoc CDMA wireless LAN networks is presented; while in [7], the performance comparison between CDMA ad hoc networks and cellular networks is given. The results show that for the same spreading gain and error control coding, CDMA ad hoc systems have higher throughput and shorter packet delay than centrally-controlled CDMA wireless LAN and cellular networks under light traffic load; however, cellular networks and centrally-controlled ad hoc systems outperform CDMA ad hoc networks when the traffic is heavy.

The advantages of CDMA in ad hoc networks are summarized in the following:

- Capacity improvement. By increasing the number of successful receptions at the link-layer, the capacity of ad hoc networks is enhanced.
- Energy saving. CDMA improves parallelism, thus decreases the possible delay a node must go through when waiting for grabbing the channel. This helps to decrease idle listening. On the other hand, predetermined schedules result in collision avoidance, which helps in reducing energy consumption.
- Routing overhead reduction. It is easy to implement multi-path routing in CDMA ad hoc networks, which reduces the overhead significantly.

However, CDMA ad hoc networks still face quite a few challenges:

- Near-Far effect [46]. When cross-correlations between different CDMA codes are non-zero, the induced multi-access interference results in collisions at the receiver. This problem can cause a significant reduction in network throughput, thus it must be carefully considered. When combined with power control issues, things become even more complex. Since each terminal can communicate with several other nodes simultaneously in ad hoc networks, the transmit power must be controlled to avoid overhearing in near-far situations.

- Code design. Distinct codes are required for different communication parties. Thus a spreading-code protocol is needed to decide which code to use for packet transmission and which to use for monitoring the channel in anticipation of packet reception [56]. Such problem is usually formulated as Graph Coloring, a well-known NP-complete problem.

- Recoding. Due to the topology dynamism of ad hoc networks, recoding is necessary. Otherwise collisions may happen. However, recoding brings about additional overhead on channel acquisition at the receiver side and synchronization between the sender and the receiver. Such process is expensive and must be minimized as well [26].

3.3 TDMA

In TDMA systems, the time axis is divided into a number of frames with fixed length. Each frame is further divided into a number of time slots. A user can only transmit in the pre-assigned time slots. By this way, interference from neighboring nodes is reduced. Compared with random access MAC protocols, TDMA protocols is advantageous in energy conservation. This is because dedicated time slots for each user have been pre-determined. Therefore collision and the corresponding overhead can be avoided.

However, the scalability of TDMA is not as good as that of random access scheme [62]. Applying TDMA protocols in wireless systems usually require all nodes to form real communication clusters, such as in Bluetooth and LEACH [30]. The control of inter-cluster communication and interference is complex, especially when nodes are mobile as in MANETs. Further, TDMA requires the sender and receiver to be perfectly time-synchronized, which is not trivial. Designers need to consider factors such as the timing difference, clock shift, propagation delay, etc..

3.4 FDMA

FDMA is a technology that transmits multiple signals simultaneously in time domain. Each signal only occupies a portion of the entire available bandwidth. The basic idea is stated as follows. The spectrum is divided into many channels using discrete frequencies, called *subcarriers*. Different terminals are allocated a different number of subcarriers, depending on their data rate requirement. By this way, all terminals can transmit simultaneously without collision.

Orthogonal Frequency Division Multiplexing (OFDM) is an emerging modulation scheme. OFDM distributes the data over a large number of carriers that are spaced apart at precise frequencies. This spacing prevents the demodulators from seeing frequencies other than their own. Such a design results in high spectral efficiency, which is important to the limited wireless resources. The IEEE 802.11a standard uses OFDM in the 5.8-GHz band [70]. OFDM has also been included in the standardization for 3G systems [71].

3.5 Related protocols

3.5.1 CA-CDMA

In [41], a novel *Controlled Access* CDMA (CA-CDMA) protocol is proposed to solve the notorious near-far problem for CDMA ad hoc networks. In CA-CDMA, all nodes use a common spreading code in the control channel to contend for the channel resource with a modified RTS/CTS mechanism. Data packets are transmitted in the data channel encrypted with different terminal-specific codes. By using two non-overlapping frequency bands, it is easy to get a code in the control channel orthogonally with each code in the data channel. Hence, nodes can transmit and receive at the same time over the control and data channels no matter how much the signal power is. This makes it possible to allow interfering nodes to transmit simultaneously. CA-CDMA adjusts the transmitting power according to the channel-gain information so that concurrent transmissions are possible. Figure 2 shows the code assignment scheme used in CA-CDMA [41]. The results show that CA-CDMA can improve the network throughput by 280% and save 50% energy consumption when compared with IEEE 802.11.

Energy savings are achieved in CA-CDMA by using orthogonal codes to achieve the goal of channel reuse. Based on the orthogonality between the control channel and the data channel, concurrent transmissions are made possible such that the throughput is improved with the same or less energy

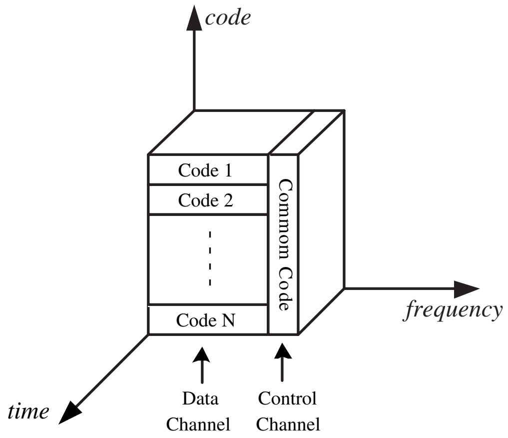

Figure 2: Code Assignment in CA-CDMA

consumption. In fact, CA-CDMA utilizes power control and dual channel mechanisms, which will be discussed in detail in the following Sections 4 and 6.

3.5.2 Energy-efficient MAC based on CDMA/TDMA

In [32], a MAC protocol based on CDMA/TDMA for energy-limited single-hop ad hoc networks is proposed. The main idea is based on the observation that radio module consumes more power in transmission mode than in reception mode, and the least power in sleep/idle mode. The motivation is to inform each terminal through MAC layer control when to wake up from sleep mode and when to sleep from transmission/reception mode in order to save battery power. This motivation is similar to that of the power control mechanism to be discussed in the following section. In this protocol, such a design objective is achieved by a scheduling and reservation method based on CDMA/TDMA.

There are two different kinds of mobile terminals defined in this MAC protocol: a pseudo base stations (PBS) and normal mobile nodes. The PBS is introduced to emulate a base station (BS) in infrastructure networks. It is responsible for the centralized control of collecting requests from mobile terminals and allocating CDMA codes and TDMA slots. The protocol is sketched below. The PBS first broadcasts synchronization message to all the other terminals at the start of each frame. Terminals with packets to deliver must send request and power level update messages to the PBS in the request/update/new mobile phase. New terminals register themselves with the PBS. Next the PBS broadcasts the scheduling information containing TDMA slots and CDMA codes whose assignment is based on the priority and battery level of each wireless node. After exchanging information during these three control phases, terminals communicate directly with no mediation from the PBS. Since data transmission in the communication phase uses only pre-assigned CDMA codes and TDMA slots, no collision will occur.

The transmission procedure in the proposed MAC protocol is based on frames controlled by PBS. In the frame synchronization phase, all normal mobile terminals are in reception mode while the PBS is in transmission mode. In the request/update/new mobile phase, nodes with no traffic to send sleep. But in the scheduling phase, all nodes must be waken-up for the reception of the schedule. A node can sleep again if it is not the source and target of any traffic. This strategy avoids the idle listening and overhearing for a traffic-free mobile. But the overhead incurred at the three control phases consumes non-negligible power. On the other hand, the schedule for data transmission ensures collision free communication, which reduces the energy for packet retransmissions. The direct data traffic between mobile nodes is independent of the PBS, further saving energy.

PBS plays an important role in power conservation. First, The PBS selection/reselection is based on battery power. Only high power node can serve as the PBS. Second, the scheduling is based on the power level of each normal terminal. Nodes with lower power have higher priority in allocating radio resources. This can effectively reduce the possibility of early termination of low power nodes. By this way, the battery energy of high power terminals is shared within all nodes and the network lifetime is extended. Simulation results show that this protocol can effectively protect mobile terminals from collision and retransmission when traffic is heavy. Low power terminals work better than high power nodes, especially in energy efficiency. However, with the centralized control by the PBS, this protocol can only support single-hop wireless ad hoc networks.

4 Power Control Techniques

Besides scheduling-based schemes, all remaining MAC mechanisms are contention-based (also named random access MAC), since mobile nodes must contend for the channel resources before transmission. Such contention schemes provide a simple but robust method for mobile nodes to efficiently share wire-

Figure 3: 802.11: Spatial reuse with CSMA/CA

less links and are especially suitable for the dynamic topology of MANETs. The introduction of contention, However, also means additional power for channel sensing, ACK schemes, retransmissions etc. Thus, conservations mechanisms are especially important to the design of contention-based MAC protocols. From this section on, we will focus on some mechanisms for energy conservation in contention-based MAC protocols. First, we will discuss the power control mechanism which allows nodes to modify the transmission power levels for network capacity improvement.

4.1 Mechanism

The most widely used MAC protocol in MANETs is the IEEE 802.11 DCF (CSMA/CA+ RTS/CTS) mechanism. In 802.11, mobile nodes try to avoid collisions with carrier sensing before transmission. If the channel is busy, the node will defer transmission and enter into backoff state. Otherwise, the nodes will begin the RTS/CTS dialog process to capture the channel and then transmit the packets.

The CSMA/CA scheme effectively reduces the amount of possible collisions. The RTS/CTS is also helpful since it will reserve the channel spatially and temporarily. RTS/CTS exchange is helpful in avoiding hidden terminal problem, since any node overhearing a CTS message cannot transmit for the duration of the transfer. However, this process severely limits available bandwidth. Measurements show that the flow can only obtain about 2% of available bandwidth. Actually, such artificial restrictions may bring about a waste of the wireless link resources. For example, in the following examples (Figure 3), the two data flows are compatible, but this is not allowed by the CSMA/CA scheme [72].

Hence, a new kind of energy conservation scheme is proposed to reduce the active link power levels to minimum values so that more than one link can access the channel simultaneously thereby excluding the prevention from parallel transmission by CSMA. The low power transmission scheme can help increase network capacity. Furthermore, such a scheme can also increase the battery mean life time, since each node only acquires the minimum transmission range needed to reach its counterpart and hence consumes less energy. In the following section, we will detail how the minimal power level can be found and applied.

The first benefit is the energy conservation when every node tries to transmit at the minimal level. This brings another benefit of spatial reuse improvement of the wireless channel, by letting more users transmit at the same time. Thus the network capacity is improved. And thirdly, by reducing the power to a minimal level, the transmission range needed is also reduced to the minimal one, thus helping in avoiding some unnecessary overhearing and reducing co-channel interference with neighboring nodes. All the above benefits help achieve the goal of energy savings in the MAC layer.

However, such a scheme will result in an inherent asymmetry. Poojary et al. [47] investigated the system performance using the IEEE 802.11 MAC protocol in which different nodes may transmit at different power levels. Results show that such scheme can lead to unfairness, since low power nodes may be overwhelmed by the higher power nodes in accessing and using channel resources. Collisions may also happen and in some cases may degrade the performance. This is even worse when the mobile nodes are of high density. A simple idea to overcome this deficiency is to broadcast CTS or its variation multiple times such that more nodes clear the channel for the initiating node, as proposed by [47]. However, simulation study shows that the potential gain of this strategy is outweighed by the corresponding overhead.

Another problem is that such multiple power levels scheme may cause additional collisions (Figure 4, [20]). When node A transmits with a low power level, node A may not detect the transmission and hence possible collision may occur because of the interference between the transmission from a to b and from A to B. This may be solved by using adaptive power control loop scheme [1], which adjusts transmission power adaptively according to a weighted history data. Another solution is to use an optimal common transmit power level for the whole network instead of per-node transmission power levels. COMPOW is one such example [43].

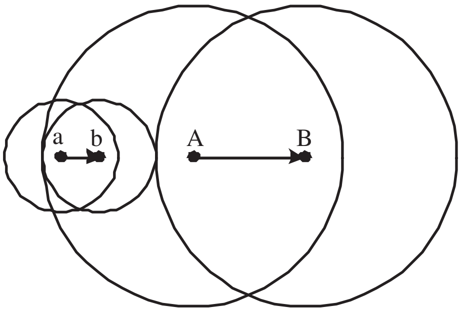

Figure 4: Problem with different power levels

4.2 Related protocols

4.2.1 PCM

A Power Control MAC (PCM) protocol is proposed in [34] to allow per-packet selection of transmit power. In PCM, RTS/CTS packets are transmitted with a max power level, P_{max}. But for data packets, they are transmitted with a lower power level. In order to avoid a potential collision caused by the reduced carrier sensing zone, during the DATA packet transmission PCM periodically increases the transmission power to p_{max}. ACK packets are transmitted with the minimum required power to reach the source node. Figure 5 shows the power level used in PCM.

By periodically increasing the power level for data transmission, PCM effectively reduces the amount of possible collisions. This way, retransmission is avoided as much as possible, and correspondingly, the goal of energy savings is achieved. Results show that PCM can achieve a throughput comparable to the IEEE 802.11 but with less energy consumption. However, PCM requires a frequent increase and decrease in transmission power levels, hence the implementation is not easy.

4.2.2 PCMA

The Power Controlled Multiple Access (PCMA) Protocol [40] proposes a flexible "variable bounded power" collision suppression model and allows variable transmit power levels on a per-packet basis. Similar with IEEE 802.11, PCMA uses RPTS/APTS handshake to determine the minimal transmission power required for successful packet reception. The difference lies in that PCMA introduces a second channel, the busy tone channel, to implement the noise tolerance advertisement. During data transmission pe-

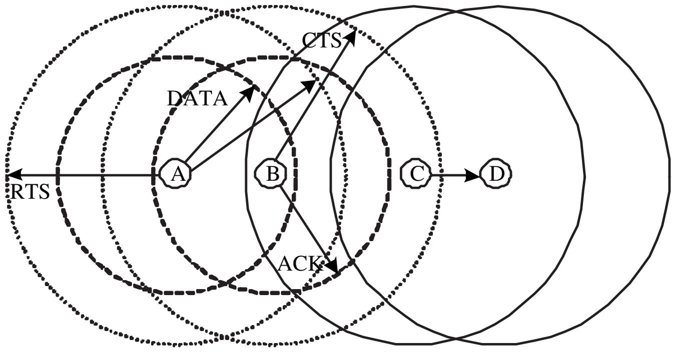

Figure 5: PCM Scheme: Data packets are transmitted with a periodically increased power level

riods, each active receiver will periodically send a busy tone to advertise the maximum additional noise power it can tolerate. Any potential transmitter must first sense the channel for busy tones to determine the upper bound of its transmit power for a minimum time period (determined by the frequency with which the busy tones are transmitted). Actually, PCMA uses the signal strength of a received busy tone message to bound the transmission power of neighboring nodes. This way, power control mechanism is realized and spatial reuse is achieved.

PCMA works effectively in energy conservation since it allows more concurrent data transmission compared with IEEE 802.11 standard by adapting the transmission ranges to be the minimum value required for successful reception on the receiver side. Results show that PCMA can improve the throughput performance by more than a factor of 2 compared to the IEEE 802.11 for highly dense networks. The throughput gain over 802.11 will continue to increase as the connectivity range is reduced. What's more, the power controlled transmission in PCMA helps increase channel efficiency at the same time preserving the collision avoidance property of multiple access protocols.

Energy efficient mechanisms using busy tone is discussed in Section 6. Similar to PCMA, [67] also uses the power control schemes with busy tone.

4.2.3 DCA-PC

A Dynamic Channel Assignment with Power Control (DCA-PC) is proposed in [66]. Similar with PCMA, this power control protocol uses one control channel to transmit all the control packets (RTS, CTS, RES etc). The difference is that multiple data channels are assigned on demand. In DCA-PC, the pair of source and destination nodes uses a RTS/CTS dialogue to decide which channel to grab and which power level to use for data transmission. A RES message is used to reserve the data channel. Then data packets and ACKs are transmitted on the reserved data channel using the assigned power level.

In DCA-PC, all the control packets are transmitted with a maximal power level in order to warn the neighboring nodes of the communication. The data packets are transmitted with proper power levels for channel reuse. Results show DCA-PC can achieve a higher throughput with the same energy consumption compared to DCA [65] protocol, which includes no power control mechanisms.

DCA-PC is the first protocol to realize the mechanisms of power control and multi- channel medium access together in MAC protocols of MANETs. By using multiple channels, it is easier to increase the throughput, reduce normalized propagation delay per channel, and support quality of service. We discuss the multi-channel scheme for energy efficient MAC in the following Section 6.

4.2.4 PCDC

The Power Controlled Dual Channel (PCDC) Medium Access Protocol [42] also uses two channels like PCMA, one control channel and one data channel. However, PCDC is the first to utilize the inter-layer dependence between the MAC and network layers to provide an efficient and comprehensive power control scheme. The idea is based on the observation that the transmission power has direct impact not only on the floor reserved for the next transmission but also on the selection of the next hop node. Hence, the interaction between the MAC and network layers can help for an effective power control scheme. In order to select the lowest possible power level while maintaining the network connectivity and proper MAC function, PCDC uses a distributed algorithm to compute a minimal connectivity set(CS) for each node. By controlling the transmission power of a route request (RREQ) packet, PCDC broadcasts the RREQ packets to the connectivity set only, hence the MAC can effectively control the set of candidate next-hop nodes.

Since RREQ packets are only transmitted to the nodes in the connectivity set, it is easy to control the potential contention. Hence, the process to find the destination in PCDC has low overhead, less contention and less power consumption. Compared with IEEE 802.11, PCDC achieves improvements of up to 240% in channel utilization and over 60% in throughput, and a reduction of over 50% in energy consumption [42]. However, the adaptive computing of the connectivity set may impose a lot of computing workload for each node.

4.2.5 Other power control techniques

We have discussed the power control mechanism and some corresponding protocols used in MAC layer in the above section. Actually, power control can also be used in network layer, for example, COMPOW [43] and clustering scheme [36].

As the analysis in Section 4.1 shows, different transmission power may cause additional collisions. Hence, it is proposed to use an optimal common transmit power level by the nodes in the networks. According to [43], a per node throughput of $O(\frac{1}{\sqrt{nlogn}})$ can be obtained using a common power level, while with per node optimal levels the upper bound of the throughput is $O(\frac{1}{\sqrt{n}})$. Thus, common power for all nodes is near optimal.

The Common Power (COMPOW) Protocol [43] proposes to use a common power level to ensure bidirectional links. Every COMPOW node runs several instances of a proactive ad hoc routing protocol (eg. DSDV), with each at a different transmit power level. A set of routing tables are maintained, each contains the corresponding connectivity information. The optimum power is defined to be the minimum power whose routing table has the same number of entries as that of the routing table at maximum power level. which achieves the same level of network connectivity as the

COMPOW is designed to maximize the traffic capacity of the network, provide power aware routes and reduce the contention at the MAC layer. Thus, energy consumption is reduced at the same time that network capacity is increased. However, COMPOW completely relies on routing layer agents to converge to a common power level. This usually incurs significant overhead, especially for constantly moving mobile nodes. In clustering ad hoc networks, such a common power level may be more difficult or even infeasible to achieve, because of the hierarchical architecture.

Clustering by power control is used for non-homogenous ad hoc networks [36]. Clustering is used for non-homogenous scenarios. It classifies nodes hierarchically into clusters, dominated by "cluster-heads“ and connected by "gateways“. Cluster-heads are used as base stations to emulate power control as in an infrastructure network. The main idea of such a kind of power control is based on the observation of the extremely high energy cost of an idle interface. Thus by emulating the infrastructure (BSS) operating mode through clustering, energy consumption can be reduced by letting the cluster-heads control the intra-cluster data transmission. Different power levels are used in the intra-cluster and inter-cluster communication with a high power level among the cluster-heads and a low common power level among most of the intra-cluster communication. On the other hand, clustering can also help in reducing the route discovery overhead. They both help reduce energy consumption. However, the dynamic topology of MANETs brings about quick connectivity changes, which means a high overhead for cluster maintenance. Thus, protocol designers must consider latency and packet loss issues. Some new problems also arise. For example, how to form routing backbones to reduce network diameter, how to abstract network state information to reduce its quantity and variability, etc [17].

5 Power off mechanism

5.1 Mechanism

In typical wireless systems, receivers have to be powered on at all time to detect any possible signals that target them. However, this "always-on" results in significant unwanted energy consumption. As mentioned in Section 2, much more energy is consumed in idle state than in sleep state. For example, measurements have shown that idle listening consumes 50-100% of the energy required for receiving [62]. Therefore, idle listening should be avoided as much as possible. Ideally, the wireless radio is powered on only when there are packets waiting to be transmitted or received. Otherwise, the radio is powered off and the node is in sleep/doze state. By this way, the wasted monitoring effort is minimized.

The motivation can be further explained as the following. If the radio is powered on at all time, the ongoing transmission is overheard by all the neighbors of the transmitter, which frequently happens in ad hoc networks. In this scene, the neighboring nodes have to monitor the channel and consume power even though the packets are not directed to them. A large amount of energy is consumed unnecessarily in this case. Take a simple example: If a transmitter T has n neighbors, then the transmit energy needed for a m-packet transmission is $m * (E_{trans}$(transmitting energy per packet)$+E_{recv}$(receiving energy per packet). However, since the transmission may be heard by all its neighbors, the actual power will be $m * (E_{trans} + n * E_{recv})$. Obviously, it produces energy waste of $m * (n-1) * E_{recv}$.

Based on this observation, a new kind of power conservation mechanism is proposed in which some nodes are allowed to stay in doze/sleep state when they are not actively transmitting, receiving, or waiting for a channel

([11], [73], [31]). Obviously, this power off mechanism can save battery power. Thus, it helps prolong the lifetime of hosts and the whole network system. With the current hardware technology, this scheme requires the CPU, transceiver and other hardware to be switched off.

Several different methods have been proposed to realize this mechanism. One method is to exploit an additional control channel to notify the wireless terminals when to power off or power on, such as PAMAS [53, 52]. PAMAS will be studied in this section and the section covering the dual channel mechanism (Section 6). Another method is to periodically power down the terminal ([74], [75]). As proposed in [24], periodically shutting down a host results in great power saving during the sleep period. Based on this, considerably longer beacon intervals may be acceptable to realize the scheduling. Both the sender and the receiver can shut down the radio according to its schedule. Scheduling helps to avoid the effort of determining when to power the radio down. But this technique requires time synchronization, which makes practical scheduling hard. One solution is to use a master host to store the data while the destination is powered down and forwarding the data when it powers up. Another solution is to provide a framing structure for hosts to synchronize their active periods [74], [75]. However, scheduling locally or globally is expensive and is not so easy to implement in ad hoc networks.

Other techniques to realize the power off mechanism include multi-sleep mode [12] and power mode scheduling method [45]. Waking up terminals from sleep mode can be done with synchronization [55] or without synchronization [25]. We will discuss the protocols in the following subsection.

However, there exist problems to be considered for this power conservation mechanism, including when to switch to sleep mode, how long to sleep, and how a host can send or receive packets when in sleep mode. Actually, it is difficult to design a protocol that allows hosts to spend most of their times with the receivers switched off.

5.2 Related protocols

5.2.1 PAMAS

The Power-aware Multi-access Protocol with Signaling (PAMAS) [53, 52] is proposed to conserve battery power by powering off nodes that are not transmitting or receiving. This is a combination of the original MACA protocol [35], and the use of a separate signal channel - the “busy tone” channel [64]. By using busy tone, the terminals are enabled to determine when and how long they should power off the radio. The determination must obey the following rules: If a host has no packets to transmit, then it should power the radio off if one of its neighboring nodes begins transmitting. Similarly, if at least one neighboring node is transmitting and another is receiving, the host should also power itself off because it cannot transmit or receive packets (even if its transmit queue is nonempty).

In the proposed protocol, each host makes the decision whether and when to power off the radio independently. As proposed in [53, 52], a host knows whether a neighboring node is transmitting because it can hear the transmission over the channel. Similarly, a host (with a nonempty transmit queue) knows if one or more of its neighbors is receiving because the receivers should transmit a busy tone when they begin to receive packets (and in response to the RTS transmissions). Thus, a host can easily decide when to switch to the sleep mode. And, PAMAS also gives several factors to determine the length of time for which nodes can be in sleep mode: empty transmit queue and t_probe(l) control packet.

The results show that PAMAS works effectively in power conservation. It achieves power saving from 10% (when the network is sparsely connected) to almost 70% (in fully connected networks) without affecting the delay and throughput behavior of the basic protocol.

5.2.2 S-MAC

An energy-efficient MAC protocol for wireless sensor networks, called S-MAC is proposed in [62]. Different from PAMAS, S-MAC uses the scheme of periodic listen and sleep to reduce the energy consumption by avoiding idle listening. However, this requires synchronization among neighboring hosts. And the latency is increased since a sender must wait for the receiver to wake up before transmission. But S-MAC uses synchronization to form virtual clusters of nodes on the same sleep schedule. This technique coordinates nodes to minimize additional latency.

Another difference from PAMAS is that S-MAC uses the in-channel signaling to put the nodes in sleep mode when its neighboring node is in transmission. The in-channel signaling helps reduce the overhearing problem and avoids the use of additional channel resource.

Compared with 802.11, S-MAC reduces the energy consumption by up to 50% for heavy traffic; and much more energy is saved for light traffic. It surely has very good energy conserving properties comparing with 802.11. Additionally, it can make trade-offs between energy and latency according to traffic conditions. This is a useful feature for sensor networks.

5.2.3 PicoNode's Multi-Channel MAC

A low power distributed MAC is proposed in UC Berkeley's PicoNode project [25]. A power saving mode based on waking up radio without synchronization is used in this MAC protocol. With a separate wake up radio, the normal data radio can be powered down when it is in idle listening state. Multiple channels and CSMA/CA are combined in the MAC for efficient energy usage. The multi-channel spread spectrum helps reduce collisions and retransmissions. It also helps reduce delay and increase throughput (see Section 6). The exploit of random access results in the avoidance of synchronization since it does not require any topology knowledge. Therefore there is no overhead in exchanging schedules and reservation information. All these measures help in energy consumption reduction. Simulation results show the proposed protocol can reduce the power consumption by 10-100 times compared with existing MAC protocols with traditional radio.

As defined by the MAC protocol, each terminal in the network is either in "mobile mode", or "static mode". Mobile nodes periodically broadcast a beacon through the wake-up channel to keep the neighboring nodes awake, thus maintaining a dynamic active zone within two hops. Channel assignment is conducted as the problem of two hop coloring in graph theory. Static hosts in the active zone remain awake. They go back to sleep mode again when no beacon has been received for a predefined period. Under two instances a node can be waken up: it has packets to send out, or it will receive packets from a neighbor. A node can be woken up by itself, or by a beacon from a neighboring node through the wake-up radio channel.

5.2.4 Power management using multi sleep states

A distributed power management policy is introduced in [12] for ad hoc networks. This policy aims to maximize energy conservation in battery-powered devices while satisfying the required traffic quality of service.

In this paper, L different states are used: the first $L - 1$ states are sleep states, while the L-th state corresponds to the active state in which nodes can transmit or receive packets. Each sleep state is characterized by a certain amount of power consumption and a delay overhead. The deeper the sleep state, the less the power consumption and the longer the time to wake up. According to the desired QoS and its own battery status, each terminal must choose an appropriate sleep state when it has been idle for a certain time period equal to or greater than the corresponding timeout value. The sleeping node will switch back to the active state when it receives the signal from the Remote Activated Switch (RAS).

Simulation is conducted to study the power gain in a simple network scenario which assumes L = 4. Results show that power gain as high as 24% can be obtained even at high traffic load. However, this gain is achieved at the expense of a limited additional delay.

Compared with periodic sleep mechanisms, the biggest advantage of this power management policy is perhaps the remote signaling scheme. By using the Radio Frequency (RF) tags technology, this policy avoids the needs of clock synchronization. In this way, nodes are woken up only when necessary, rather than switched back to an active state periodically to check for potential traffic.

6 Multi Channel Mechanism

6.1 Mechanism

As mentioned before, the main function of MAC layer protocols is to control and coordinate the multiple access of wireless terminals to share the communication medium, while at the same time maintain high network utilization. Most MAC protocols assume that there is only one channel shared among different mobile nodes in ad hoc networks. Thus the essential design goal is to increase the channel utilization while avoid hidden terminal and exposed terminal problems. As shown in Figure 6, hidden terminals and exposed terminals cause collisions if no measures are taken. This problem is more serious if transmission delay is longer. In MAC layer, unnecessary collisions should be avoided, since retransmissions cause additional power consumption and further increase packet delay. MAC protocols based on RTS/CTS, such as [35], [8], [22] have been proposed to alleviate these problems. However, as the number of mobile terminals increase, more energy will be consumed for channel contention and the network performance will degrade quickly. On the other hand, as explained in the following, RTS/CTS-based protocols do not completely solve the hidden terminal and exposed terminal problems.

As shown in Figure 6, exposed terminals are allowed to send their RTS packets. However, they could not receive any CTS replies if another node is transmitting on the same channel. Similar scenario happens on the hidden terminals: they are forbidden to access the channel because they can not reply to RTS packets. Since the in-band transmission of RTS/CTS packets inhibits the data transmission of the exposed terminals and the data reception of the hidden terminals, the introduction of an additional control channel may be a proper solution to relieve the hidden terminal and

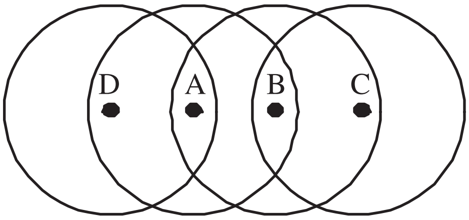

Figure 6: (a) Hidden terminal: A is sending packets to B. Since C is in the range of B but not A, it cannot sense the on-going transmission. Therefore collisions may happen at B if C transmits before the termination of the traffic from A to B. In this case, C is referred as the hidden terminal that needs to be notified explicitly. (b) Exposed terminal: A is sending packets to D. B is in the range of A and hence delays its transmission to C. B is called the exposed terminal. The postpone of B's transmission is unnecessary: these two transmissions can happen at the same time without collision.

exposed terminal problems. Motivated by this observation, multi channel mechanism has been proposed. With an additional control channel, the hidden/exposed problem is avoided. Therefore the corresponding unnecessary energy consumption is conserved.

One notice should be mentioned here: "channel" is used upon a logical level [65]. From the physical level, transmission can be based on CDMA or FDMA, and hence the channel can be a frequency band or an orthogonal code. In this section, we disregard the transmission technology and discuss those mobile hosts that can access multiple channels at the same time.

6.1.1 Basic multi channel scheme

An ad hoc network built on multi channel scheme can be considered as a system composed of one control channel, together with one or more data channels. In other words, the overall bandwidth is divided into one control channel and n data channels. The introduction of the control channel is to resolve the contention that may happen on data channels and to distribute data channels among mobile nodes. Data channels are used to transmit data packets and acknowledgements. A special case is the "Dual Channel" scheme in which only one data channel is used along with a control channel. Examples include [18] and [67].

6.1.2 Busy tone scheme

Another scheme to resolve the contention on data channels is to use a busy tone channel. Busy tone scheme is first introduced in [59] that uses a busy tone to solve the hidden terminal problem. However, this protocol, named as Busy Tone Multiple Access (BTMA), relies on a centralized network operation.

Later, Wu and Li [64] propose a Receiver-Initiated Busy-Tone Multiple Access scheme (RI-BTMA). In this protocol, the busy tone provides two functions: to acknowledge the request for channel access and to prevent transmissions from other nodes. However, the performance of RI-BTMA is dependent on the synchronization, which is usually not easy to achieve in a distributed system. Synchronization is especially hard when considering the mobile behavior of the ad hoc networking environment.

Another scheme is proposed in [67], which combines the busy tone scheme with power control technique. In this protocol, the sender transmits the data and the busy tone at the minimum power level, while the receiver transmits its busy tone at the maximum power level. Each neighboring node estimates the channel gain from the busy tone and is allowed to transmit if its transmission is expected to add no more than a fixed “noise” value to the ongoing reception. This combination of busy tone and power control prevents channel interference and hence helps to reduce the power consumption.

6.2 Related protocols

6.2.1 DCA

Wu et al. [65] propose a Dynamic Channel Assignment(DCA) protocol that assigns channels dynamically in an on-demand style. This protocol exploits one control channel to resolve contentions on data channels and assign data channels to mobile hosts. Multiple data channels are available for data transmission. In this protocol, all data channels are equivalent with the same bandwidth. Each host has two half-duplex transceivers, thus it can listen on the control channel and its data channel simultaneously.

This protocol is sketched below. For a mobile node A to communicate with B, A sends a RTS to B carrying its free channel list (FCL). Such list includes all information about the data channel condition around A. Then B matches this FCL with its channel usage list(CUL) to select a data channel (if any) for subsequent communication and replies A with a CTS. After receiving B’s CTS, A sends a RES (reservation) packet to inhibit its neighborhood from using the same channel. Similarly, the CTS inhibits B's neighbors from using that channel. All these message are transmitted on the control channel. After this handshake protocol is done, DATA packets and their ACK messages are exchanged on the selected data channel.

Channels are assigned on demand in this protocol. There is no need for clock synchronization. Thus channels are used with little control message overhead. Results show that DCA suffers less collision and corruption compared with a simple 802.11-like multi channel protocol. The introduction of the control channel and multi data channel helps to reduce unwanted power consumption.

6.2.2 DBTMA

In Dual Busy Tone Multiple Access protocol (DBTMA) [18] [28], two busy tones, namely transmit busy tone and receive busy tone, are placed on the available spectrum at different frequencies with enough separation.

The receive busy tone provides two functions: 1) Acknowledge the sender that the channel has been successfully acquired, and 2) Notify its neighboring nodes of the following transmission and provides continuous protection for the on-going traffic. The transmit busy tone is used to protect the RTS packets. With these two busy tones, exposed terminals can establish their own transmission, since there is no need for them to monitor the channels to receive the acknowledgment from their intended receivers. Instead, the acknowledgment of the successful channel request will be sent by means of the receive busy tone. Furthermore, the hidden terminals can reply to the RTS requests by simply setting up its receive busy tone. Power control technique is also exploited in DBTMA. Simulation results show that DBTMA protocol is superior to RTS/CTS-based protocols, such as MACA [35], MACAW [8], and FAMA-NCS protocols, which works on a single channel. DBTMA achieves the performance gain as high as 140% over MACA and FAMA-NCS, 20% over RI-BTMA. It also reduces the number of possible collisions and corruptions. However, this scheme requires hardware support. Additional busy tone transmitters and sensing circuits need to be incorporated into each wireless terminal.

7 Antenna-based mechanism

7.1 Mechanism

Antenna is an effective way used in ad hoc networks for energy conservation. There are a lot of factors resulting in energy consumption such as transmission/receiving, collision, interference and so on. To save energy for transmission and receiption is the main goal of antenna design. Different antenna designs lead to different reduction in energy consumption. Three kinds of antennas are discussed in this section, namely omni-antenna, directional antenna, and smart antenna. Omni-antenna is the pervasive way used in ad hoc networks due to its simplicity, although it consumes the most energy among these three kinds of antennas. Compared with omni-antenna, directional antenna achieves more energy saving by distributing the energy directionally and purposely. The most energy conserving method may be smart antenna that has more "intelligence" than directional antenna has.

Significant improvements and benefits can be achieved by using directional antennas or smart antennas. However, it is important to note that the deployment of directional or smart antennas involves additional complexity. Despite the complexity, typically there are many gains in throughput and power consumption reduction.

7.1.1 Omni-antenna

Omni-antennas radiate or receive energy equally well in all directions. That is, all hosts have a 360 degree coverage angle and do not need to aim at each other for communication. The advantage of this approach is its simplicity. However, a lot of energy is wasted this way, since the power is broadcasted towards all directions and therefore attenuates rapidly with distance. Furthermore, it causes unwanted interference. It may be therefore advantageous to use directional antennas or smart antenna instead.

7.1.2 Directional antenna

Directional antennas, with the advantage of reducing unwanted interference, can provide higher gains than that of omni-directional antennas. Also, directional antennas have the capability to receive/transmit more energy in one direction as compared to other antennas. In addition, the use of directional antennas allows hosts to communicate using less power than omni-directional ones, because the power savings of a directional antenna over an omni-directional one depend on the primary beam/lobe and the suppressed

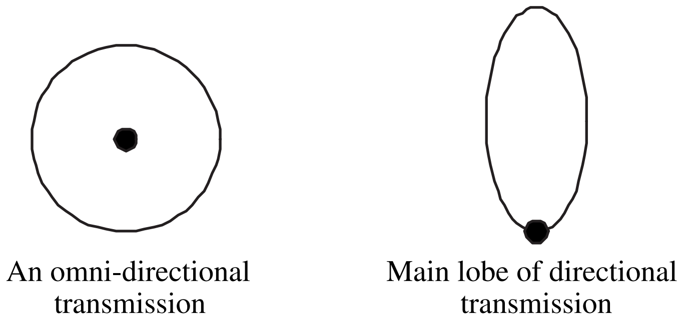

Figure 7: Antenna-based transmission

secondary lobes [2]. These characteristics can potentially provide larger frequency reuse, reduce collisions, interference. So directional antennas can be useful in power saving and increasing host and network lifetime in wireless ad hoc networks.

MAC design with directional antennas in ad hoc network is a relatively new area. Some researchers have proposed the use of directional antennas in packet radio networks to achieve better performance. In [68], directional transmissions were proposed in a slotted ALOHA packet radio network. Thereafter, more attention is paid to the MAC layer protocol design using sectorized and beamforming directional antennas for mobile ad hoc networks ([4], [50], [37], [49], [15], [57]). The usage of directional antennas offers benefits to mobile ad hoc networks since it helps isolate independent transmissions in the network and thereby increase the network performance.

7.1.3 Smart antenna

Smart Antennas can null out interference from other hosts. A smart antenna contains an array of antennas elements, and each element has an associated “eight” that determines the weight. The antenna has complex signal processing techniques to decide which elements to receive signals (or transmission) from and how much power to use on each element.

7.2 Related protocols

7.2.1 Directional MAC

In [37], directional antennas are applied to the IEEE 802.11a MAC protocol. RTS, data and ACK packets are sent directionally and a better performance is achieved than current MAC protocols since it allows simultaneous transmissions that are not allowed by the current MAC protocols.

The Directional MAC protocol works under the following assumptions: All the terminals in a region share a wireless channel and communicate on the shared channel. Each node is equipped with multiple directional antennas. Transmissions from two different nodes will interfere at some node X, even if at X, different directional antennas are used to receive the two transmissions. Simultaneous transmissions to different directions are not allowed at any node. Under these assumptions, several possible cases are considered and two different schemes are proposed in [37]: Directional MAC scheme 1 for using only directional RTS (DRTS) packets, and Directional MAC scheme 2 for using both DRTS and omni-directional RTS (ORTS) packets. The use of ORTS and CTS packets allows the corresponding recipients to determine the direction of the transmitters. These directions are then used for directional transmission and reception of the data packets. [37] also discussed an optimization using directional Wait-to-Send (DWTS) packets to prevent unnecessary retransmissions of RTS packets. However, it relies on an accurate tracking and locating technology, such as GPS or periodic location beaconing, which may be impossible in some cases.

7.2.2 DMACP

In [44], a new directional antenna based MAC protocol with power control (DMACP) is proposed which uses directional antennas along with power control technique. DMACP focuses on the adaptation of IEEE 802.11 so as to find practical solutions for: (a) Finding the directions of transmission/reception at mobile nodes, (b) Designing appropriate transmission and reception strategies for the MAC control packets to minimize interference amongst distinct pairs of communicating hosts, (c) Implementing the power control strategy for data transmission to reduce power consumption. In addition, [44] discuss how to take advantage of directional antennas and present some practical schemes for implementing directional RTS and CTS transmissions.

Results show that the use of directional antennas offers many benefits, such as significant power savings, network throughput improvement, and much less interference. However, all these benefits do not come for free. Different from the omni-directional antennas based scheme, the antennas of transmitters/receivers have to be aimed at each other before the communication starts. The implementation is complex, and the hidden terminals, deafness problems may also exist [14].

7.2.3 A MAC Protocol Using Directional Antennas

[49] avoids the requirements for hardware support by exchanging omni-directional RTS/CTS frames. The direction of a transmitting host is determined through measuring the signal strength, and hence the need for GPS receivers is eliminated. The scheme is based on the IEEE 802.11 protocol, except for some modifications for adapting the use of directional transmission. The key modification is a mechanism for the pair of communicating nodes to recognize the direction of each other through the RTS/CTS exchange. No location information is needed, which helps reduce the interference.

According to [49], the radio transceiver in each mobile node is assumed to be equipped with M directional antennas. Each of the antennas has a conical radiation pattern, spanning an angle of $2\pi/\mathrm{M}$ radians. The M antennas in each host are fixed with non-overlapping beam directions, so as to collectively span the entire plane.

Simulation experiments indicate that by using the proposed protocol with 4 directional antennas per node, the average throughput in the network can be improved up to 2 to 3 times over those obtained by using CSMA/CA schemes based on RTS/CTS exchange with traditional omni-directional antennas. However, since the proposed protocol uses omni-directional RTS/CTS exchange, it loses the benefits of reduced transmission area.

7.2.4 DPC with smart antenna

A distributed power control(DPC) protocol is proposed for ad hoc network stations with smart antennas in [19]. In the proposed protocol, the receivers gather local interference information and send it back to the transmitters. Then the transmitter can use this feedback to estimate the power reduction factors for each activated link. The feedback information consists of the corresponding minimum SINR (signal to interference plus noise) during RTS, CTS, DATA and ACK transmission. Here DATA and ACK transmissions are in (beamformed) array-mode since smart antennas are used at both ends of the link.

In DPC protocol, the interference information is collected during both omni-directional RTS/CTS transmission and the beamformed DATA/ACK transmission. RTS /CTS packets are always transmitted with full power in omni-directional mode, and the power level of DATA/ACK transmission is determined by a power reduction factor which is determined by the maximum interference. According to the simulation results, significant performance improvement has been achieved compared with a system using conventional IEEE 802.11 protocol. And the results indicate that the DPC protocol enables the network to dynamically achieve capacities close to the optimal levels which is achieved by a system where the power control has been statically optimized.

8 Others

Besides the protocols discussed above, there exist other MAC layer techniques proposed to reduce energy consumption for wireless ad hoc networks.

The Multiple Access with Collision Avoidance protocol(MACA) [35] solves the hidden terminal and exposed terminal problems. Therefore MACA outperforms CSMA in wireless multi-hop networks. MACA uses three-way handshake, RTS-CTS-DATA, to reduce the number of collisions. MACAW [8] expands MACA to five-way handshake (RTS/CTS/DS/DATA/ACK). However, each additional handshake brings about a longer turn-around time, and more control (e.g. source-destination information) and checksum bits. This enlarged overhead clearly reduces the channel utilization and causes more power consumption. Therefore, decreasing the number of handshakes may be an effective way for reducing the control overhead. MARCH [61] and MACA-BT [58] explores this technique. MARCH reduces the control overhead by reducing the number of RTS's along the multi-hop path. MACA-BI uses a two-way handshake, RTR(Ready To Receive)-DATA, which reduces transmit/receive turn-around time (up to 25 microseconds) and control packet collisions. Simulation results confirm the superiority of MACA-BT to existing MACA type schemes in CBR traffic. However, its performance degrades in bursty traffic compared to MACA.

As we have discussed in Section 3, scheduling-based mechanisms are established by either dynamically exchanging and resolving channel requests, or prearranging a set of channels for individual nodes or links before hand. In this way, transmissions from these nodes or on these links are collision-free. Contentions are avoided, and power consumption is reduced. However, it is difficult to realize scheduling in distributed mobile ad hoc networks. A novel solution is to use GPS neighborhood information to realize scheduling([69] [5] [9]). For example, in SNDR (Sequenced Neighbor Double Reservation) [9], the neighbor sequenced method is used to realize scheduling, and the double reservation method is adopted to improve the throughput. No handshake or carrier sensing is needed in SNDR, but it avoids contentions, hidden terminal and exposed terminal problems. However, in dense ad hoc networks, or when the network topology changes very often, the control overhead will be very high. In this case, it consumes significant power and bandwidth.

9 Conclusion

As the dynamic, fast deployable ad hoc networks have many promising applications such as e-conference, emergency services, home networking, etc., more and more attention are focused on ad hoc network research, especially on energy-aware mechanisms. It is important to study how to reduce the power consumption while at the same time fully-utilize the bandwidth resource. Moreover, third generation wireless networks are supposed to carry diverse multimedia traffic that will consume more power than a normal data device. Thus energy-aware mechanisms play an important rule in future wireless networks. In this paper, we study the low-power MAC layer mechanisms. We not only analyze the design motivation of each mechanism but also study multiple example protocols in each category. However, MAC layer is not the only layer for power conservation. As claimed by [33], enhancing power efficiency can be achieved in the entire network protocol stack of wireless ad hoc networks. For example, it is common to use power conservation schemes in the hardware design of wireless systems. On the other hand, attention should also be paid on higher levels of the protocol stack.

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