A survey of MAC protocols for Mobile Ad hoc Networks

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Abstract

Ad hoc wireless networks have enjoyed substantial research attention due to their wide scope of application and promise of ubiquitous connectivity. The medium access control (MAC) mechanism for MANETs has, appropriately, also come under intense study as better understanding of wireless networks has revealed potential problems with existing mechanisms used in this crucial piece of the MANET protocol stack. In particular, the advent of new wireless transmission technologies, concerns with respect to hidden and exposed terminals and power conservation issues have lead to the introduction of several new MAC-layer oriented mechanisms in recent times. This report presents an outline of selected technologies with a view of identifying techniques that are interesting or representative of a particular research trend with respect to the problem area addressed. Throughout, particular emphasis is placed on the discussion of compatibility issues for each technology with respect to the existing 802.11 standard. Finally, after a view of recent research work has been provided, the report concludes by offering some insight into future developments in this area.

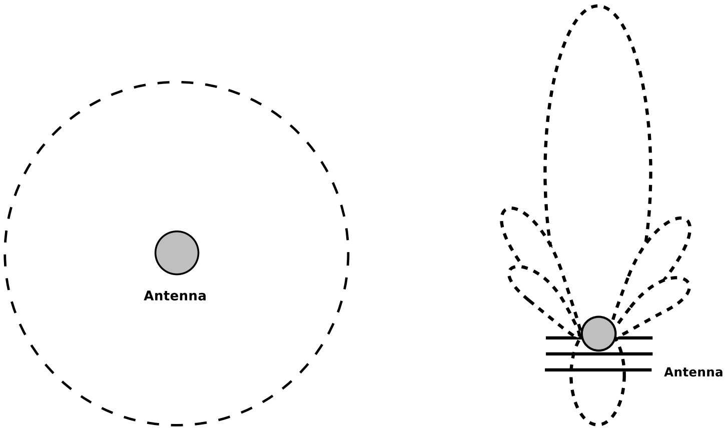
1 Introduction

Mobile Ad hoc NETworks (MANETs) have come under intense research focus, in recent times, due to the proliferation of wireless devices and the wide adoption of a common MAC protocol in the form of IEEE 802.11 standard [6] which ensures interoperability. The hosts participating in a MANET network may be mobile and, furthermore, dedicated routing hardware is not a necessity in order to forward segments; the hosts themselves collaborate in a peer-to-peer fashion, acting as routers to provide connectivity and services as required [7].

The IEEE 802.11 MAC protocol (including the a,b and g variants), as originally introduced, contains provisions for ad hoc networking, i.e. achieving decentralised connectivity (without the use of access points), through its Independent Basic Service Set (IBSS) mode of operation. However, as wireless transceiver technology has progressed, the 802.11 protocol may be extended to accommodate the new possibilities that have come into view. Essentially, the 802.11 standard defines (for its ad hoc mode of operation) a single-channel, single transceiver MAC to be used with omnidirectional antennas and, further, has limited power conservation functions and is devoid of error correction capability [6]. The new possible areas of improvement indicated by recent research (and the ones this report deals with) are: the introduction of unidirectional transceivers, whereas the signal emanating from a source may be directed towards a given host rather than be spread in all directions; the utilisation of multiple wireless channels, whereas it is possible for a host to communicate on more than one set of frequencies (channel); the reduction of power consumption for wireless devices, which can now be done more efficiently drawing on past research work and experience; and finally the possibility of implementing error correction as well as introducing Quality of Service functionality.

This report aims to introduce recent MAC protocol developments addressing issues in the areas mentioned above and discuss the applicability of proposed new techniques to 802.11-based ad hoc networks. The reader is assumed to have some familiarity with MANET nomenclature including routing concepts in MANETs and mobile host characteristics. Also note that the term ad hoc networks as used throughout this work refers to MANETs; the terms are used interchangeably for the rest of this report.

The rest of this report is organised as follows. Section 2 presents an overview of the challenges a MAC protocol would need address in an ad hoc network. Notably, the rest of this work contains an overview of a selection of MAC protocols implementing mechanisms to address those challenges. Section 3 describes two MAC protocols for use



(a) Omnidirectional (b) Directional

Figure 1: Signal propagation of different antenna types

with wireless transceivers having directional antennas. Section 4 overviews two techniques which utilise multiple channels for transmission so as to improve throughput and make better use of the wireless medium. Section 5 describes the workings of a forward error correction (FEC) MAC mechanism which deals with the high bit error rate which is often present in wireless communications. Then, section 6 discusses a recent proposal for power conservation in ad hoc networks using MAC layer estimates to determine transmission power. Finally, section 7 concludes this report and offers some thoughts on future ad hoc research.

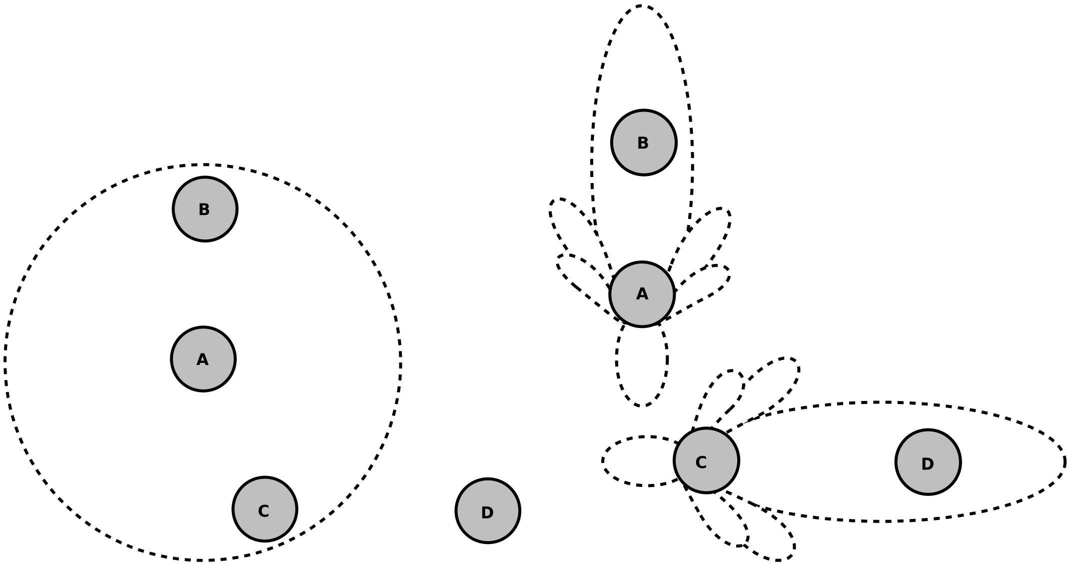
2 MAC issues in MANETs

Several important considerations arise when mapping the requirements of a MAC protocol for use in ad hoc wireless networks. The first of these stems from the wireless nature of transmission, which results in *error-prone* data propagation due to signal fading effects, noise and interference. Further, most ad hoc wireless networks are expected to make use of the Industrial, Scientific and Medical (ISM) band, as it is free of licensing fees, and as such have to effectively use the *limited available bandwidth*. Also, when considering the use of the wireless spectrum, there might be more than one channel available for communications, which consequently means that a MAC protocol may be designed in such a way as to employ *multiple channels*. Moreover, the transceiver used may allow the transmitted signal to radiate in a controlled fashion, either *omni-directionally or directionally*; in either case an appropriate MAC protocol would be needed to exploit the transceiver's transmission properties. In addition, considering that most nodes in ad hoc networks may be battery-operated mobile devices, the MAC protocol in use can also include considerations for minimal *power usage*. Finally with the proliferation of ad hoc networking, the differing requirements of users may potentially be met through the implementation of a *Quality of Service (QoS)* infrastructure, which the MAC protocol may be tuned to satisfy partly or in whole. All these considerations are examined in more detail, below.

2.1 Omnidirectional vs unidirectional

A wireless transceiver may radiate or receive signals from certain directions (in the case of unidirectional transceivers) or equally well in all directions (in the case of omnidirectional transceivers). Figure 1 illustrates the two cases by considering a bird's eye view of the radiation pattern of an antenna as used in wireless transceiver. Note that in reality radiation patterns are three dimensional but for illustration purposes Figure 1 only considers the azimuthal pattern, i.e. as seen from "above".

Most MAC protocols, including the popular 802.11, are designed to work with omnidirectional transceivers as these are commonly in deployment and most well-understood in the context of MAC related research in ad hoc



(a) Omnidirectional antenna (single transmission)   (b) Directional antenna (two transmissions)

Figure 2: Possible transmissions for different antenna types

networks. However, proper use of a directional transceiver may result in better spatial reuse (i.e. better utilisation of the wireless medium by exploiting concurrent transmissions) and thus better overall throughput for the nodes participating in an ad hoc network. A case of improved spatial reuse through employment of directional antennas is shown in Figure 2. In the case depicted in Figure 2(a) all nodes employ omnidirectional antennas. As such nodes A and B may not converse at the same time as C and D, as the former pair's conversation "reserves" the area around the transmission radius of A (which includes node C). Indeed, if both pairs attempted to communicate simultaneously a collision would occur. In the same scenario, if directional antennas were employed, the situation would be as in Figure 2(b). Nodes A and C would transmit their signals to their intended destinations without interfering with one another. Such a development also allows for better *spatial reuse* as in the same physical space two concurrent transmissions are possible rather than one.

A short note should be made here on the issue of *deafness* in directional MAC protocols. This situation can arise when a node (say node A) uses a directional antenna to communicate with another node (say node B). Should a third node (node C) try to send a signal to node A, then A would fail to receive the message if node C's signal lay outside the directional pattern of the A's antenna beam. In the case of omnidirectional antennas C might have overheard A's transmission and realised it was busy because A would have sent its signal in all directions around it and not just towards B. The deafness issue is illustrated in Figure 3.

Facilitating directional transmissions is not a trivial task as a correct direction should be provided and the antenna should direct the signal toward it in real time. Also, currently directional transceivers are more expensive than omnidirectional ones and there is still substantial research to be done so that a new MAC protocol would inter-operate smoothly with existing unidirectional MACs (such as IEEE 802.11). Nonetheless, it should be noted that employment of directional transceivers does not imply that the direction of transmission has to be set statically or requires moving the antenna in order to change it. By utilising analog phase array antennas [13], it is possible to design a transceiver which can radiate at different chosen directions and which does not contain any moving parts.

2.2 One vs multiple channels

All wireless communications inevitably take place over some section of the radio communications frequency spectrum, which can in turn be distinguished into channels. Particularly, in the case of 802.11 compatible transceivers [6] communications take place over the ISM band and over specific channels defined in the ISM range. However, only one channel is utilised at a time when transmitting and, as a result, the 802.11 MAC can be classified as a *single*

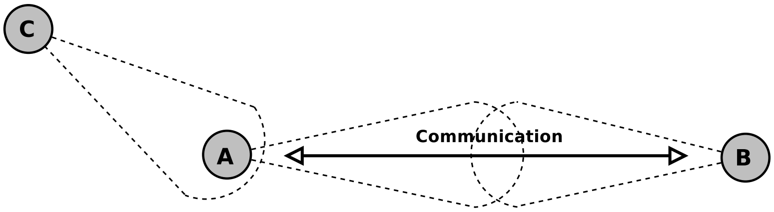


Figure 3: An example of *deafness*. Node A is communicating with node B. During this transmission node C transmits a packet to A (C is unaware that A is already in communication with another node), but A fails to receive it.

shared-channel scheme.

The main problem with schemes of this type is that as multiple participating nodes in an ad hoc network come in close proximity to one another, the probability of collisions increases, as the number of nodes increases. A possible way to solve this problem is to utilise a *multi-channel* scheme in which, as the name suggests, more than one channel is utilised per transmission. Multi-channel schemes can be further separated into two categories. Firstly, a dedicated channel may be used for signalling or control packets and the other for data transmissions; in such cases there might be a "busy tone" on the signalling channel to help coordinate transmissions whilst in order to avoid waste of bandwidth the signalling channel itself might occupy a small frequency range. The main advantage of such an approach is that coordination of transmissions can be done simply and efficiently as there is a dedicated channel for this purpose. The trade-off is of course the bandwidth spent with the reservation of an extra channel as a dedicated signalling conduit, which could otherwise be used for data transmissions.

On the other hand, it is feasible to utilise all available channels for data transmissions alone; in this case, there might not be a dedicated signalling channel and the channels themselves may have equivalent capacity. The most obvious advantage in this case is that the use of multiple channels at the same time effectively increases the available transmission bandwidth. Also, as transmissions on different channels do not interfere with one another, multiple transmissions can take place in the same region at once, which reduces the possibility of collisions. However, a multi-channel MAC protocol still needs to dynamically assign different channels to different nodes in real time whilst maintaining fairness and adhering to QoS requirements. Further, it may not be possible to utilise multiple channels in some countries at the ISM band (which ensures royalty free use) as there might not be many channels available to begin with; in those cases the application scope of multi-channel techniques may be limited if royalty-free use of the communications spectrum is desired.

2.3 High Bit Error Rate

Due to the nature of signal propagation, the wireless medium utilised in ad hoc networks potentially exhibits a high Bit Error Rate (BER) as a result of a noisy or fading channel.

Taking into account the inherent unreliability of the wireless medium, the popular IEEE 802.11 standard has included provisions to accommodate for reliable point-to-point transmissions. In particular, the link layer frame format used in 802.11-based ad hoc networks is similar to 802.3 (Ethernet) frames [17] and uses the same 48-bit MAC address fields. For error protection, the standard also includes the 802.3 32-bit CRC polynomial-based error detection mechanism, which nonetheless allows, though this is somewhat unlikely, for corrupt data to be accepted by the receiver and passed on to higher layers of the protocol stack. This adverse possibility is offset by the adoption of error discovery as implemented at higher layers.

A useful technique which may be employed to improve reliability in point-to-point transmissions is Forward Error Correction (FEC). FEC methods allow for a receiver to correct, within a given bound, incoming erroneous data, without requiring a retransmission; in this context, the sender includes along with the message some redundant data, which allow for reconstruction/repair of damaged or missing data segments. The main advantage of FEC is that costly retransmission of messages, in terms of bandwidth and power, may be avoided, but at the cost of some bandwidth overhead. On average though, and given a relatively unreliable medium and an efficient coding scheme, the savings significantly outweigh the costs.

Overall, in wired networks, the need for error-correction is not as prominent as in wireless communications because the physical medium exhibits much higher reliability. In multi-hop wireless communications (as is the case

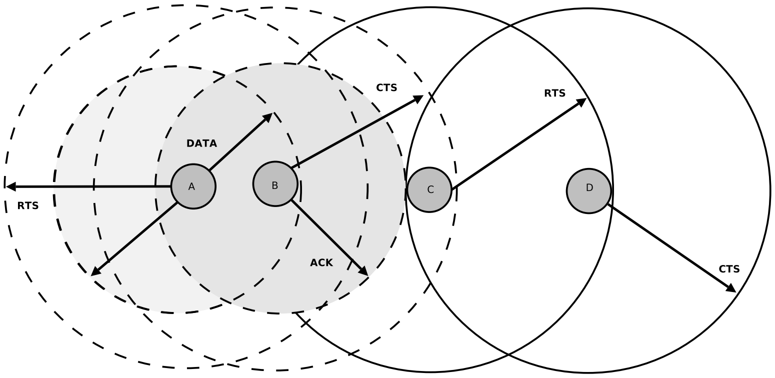


Figure 4: To conserve power but also avoid collisions, nodes A and B exchange RTS/CTS frames at full power level but DATA/ACK at a lower power level

with ad hoc networks), the possibility of erroneous transmissions is significant, especially given a long enough path or sufficiently adverse transmission conditions.

2.4 Power Usage

The mobile nodes that participate in an ad hoc network could be as diverse as laptops, PDAs or even desktop systems. It is expected that some of these will be mobile, which in turn implies that they would have limited power reserves. As such it is important for the MAC layer to contain some provisions for power conservation [9, 21].

As means of power conservation, it is possible for the MAC protocol to dictate on/off (or sleep/wake) states for the transceiver which roughly correspond to minimal and normal power expenditure respectively. The transceiver may thus be put in a "sleep" state, where it does not monitor the use of the channel, and be switched to a "wake" state only when it needs to transmit or scan the channel for incoming transmissions, which would result in power savings [9].

Furthermore, it should be noted that the power of a transceiver also throttles its transmission radius; if the destination node is close to the source a moderately powerful transmission would suffice and would not strain the power reserves as much a full power one. Particularly, in the case of omni-directional antennas, the MAC protocol may use a full power transmission to reserve the area around the node and then only as much power as necessary to communicate with the intended destination. This principle is depicted in Figure 4. In that case, nodes A and B first complete the RTS/CTS handshake at full power, thereby ensuring that node C becomes aware of the impending transmission and will not interfere. Then the DATA/ACK exchange between A and B is performed at a much lower power level and at a lower power expenditure. The power savings achieved in such cases may be significant.

2.5 QoS requirements

As ad hoc networks gain in popularity it would be expected that users might require some guarantees of a given level of QoS. These guarantees may concern bandwidth requirements, end-to-end delay, probability of packet loss and so on. However, as mobile ad hoc networks have no centralised infrastructure, exhibit dynamic and erratic topologies, are characterised by error-prone transmissions and demand conservative power expenditure, providing QoS in such networks becomes a challenge.

In general, QoS requirements are met by providing facilities throughout the networking stack [16]. At the routing layer forwarding priority may be given to segments that have particular QoS requirements, whilst best-effort traffic may be back-logged or even dropped. At the MAC layer, a node may request transmission priority in order to meet the QoS requirements, and thus suppress or delay transmissions by neighbouring nodes.

Although the original 802.11 standard did not include any QoS provisions, it has been augmented with the proposed 802.11e extension [2, 6] to provide some degree of assurance for the service level. This work does not contain a review of particular QoS techniques in wireless communications. Interested readers may instead refer to the report titled "Quality of Service in Wireless Local Area Networks" by Simsek et al. included in this collection, or consult [16] for a succinct survey on the subject. It should, however, be noted that QoS assurances are a difficult proposition in ad hoc networks and still remain, it would be fair to say, subject to ongoing research.

3 Utilising directional antennas

The popular IEEE 802.11 protocol used widely in ad hoc network research and in wireless networks in general assumes that transceivers in hosts are omnidirectional and works within the limitations of such setups. However, with the advent of cheap directional antennas and related hardware [13] it is increasingly becoming feasible to equip mobile devices with transceivers which can radiate and receive transmissions at some given direction rather than uniformly around the transceiver. In this section, two MAC techniques using directional antennas in ad hoc networks are presented. The first one deals with techniques to avoid collisions when using directional antennas. In this fashion, some insight of solutions to issues in this field is provided.The second technique has been designed to integrate well with a given routing protocol and thus presents a complete cross-layer solution on the networking stack for utilising omnidirectional transceivers.

3.1 Collision avoidance using directional antennas

Avoiding frame collisions, i.e. simultaneous conflicting transmissions, is one of the elementary functions of any MAC protocol. In wireless networks, avoiding collisions becomes a complicated issue especially when considering the existence of hidden terminals [20]. One of the most popular collision avoidance schemes is the Request-To-Send/Clear-To-Send (RTS/CTS) method, whereas data transmission is preceded by a short RTS/CTS handshake (frame exchange) between the source and destination nodes. This exchange reserves an area (as big as the transmission radius of the communicating parties) around the source and destination so that while the transmission occurs, no other neighbouring node transmits at the same time.

When omnidirectional transceivers are used, the RTS/CTS scheme reserves an area in which the transmitted signal would propagate (this is reserved by the RTS frame sent by the source) as well as an area where if some other node were to transmit at the same time a collision would occur (this is reserved by the CTS frame sent by the destination). When directional antennas are used though, such a large area need not be reserved as it suffices to just reserve the area between the source and destination where the directed transmission travels; this also allows other transmissions in the same region to occur simultaneously as presented in Section 2.1 (i.e. improve spatial reuse). Research conducted by Wang et al. [18] has examined the efficiency of conducting the RTS/CTS reservation in directional and omnidirectional transceiver scenarios. In particular three scenarios have been examined, as follows;

1. In the "ORTS-OCTS" scheme all frame transmissions are omnidirectional. This behaviour mirrors omnidirectional transceivers and is the case for 802.11 compatible wireless devices.
2. In the "DRTS-DCTS" scheme all frame transmissions are directional, including RTS/CTS. This scheme maximises spatial reuse, as it only reserves the area directly between the source and destination nodes. That also implies that nodes not located between of the communicating pair are unaware of the transmission and may attempt to transmit along paths that interfere with the source's transmission or the destination's reception.
3. In the "DRTS-OCTS" scheme the RTS frames are transmitted directionally whilst the CTS frames are transmitted in an omnidirectional fashion. Data and acknowledgements are transmitted directionally. The basic idea is to reserve the whole area around the destination but only the transmission path between source and destination. In this respect all nodes around the destination would be informed of the impending transmission and nodes between the source and destination's communicating path (but not all nodes around the source as these cannot affect the reception of the transmission at the destination).

In short, methods (1) and (2) represent the two extremes of maximal area reservation (and thus protection from the hidden terminal effect) versus maximum spatial reuse (with limited protection against hidden terminals). Method (3) represents a compromise between the two techniques (full protection against hidden terminals, only at the destination). Simulation results and analytical analysis done in [18] show that as long as the antenna beamwidth is narrow enough, the directional transmission of all control and data frames of method (2) (i.e. the "DRTS-DCTS" method) outperforms (in terms of throughput and delay) all other methods of collision avoidance.

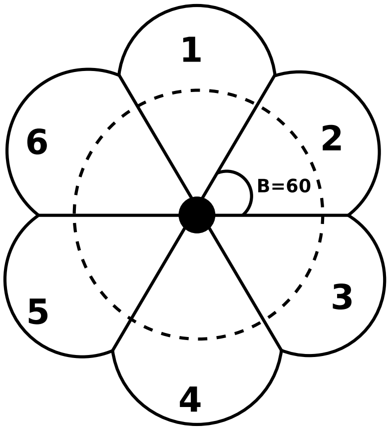


Figure 5: A directional antenna with complementary omnidirectional transmission functionality. The dotted circle is the omnidirectional signal radius while the 6 solid line slices represent the available unidirectional 60^o beams.

This occurs even though the "DRTS-DCTS" method results in more collisions. In the case of a wider beamwidth, the "DRTS-DCTS" performs comparably to the "DRTS-OCTS" method, which marks a compromise between the two extremes. Overall, it is demonstrated that the cost of coordinating neighbouring nodes well to avoid collisions resulting from hidden terminals is too high, as the gain in silencing potentially interfering nodes is not as significant as the gains in throughput as a result of the better spatial reuse achieved with the "DRST-DCTS" method. Note that in any case the "ORTS-OCTS" method is the worst performer by a large margin.

These results, as presented in [18], are significant in two ways. Firstly, they demonstrate (counter-intuitively) that an increase in collisions (as evident in the "DRTS-DCTS" method) does not necessarily lead to a performance penalty; secondly it is shown that simply "porting" the 802.11 protocol to directional transceivers without changing its fundamental RTS/CTS mechanism in any way may in fact be an efficient solution. In fact, in this case imposing orderly transmission (in the form of omnidirectional RTS/CTS) is harmful rather than beneficial.

3.2 Ad hoc routing using directional antennas

It is possible to conduct a MAC protocol study in isolation of other protocols in the networking stack. In fact, the study presented in the previous section has presented results in such a fashion. However, Choudhury et al. in [4] have opted to examine the use of a directional MAC protocol in the context of routing protocols and identify potential issues in their interaction.

The authors in [4] have opted to evaluate the Dynamic Source Routing (DSR) [8] protocol, which was originally designed for omnidirectional antennas, over their own directional MAC protocol called DiMAC. Although a description of the DSR routing protocol is beyond the scope of discussion in this context (interested readers may refer to the [8] for more information), the DiMAC operation may be summarised as follows. The directional antennas are assumed to have two modes of operation; an omnidirectional mode, which helps detect from which direction an incoming beam is more powerful (i.e. where a directed beam is coming from) and a directional mode where the antenna can chose one direction for its beam (with a given beamwidth) and transmit at a longer distance (because directional transmissions have higher gain). This type of antenna is depicted in Figure 5. The unevenness of the transmission distance between omnidirectional and directional modes of operation makes the broadcast operation an expensive one in the case of the directional mode; the antenna has to use all its different beams in sequence so as to broadcast a message in all directions, referred to as a "sweep" (slices 1-6 in Figure 5), whilst in the case of the omnidirectional mode a single transmission suffices (dotted circle in Figure 5). This last observation provides some indication of the additional overhead involved in broadcasting with a directional antenna in terms of delay. Overall, the DiMAC protocol utilises a directional RTS/CTS handshake and maintains a lookup table of neighbouring nodes and the associated antenna beams they can be reached at.

As the DSR protocol relies heavily on broadcasting Route Requests (RREQs) to discover new routes the MAC "sweep" function is employed several times and the effect of added delay becomes substantially. Even neighbour discovery becomes more complicated as a broadcast of "hello" packets cannot be replied to immediately but the

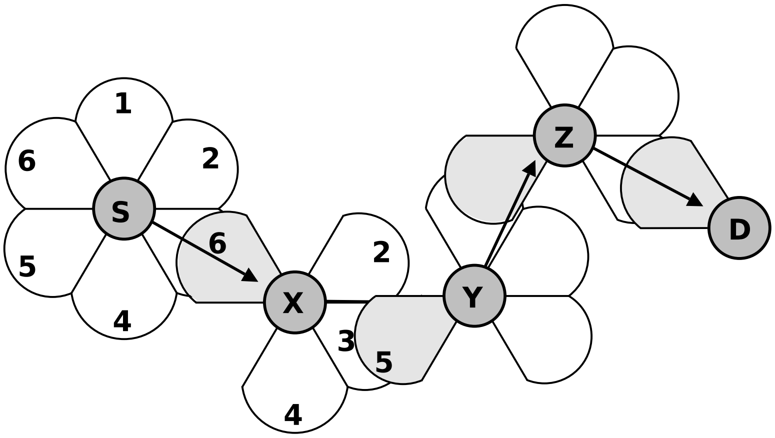


Figure 6: Demonstrating selective forwarding; each node apart from the source (S) forwards the broadcast packet with the beams located at the opposite side from the one that received it

receiving node must wait for some time period as the sending node needs sometime to complete its “sweep” before it can hear a reply (if nodes were to reply immediately the “deafness” effect might take place as described in Section 2.1). The DSR variant working over DiMAC is named Directional DSR (DDSR).

Simulation experiments have been conducted in [4] with DSR (over omnidirectional antennas) against DDSR. The results indicate that the sweeping delay of DDSR has a detrimental effect on route discovery latency when the distance between the source and destination is small. As the distance increases, the advantage of higher transmission range of DDSR (because of the higher gain of the directional antenna) results in shorter delay as the hops required to reach the destination are fewer than in the case of DSR. It is also indicated that as the network density increases, DDSR performance degrades over DSR mainly because of interference caused as the antenna radiates from its sidelobes and it affects the closely packed nodes leading to collisions.

In terms of throughput two interesting effects occur. Due to the way that sweeping works it is possible for neighbours to get the same RREQ at different points in time. Neighbours that receive it earlier are more likely to deliver the RREQ earlier to the destination as well. However, earlier in this case does not mean a shorter route (as in the case of omnidirectional antennas), because of the delay involved in the “sweep” (it takes sometime to reach all directions, unlike in the omnidirectional case). As such it is noted that it some delay may be needed at the destination so that it replies to the RREQ travelled the shortest distance and not the one that has been received the earliest. Nonetheless, the effects of “deafness” make the transmission of Route Replies (RREPs) more difficult as there may still be RREQs being broadcast in the network when a RREP is unicast back to the source.

Still another optimisation concerns the broadcast “sweep” of RREQ packets. In order to avoid swarming the network with unnecessary broadcasts the authors propose a selective forwarding optimisation whereas a node only forwards a packet with n beams (apart from the initiating nodes which uses all beams). Following the rationale that beams may be forwarded outwards from the source node, only opposite beams to that with which the control packet was received are used. In Figure 6 this mechanism is demonstrated as node X uses beams 2,3 and 4 to forward to node Y, which receives the packet with beam 5.

Overall, with the above described optimisations applied DDSR outperforms DSR in terms of both delay and throughput. However, it should be noted that the work in [4] has shown that routing has to be taken into account when evaluating directional MAC protocols as unexpected interactions (such as the effects of delay during a MAC “sweep”) may negatively impact performance. It has also been shown that replacing the 802.11 protocol (or augmenting in a significant way) could impact performance due to unwanted interactions with other protocols in the networking stack. Thus, importantly, this work suggests that future research should place some focus on the interaction of the MAC layer with other elements of the protocol stack in order to be relevant and useful.

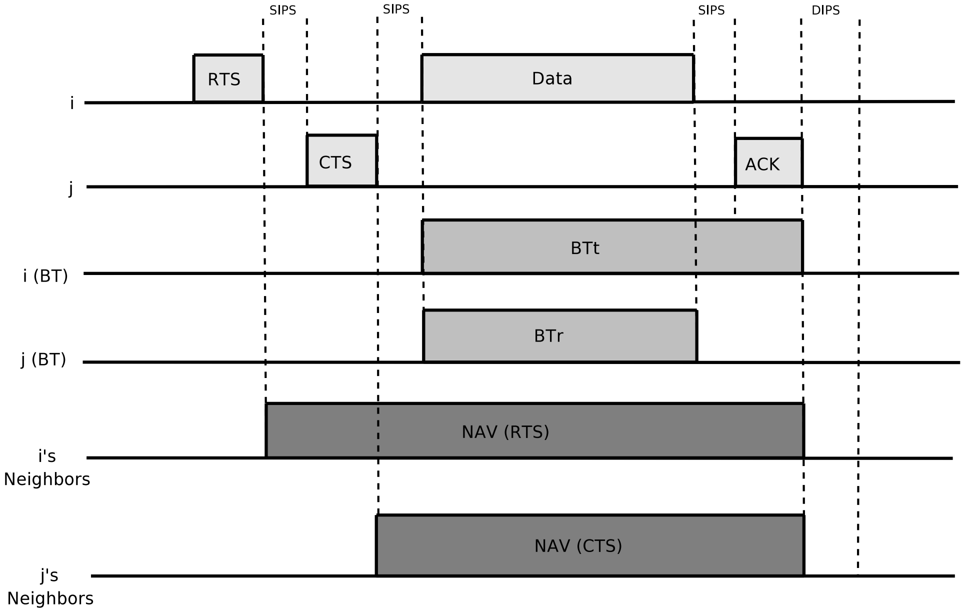


Figure 7: Frame exchange using the FPDBT scheme

4 Utilising multiple channels

The vast majority of wireless networks in deployment today use the IEEE 802.11 protocol for communications over the ISM band [6], which is free of licensing concerns and is divided in multiple overlapping (and non-overlapping) channels. It is, therefore, possible to utilise multiple channels to allow nodes to transmit at the same time (but at different frequencies) without interfering with one another. Alternatively, a node may even transmit on multiple channels to exploit the added available bandwidth or even use one of the channels as a an aid to coordinate transmissions. This section presents two techniques which facilitate multiple channel exploitation and which are indicative of the latter two paradigms.

4.1 Utilising busy tones

The hidden and exposed terminal effects have been shown to be detrimental to the throughput performance of 802.11 based ad hoc networks and, further, it has been noted that they may not be mitigated successfully with the use of the RTS/CTS handshake [20].

In [11], Leng et al. suggest two novel MAC schemes which solve the hidden and exposed terminal problems by utilising multiple channels and busy tones. Specifically, in [11] two schemes are presented both of which are based on the principle that a busy tone on a separate channel will always be detected by neighbouring nodes and is furthermore immune from interference effects by data transmissions from other nodes (since those happen at a different channel). The two schemes are now outlined in turn.

In the *Fixed Power Dual Busy Tone* (FPDBT) scheme, a mobile host transmits only when it has sensed an idle channel (on the data frequency range) and no busy tone (on the tone channel frequency range). It should be noted that the authors in [11] first identify a power threshold $P_{r0.56}$[1] which helps determine from the sender or receiver's perspective whether the interference range is larger than the transmission range of a given host. For instance if at the receiver an RTS frame is received with power $P_r(x)$[2]$< P_{r0.56}$ then the interference range is higher than the transmission range (and this is the threshold where the RTS/CTS handshake fails [20]). Figure 7 shows how a transmission between two nodes (i and j) would proceed in such a case. Assume that host j receives an RTS frame from i. Then host j detects whether the receiving signal power is greater than the $P_{r0.56}$ threshold (i.e. whether the interference range is larger than the transmission range). If that is the case then both hosts utilise

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[1] $P_{r0.56}$ stands for the received signal power of a frame at a distance of $0.56r$, where r is the transmission range of the sender

[2] $P_r(x)$ stands for the received signal power of a frame at distance x

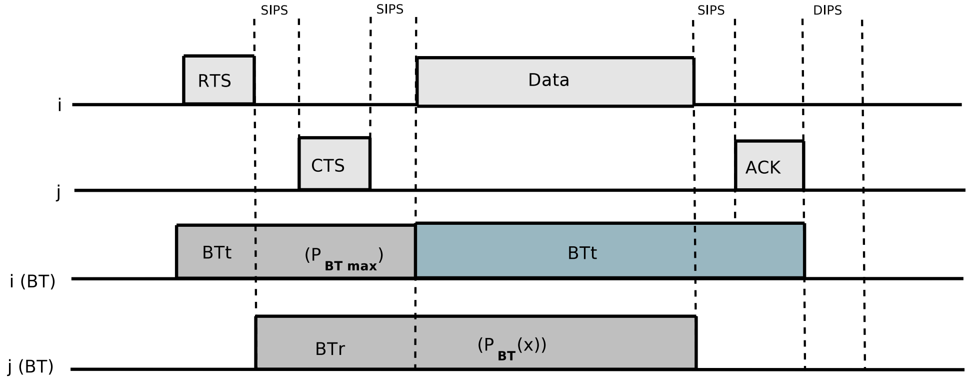


Figure 8: Frame exchange using the VPDBT scheme

busy tones BTt for the transmitter and BTr for the receiver respectively. BTt extends to the transmission of the ACK frame whilst the Btr only extends up to the reception of the DATA frame (there is no need for j to protect the reception of i's signal after that time as it would have already received the DATA frame). As per usual 802.11 rules, upon receiving an RTS or CTS packet, neighbouring nodes of i and j refrain from transmission by setting their Network Allocation Vector (NAV) to an appropriate length according to the duration information embedded in the RTS/CTS frames. Neighboring hosts also refrain from transmitting if BTt or BTr is detected. On the other hand, if the threshold conditions are not met then the normal 802.11 DCF scheme is employed.

Compared to the 802.11 protocol the FPDBT scheme requires an additional channel to be used to protect against hidden terminal. Nodes that cannot decode the RTS/CTS exchange need only identify some signalling on the busy tone channel to refrain from transmission. Nonetheless, the busy tone solution as presented above does reserve a large area around the sender/receiver pair and thus does not aid spatial reuse.

For the above reason, the authors in [11] have proposed a second scheme called the *Variable Power Dual Busy Tone* (VPDBT) scheme. In this scheme, hosts adjust the transmission power of their busy tones so as to indicate their interference ranges precisely (in the previous scheme, i.e. FPDBT, the hosts transmit their busy tones in full power). This allows for greater spatial reuse as only the necessary spatial amount around the transmitting pair is reserved.

The RTS/CTS exchange works as previously with one difference. When node i has received the CTS from node j, its busy tone (BTt) changes the power level to $P_{BT}(x)$ which is calculated according to the signal power of the CTS frame. In the mean time, node j, after having received the RTS frame from i also transmits a busy tone at a $P_{BT}(x)$ power level, calculated in turn according to the signal power of the RTS frame received. The net result of this modification is that the busy tone covers exactly the interference range, which depends on the distance between the source and destination, and does not cover the whole theoretical maximum interference area as it happens in the case of FPDBT. So, spatial reuse is optimised as only the necessary spatial area is reserved from transmission and other nodes are free to transmit in non-reserved areas. The exchange is shown schematically in Figure 8, where $(P_{(BTmax)})$ stands for maximum transmission power for the busy tone signal.

Subsequent analysis in [11] has shown that both techniques outperform by a factor of up to 2.6 times the throughput achievable by the 802.11 MAC mechanism in dense networks (where collisions are more likely to occur). In particular, given a dense network with significant transmission activity the VPDBT technique outperforms FPDBT. The overall conclusion that can be derived is that using a busy tone signal in a multichannel setting can substantially improve 802.11 performance at the cost of having to utilise an extra channel (frequency range) off the available ones.

4.2 Utilising multiple channels for data transmission

The IEEE 802.11 protocol allows the simultaneous use of eight and three channels at ISM frequencies for 802.11a and 802.11b conforming transceivers, respectively. In infrastructure wireless networks the use of multiple channels is common when defining the communication frequency of access points; it is beneficial to have access points operating at different channels so that simultaneous transmissions from mobile hosts to different access points may

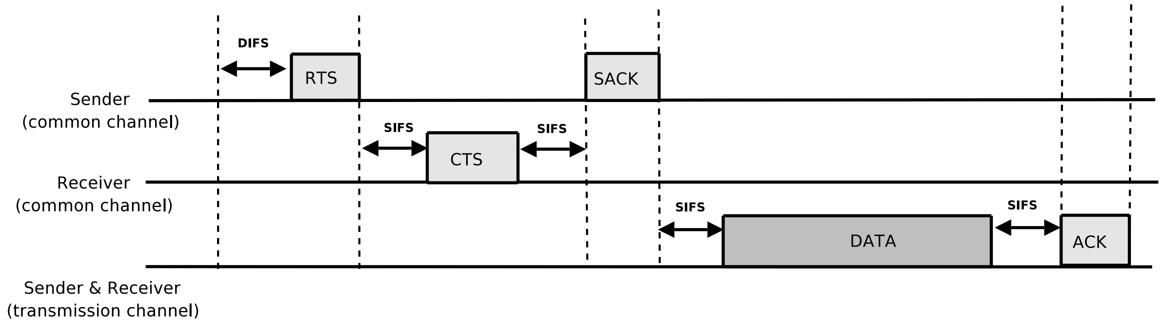


Figure 9: The MTMAC scheme

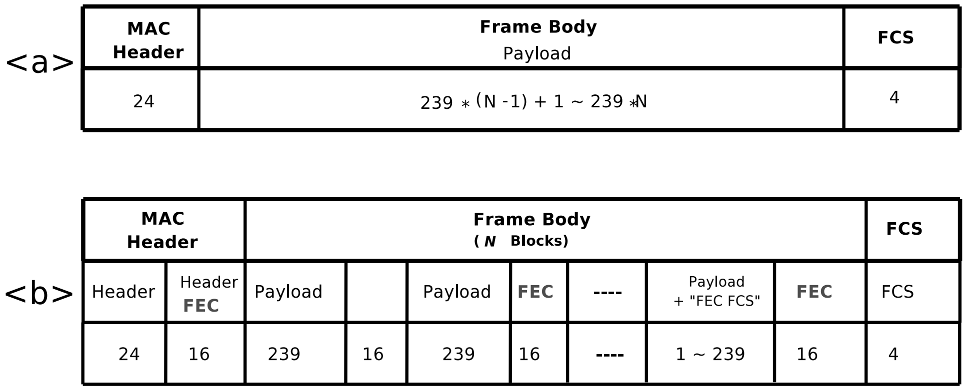
be achieved without collisions. In contrast, in ad hoc mode, nodes are assumed to use only one channel.

Since there may be several channels available for use, a transceiver may employ multiple channels to improve throughput by either employing all channels at once or by choosing not to contend for transmission in a busy channel but instead transmit on a less busy frequency. In the work by Xu et al. examined here [19] the former approach is chosen. In particular, a multi-transceiver based MAC protocol for IEEE 802.11 ad hoc networks is proposed. In that scheme several sub-nodes are equipped with independent wireless transceiver (which are IEEE 802.11 conforming wireless cards). A node (i.e. a mobile host) may contain several sub-nodes (meaning wireless cards). One channel is reserved as a common control channel via which communication between hosts is coordinated. The rest of the available channels are set as traffic channels, through which data frames are transmitted. Through an RTS/CTS exchange at the common channel every sub-node dynamically reserves an idle traffic channel and performs parallel communications with other nodes. Within the same node fast packet switching is enabled between sub-nodes.

The MAC protocol suggested in [19] is named Multi-Transceiver based MAC (MTMAC) and its fundamental operation is outlined in Figure 9. In short, each node maintains a channel state table by monitoring the common channel via its sub-nodes, and all sub-nodes have access to this table. The channel table maintains, essentially, the time reserved for data transmission for each channel, not unlike the Network Allocation Vector (NAV) in 802.11. Communication between two nodes, say i and j proceeds, thus, as follows. If the m-th sub-node of i (i.e. i_m) needs to communicate with the n-th sub-node of node j (i.e. j_n), i_m first transmits an RTS frame (on the common channel) to j_n. In the RTS frame the sender denotes the idle channels it has recorded in its channel table. The receiver then embeds its choice of communication channel in the CTS frame after consulting its own table; as a consequence j's neighbours get informed of its choice. The sender (in this case i_m) also informs all its neighbours of j's choice by transmitting a sending acknowledgement (SACK) frame. Every sub-node overhearing the CTS or SACK frame would then know of the impending transmission on the negotiated channel, and defer transmission on the channel until the ACK frame (from j_n to i_m) has been transmitted. In the case of SACK reception, every sub-node that receives it updates its channel table, otherwise the channel is considered idle.

In the above fashion and by separating the traffic channels from the common control channel, the MTMAC protocol can avoid collisions and mitigate hidden and exposed terminal problems. Theoretical analysis done in [19] reveals that both in the case of 802.11a and 802.11b networks (where seven and two data channels are employed respectively), as the offered load increases, throughput increases dramatically compared to the original 802.11 protocol.

The main drawback of multi-transceiver based schemes such as the one presented here is an increase in energy consumption which might strain the limited power reserves of mobile devices. Also, it should be noted that the amount of channels required might not always be available due to licensing concerns (not all countries allow free use of three non overlapping channels for 802.11b, for instance). However, if those limitations are not serious concerns for a particular scenario, employing multiple channels might provide substantial throughput benefits.



<a>

MAC Header	Frame Body Payload	FCS
24	239 * (N -1) + 1 ~ 239 *N	4

<b>

MAC Header		Frame Body (*N* Blocks)							FCS
Header	Header **FEC**	Payload		Payload	**FEC**	----	Payload + "FEC FCS"	**FEC**	FCS
24	16	239	16	239	16	----	1 ~ 239	16	4

Figure 10: The MPDU format implementing the MAC-level FEC. $< a >$ is the IEEE 802.11 MPDU format without and $< b >$ with the proposed format changes. Each number represents size in bytes, with N=1~10

5 Dealing with Errors - Forward Error Correction (FEC)

In wireless communications, in general, transmissions are not as reliable as in their wired counterparts. In the 802.11 standard, a transmission received that does not pass the cyclic redundancy code (CRC) check is determined to have been corrupted in transit; subsequently the frame is dropped and an ACK frame is not transmitted towards the source. After a brief period, the source, having not received an ACK, attempts to resend the frame in question (this process is repeated four times before the MAC protocol at the source node gives up on the transmission). Re-transmission of corrupt segments can be a frequent occurrence when the transmission conditions are adverse (say when the destination node is at the fringe of the source's transmission range).

Forward Error Correction (FEC) schemes can significantly increase the reliability of communications in such cases by including redundant information on the data delivered which can help repair data segments. In ad hoc network nomenclature and as far as the 802.11 protocol is concerned there is a significant choice to be made on where in the protocol stack the incorporation of the FEC is to be made. Specifically if the FEC mechanism requires new MAC functionality (or requires a new frame format), then the method cannot capitalise on the existing wide base of 802.11 based transceivers. Such an approach is included in [14]. On the other hand, if the approach does not require new MAC functionality, limitations of the legacy 802.11 MAC may hinder efficiency; for instance the work in [12] and [5] proposes the implementation of FEC that is located between the IP layer and the Logical Link Layer (LLC), which although does not require MAC alterations exhibits some drawbacks. For instance, the MAC cannot realise if an erroneously received frame is eventually corrected by the FEC decoder, which is located above the MAC layer (as no feedback functionality is included in the original 802.11 specification), and hence an unnecessary retransmission would occur.

To illustrate how a FEC method may be implemented at the MAC layer, an FEC method as applied to IEEE 802.11 MAC is now outlined. Choi et al. [3] have proposed a new MAC-level solution for FEC based on 802.11 compatible transceivers. Figure 10 shows the original and modified frame format necessary for the FEC mechanism to function. Through the simple addition of FEC fields, this MAC-level FEC can repair partially damaged payloads and operate in a mixed environment; the authors in [3] further acknowledge that in good transmission conditions the overhead of FEC might not be desirable and so have utilised a bit in the MAC header to identify whether the frame uses and FEC mechanism or not. Finally the solution in [3] also employs a technique named "retransmission combining". This means that partially corrected frames are not discarded but stored instead and when the retransmission of the frame is also partially erroneous, then combining its corrected parts with the originally corrected parts may result in a fully correct frame, thus avoiding another retransmission. Notably, in their evaluation in [3], the authors have observed significant performance improvement in terms of throughput when the wireless hosts are sufficiently far apart (over 10m), whilst the performance penalty (because of the FEC overhead) is negligible even when the packet error rate is very low.

Overall, FEC correction schemes can improve performance and exhibit little overhead. The biggest drawback to their adoption, in the context of 802.11, is that FEC schemes may require changes at the legacy 802.11 format which in turn implies that alterations at the firmware of wireless transceivers would be needed which makes deployment on the existing wireless hardware base problematic.

6 Dealing with Power Conservation

Generally, in ad hoc networks, mobile nodes operate under limited power reserves, which signifies the importance of designing algorithms that minimise energy consumption whenever possible. This can be achieved mainly in two ways:

- Topology control: this method refers to adjusting the transmission power of each node in a way such that energy consumption is reduced but some property of the network topology (such as connectivity) is maintained [15]. As a side-effect of reducing power consumption, topology control may increase the capacity of the network as interference is reduced. In short, the network as a whole is in focus in this case, as it is a property of the network that needs be maintained while overall power requirements are reduced, and each node adjust its behaviour accordingly to achieve that goal.
- Power control: this approach allows each node to make decisions on its own transmission power based on the surrounding interference levels. Some attention may be paid to the overall network conditions but the focus in this case remains firmly on the individual node.

To examine the power control principle the power saving method presented in [21] is outlined below. In that work Zhang et al. propose an adaptive power control mechanism for IEEE 802.11 based ad hoc networks, aiming to achieve sufficient throughput at a lower energy cost than the original 802.11 method. To achieve this the proposed method takes into account correlations that exist in the transmission power between successive frames in the long and short term.

The rationale for throttling transmission power in [21] can be outlined as follows. First, it is noted that the power requirements which ensure a successful RTS/CTS→DATA→ACK series of transmissions (which signify overall successful communication between source and destination), differ according to the frame type. Also it is noted that increasing power after an unsuccessful transmission (and thus assuming that the transmission failed due to insufficient power) is not always the right course of action (as happens in other power adapting algorithms [1]). For instance, an RTS frame may not prompt a CTS response because the destination's NAV does not allow such a response (because the medium around it is busy); increasing power for subsequent transmissions is unproductive in such cases.

The power adaptation method in [21] is titled the correlative adaptive power control (CAPC) algorithm and its rules may summed up as below. The transmission power of the CTS frame is set to the same level as that of the corresponding RTS and the ACK frame power level as that of the DATA frame. This information is added to an extra field in the headers of RTS and DATA frames. Also, in order to distinguish between losses caused by insufficient power to those due to infeasibility of any power assignment, the transmission power of DATA/ACK is not allowed to decrease at the same time as that of RTS/CTS and vice versa. This means that when action is taken and a subsequent metric does not show the desired results, it is possible to distinguish whether that is a result of insufficient transmission power of the RTS/CTS or DATA/ACK frames. The metric used to judge whether performance using a given power level is adequate is called the *packet delivery curve*. Interested users should refer to [21] for full details on this metric, but it should be noted that a packet delivery curve for a transmitting pair represents the relationship between the number of packets successfully received and those transmitted. According to measurements taken during packet exchanges at a full power state (say state **M**) it is possible to construct feasible and infeasible curves bounds for RTS and DATA packet delivery. These represent the fulfilment of a specific requirement which in this case is equivalent throughput to 802.11 transmission. Overall, the algorithm tries to reduce power consumption but at the same time monitors performance to ensure that 802.11 level performance is achieved.

The main algorithm is shown in Algorithm 1 which corresponds to the state diagram in Figure 11. State **M** (as mentioned above) is a is a parameter measuring state where full power is used for transmissions, state **D** is a state where the transmission power of DATA or ACKs is not allowed to decrease (but can increase) and state **R** is the equivalent state for RTS or CTS frames. The number of frames transmitted for each receiver is reflected in the *count* variable. In the **M** state when count reaches an R1 limit, the packet delivery curve is computed and checked against the measured values. In the **R** or **D** state a longer limit R2 dictates returning to the **M** state to restart measurements, which keeps the objective up to date.

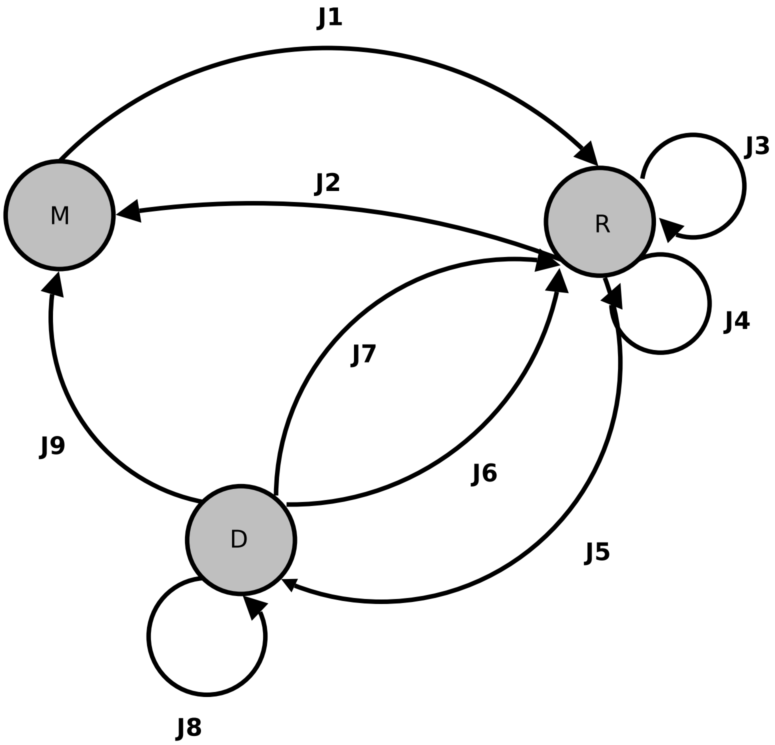


Figure 11: Accompanying state diagram for the CAPC algorithm

Algorithm 1 CAPC algorithm

```
J1: **when** $count \geq R1$ **do** $count \leftarrow 0$
J2: **when** $count \geq R2$ **do** $count \leftarrow 0$
J3: **when** DATA packet delivery curve is feasible **do** decrease DATA transmission power
J4: **when** RTS packet delivery curve is infeasible **do** increase transmission power
J5: **when** DATA packet delivery curve is infeasible **do** increase DATA transmission power
J6: **when** RTS packet delivery curve is infeasible **do** increase RTS transmission power
J7: **when** DATA packet delivery curve is infeasible **do** increase RTS transmission power
J8: **when** RTS packet delivery curve is feasible **do** decrease RTS transmission power
J9: **when** $count \geq R2$ **do** $count \leftarrow 0$
$count \leftarrow count + 1$ after each transmission attempt
```

The authors have evaluated the CAPC algorithm in a variety of scenarios where it has been shown to result in significant energy savings over both the standard 802.11 MAC as well as over another power adaptation mechanism called BASIC [10]. It is noted however, that the CAPC algorithm may lead to some unfairness in the case of TCP traffic even though it performs competently over UDP.

Concluding it should be noted that power adaptation is a major challenge in ad hoc networks. As shown by the CAPC algorithm presented above it might be necessary to include extensions to the 802.11 protocol to provide sufficient savings under a broad range of scenarios (in the case of CAPC extra information is needed on DATA and RTS frames). Such proposals make it difficult to deploy the solution on existing devices and interoperability with legacy hardware may be an issue; nevertheless it might be necessary to introduce at least minimal MAC changes in order to achieve considerable energy savings.

7 Conclusions

This report has presented selected works on the research conducted in the field of ad hoc wireless networks with respect to MAC protocols. This work has been motivated by the introduction of new features in wireless transceivers and the advances in understanding of ad hoc networking characteristics by the research community; both factors have resulted in improvement proposals on the legacy (but widely popular) IEEE 802.11 protocol. Each proposal outlined in this report has in turn been discussed with respect to its applicability and backwards compatibility with existing wireless transceivers.

The area of ad hoc wireless networking is still attracting significant research interest. As such, although simulation is the preferred evaluation technique for many literature studies, it is of little doubt that as ad hoc network deployments become commonplace, proposed new technologies will also be evaluated in testbeds. Such a development would increase confidence in the conclusions presented in the literature, as certain important side-effects of an evaluated technique may be lost in the simplifying assumptions of simulation but captured by testbed experimentation. Finally, with the proliferation of MANET deployments, certain scenarios or patters of use of ad hoc technology may emerge which would have very specific requirements. For instance, use of ad hoc networking in rescue operations over volatile environments may dictate additional MAC error correction facilities as opposed to, say, use of ad hoc networks in a classroom. As such, future proposed MAC techniques in MANETs may choose to emphasise their applicability in particular environments or scenarios and evaluate their effectiveness using typical scenario specific settings, such as particular node mobility patterns or traffic load and so on.

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