Survey Paper

A survey of MAC layer solutions to the hidden node problem in ad-hoc networks

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Abstract

Ad-hoc networks suffer from the problem of hidden nodes (terminals), which leads to severe degradation of network throughput. This survey gives a comprehensive overview of Medium Access Control (MAC) protocols which directly or indirectly address this problem. The presented protocols are grouped in several categories and are described in the order of their publication date. To give the reader a deep understanding of the progress made in the area of alleviating the hidden node problem a brief summary of the key ideas as well as a detailed comparison of different protocols are presented. Open research directions are also discussed to serve as a starting point for future protocol design and evaluation.

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1. Introduction

One of the most important roles in the performance of IEEE 802.11 networks is played by Medium Access Control (MAC) protocols. They must define an efficient way of sharing bandwidth and controlling access to the wireless channel. The most popular wireless MAC protocol is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In this scheme, a node must perform physical carrier sensing before each transmission. If the medium is busy, the node defers its transmission. When the medium becomes idle, the node transmits its data. However, collisions may occur at the destination if hidden nodes are present in the network.

A basic example of the hidden node problem is illustrated in Fig. 1. Node B is within the range of nodes A and C, while nodes A and C cannot hear each other's transmissions. Therefore, they can cause collisions at node B. In such a case, nodes A and C are called hidden nodes.

The hidden node problem has been known for many years. It was first described in 1975 by Kleinrock and Tobagi [1]. Since then it has been considered as a very interesting challenge and, therefore, a number of MAC protocols have been proposed in the literature which directly or indirectly address this problem. In general, they can be classified as: pure contention-based, multiple channel-based, busy tone signal-based, power-aware (also called energy-efficient), and directional antenna-based (Fig. 2). Obviously, protocols often fall in more than a single category. In this survey such protocols are described in their dominant category.

Several older solutions of the hidden node problem have already been described in [2–4], which included general overviews of MAC layer protocols and commented on different issues related to the area of ad-hoc networks. In this paper, only the problem of hidden nodes is investigated. Additionally, both old and new MAC protocols (starting 1987–2011) are described to present a comprehensive survey. Furthermore, for the convenience of the reader the descriptions of different protocols are supported by figures explaining their way of operation.

The rest of this paper is organized as follows. Sections 2–6 contain descriptions of MAC protocols addressing the problem of hidden nodes. They are divided based on their
category and presented according to their publication date. A short introduction at the beginning of each section provides a general description of each protocol category. A comprehensive comparison of protocols presented in this survey is included in Section 7. Future research directions are given in Section 8. Finally, the paper concludes with Section 9.

2. Pure contention-based protocols

Pure contention-based protocols are in most cases based on CSMA/CA. They can be divided into three groups: sender-initiated, receiver-initiated, and hybrid. They have two major advantages. Firstly, nodes use standard hardware with a single transceiver, which is relatively inexpensive and available on the market. Secondly, compatibility with IEEE 802.11 is possible if standard frames are used.

2.1. MACA (1990)

Multiple Access with Collision Avoidance (MACA) [5] is a sender-initiated protocol which first introduced two fixed-size signaling frames (Request to Send – RTS and Clear to Send – CTS) in order to alleviate the hidden node problem. The RTS frame is sent by the source to the destination. Every time when the sender’s neighboring nodes overhear the RTS frame they must defer their transmission. The RTS frame contains information on the length of planned transmission to inform other nodes in the network. As a result, after the neighboring nodes overhear the CTS frame, they must defer for the length of the expected transmission. Moreover, if two RTS frames collide which each other, each sending node must wait for a randomly chosen Backoff interval before invoking its

### MACA Protocols Addressing the Hidden Node Problem

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transmission again. This procedure is repeated until one of the senders overhears CTS from its destination or the frame is dropped. For the situation presented in Fig. 1, if node A sent an RTS frame to node B, node B would immediately send a CTS frame in reply. The CTS frame would be overheard by nodes A and C. Node C would defer its transmission and no collision would occur.

One of the biggest disadvantages of MACA is the lack of acknowledgments of a successful transmission at the MAC layer. With MACA all retransmissions must be performed by the transport layer of the OSI model, which increases the overall transmission delay. This makes the protocol unsuitable for delay sensitive traffic, e.g., voice and video.

2.2. MACAW (1994)

MACA for Wireless (MACAW) [6] is a sender-initiated protocol designed on the basis of MACA. This mechanism uses four signaling frames (RTS, CTS, Acknowledgment – ACK, and Data Sending – DS) to alleviate the problem of hidden nodes. The DS frame is used to inform deferring nodes about the successful RTS/CTS exchange and the length of the subsequent DATA frame. In comparison to MACA the acknowledgments at the MAC layer significantly decrease transmission delay, which also allows for faster error recovery.

MACAW can also take advantage of RRTS (Request for RTS). This frame is sent whenever a deferring node receives an RTS. After the successful contention during the next contention period it sends the RRTS frame to the sender of the RTS which immediately responds with an RTS frame. All other nodes overhearing RRTS must defer for long enough to hear the successful RTS/CTS exchange. Such a situation is illustrated in Fig. 4.

2.3. MACA-BI (1997)

MACA By Invitation (MACA-BI) [7] is another mechanism based on MACA. However, it is a receiver-initiated protocol. Instead of the RTS/CTS frames it uses a single Ready To Receive (RTR) frame, which contains the same information as a CTS frame. It serves as a polling frame (Fig. 5) and is sent by the destination node to the sender node. This allows to inform possible hidden nodes being in the transmission range of the RTR frame of the planned transmission.

In MACA-BI a sender cannot transmit data before being polled, therefore, the destination needs to have a built-in traffic prediction algorithm so as to know when to ask the sender for its data [2]. To achieve this, the authors of MACA-BI propose piggy-backing the information regarding the frame queue length and data arrival rate in the sender’s DATA frame. Additionally, whenever an RTR frame has not been received by the sender for a given time it can send an explicit RTS frame (in such a case the mechanism changes into MACA). Therefore, MACA-BI is suitable for networks with predictable traffic patterns as its performance degrades to MACA in case of periods of inactivity, which are common for bursty traffic [2]. Furthermore, the authors of MACA-BI stress that the control frames may collide with each other and/or DATA frames and lead to protocol failures. Recovery from such a situation is possible only by using ACK frames, however, explicit acknowledgments are not implemented in MACA-BI.
In 2002 a modification of MACA-BI was proposed which employs smart antennas [8]. It introduces the idea of omni-directional RTR frames which are used to simultaneously poll all neighboring nodes for data. All other frames are transmitted directionally. This minimizes the probability of collisions (including collisions caused by hidden nodes) and increases network throughput. A similar idea is also described in Section 6.6.

Additionally, in 2009, a Slotted MACA-BI [9] proposed to divide the wireless channel into fixed slots of equal size. The length of each slot is equal to the sum of the end-to-end propagation delay and the RTR frame size. This length was assumed to assure that RTR frames may only collide with each other and not with DATA frames. This minimizes the delay related to failure recovery and, therefore, the negative impact of hidden nodes on network performance.

2.4. FAMA (1997)

The group of sender-initiated Floor Acquisition Multiple Access (FAMA) protocols includes: FAMA with Non-persistent Carrier Sensing (FAMA-NCS) and FAMA for Non-persistent Packet Sensing (FAMA-NPS) [10]. Both protocols require the sender to obtain control of the floor (i.e., the wireless channel) before it is allowed to send any data.

The reservation of the wireless channel is done with the use of the RTS/CTS exchange. In order to obtain the medium, the sender transmits RTS after performing either carrier sensing (like CSMA) or packet sensing (like MACA). The destination node responds with a CTS frame long enough to avoid hidden nodes’ transmissions (Fig. 6). This behavior corresponds to a single channel Busy Tone Multiple Access (BTMA) scheme [11] which uses a busy tone signal sent on a separate busy tone channel to signalize transmission on a data channel.

In FAMA-NCS the duration of RTS frames is longer than the maximum propagation delay and the duration of CTS frames is longer than the duration of an RTS frame plus a maximum round-trip time and a maximum hardware transmit-to-receive transition time. FAMA-NPS does not require nodes to sense the medium before transmission. Additionally, it uses RTS and CTS frames of the same length. The time of transmission of these frames is longer than the maximum round-trip delay. The authors assume that FAMA-NPS may help avoid problems caused by hidden nodes only in fully connected networks in which CTS frames are transmitted just once (i.e., every hidden sender recognizes at once the node which has acquired the wireless channel). Therefore, FAMA-NCS is recommended by the authors because, in their opinion, it addresses the hidden node problem more effectively. However, FAMA-NCS requires each node to hear the interference to force it to keep silent for a period of a maximum data unit. As a consequence, when the RTS/CTS negotiation fails or the transmitted DATA frames are short this solution is ineffective.

2.5. Four-way handshake mechanism (1999)

In order to minimize the negative effects of hidden nodes on network performance the IEEE 802.11 standard [12] uses a four-way handshake exchange. The four-way handshake is a sender-initiated mechanism which involves four different types of frames: RTS, CTS, DATA, and ACK as illustrated in Fig. 7.

Each time an ad hoc node wants to transmit data the wireless channel has to be sensed idle for a predefined time period. For the Distributed Coordination Function (DCF), nodes wait for the DCF Inter-Frame Space (DIFS) time interval and for the Enhanced Distributed Channel Access (EDCA, standardized in 2005) they wait for the Arbitration Inter Frame Space (AIFS) time interval. If the medium is busy, the node must set its Backoff timer. When the Backoff timer expires the node is allowed to start the four-way handshake procedure. The RTS and CTS frames include information on the duration of the intended transmission. This allows other nodes to appropriately set their Network Allocation Vectors (NAVs)\(^1\) and minimize the number of collisions in the network.

2.6. AA (2003)

Advance Access (AA) [13] is a sender-initiated protocol which uses modified RTS and CTS frames in order to reserve the wireless channel and inform possible hidden nodes of planned transmissions. Those frames contain special lag times. This separates the control frames from their associated DATA frames (Fig. 8) and allows for scheduling simultaneous transmissions which are not possible if the standard DCF function is used. Additionally, ACK frames can be detached from their associated DATA frames or piggy-backed on the RTS/CTS (Fig. 8) or DATA frames.

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\(^1\) NAV is a counter which determines how long a node must defer from accessing the wireless medium. This mechanism is known as virtual carrier sensing.
2.7. Hybrid channel access scheme (2004)

The hybrid channel access scheme for ad hoc networks [14] adapts its channel access procedure and takes advantage of either sender-initiated (SI) or receiver-initiated (RI) handshakes (Fig. 9). The SI mode is set by default and the RI mode is triggered only if the SI mode fails. The authors claim that their scheme fits within the IEEE 802.11 standard, is simple and does not introduce any new control frames.

The source/destination pair decides on the RI mode when the sender transmits the same RTS frame for more than half of the time allowed by the IEEE 802.11 standard. In most cases, if the destination is unable to send a response to the RTS frame the contention around it is very severe. Therefore, according to the authors, it is better to let the sender change to the RI mode. In this mode the sender sets the RI flag in every frame it transmits to the destination. If the sender does not receive a CTS frame from the destination it can assume that the destination node is down. However, if the CTS frame is received, the sender enters the RI associated mode and sets the RI flag in each DATA frame it sends to the destination node. The RI flag can be cleared only when the sender does not have any more data to send. After the overload...
conditions are mitigated, the sender/destination pair returns to the SI mode. The two most important advantages of the described behavior are the reduced number of collisions (also those caused by hidden nodes) and shorter queuing delays [14].


Multiple Access Collision Prevention (MACP) [15] is a family of sender-initiated protocols in which nodes use prohibiting signals in order to compete with other nodes. The competition among nodes is done using a Distributed Multi-hop Binary Countdown (DMBC) procedure based on CSMA/CP (CSMA with Collision Prevention) [16]. In each round of DMBC competing nodes select appropriate binary Competition Numbers (CNs). During the competition period nodes send buzz signals in the i-th slot if the i-th bit of their CN is equal to one. Otherwise they listen to the channel and if during this time they hear a buzz signal they refrain from further transmission. As a result, a node with the largest CN wins the competition. After the competition is won MACP uses a traditional four-way handshake mechanism to send DATA frames. Additionally, MACP introduces the idea of mutually hidden terminal detectors. These are nodes which do not take part in competition but only receive RTS/CTS frames. The detector listens to the wireless channel to determine if there are any mutually hidden terminals in its range. After detection of such terminals it transmits a short Object-To-Send (OTS) signal during a dedicated detection slot to prevent hidden nodes from transmitting their control frames and force them to backoff (Fig. 10). The protocol can be extended to support QoS by assigning large CNs only to high priority frames and performing better with two transceivers.

2.9. EDCA/RR (2006)

EDCA with Resource Reservation (EDCA/RR) [17] is an enhancement of the IEEE 802.11 EDCA function. In order to reserve the wireless channel EDCA/RR uses Add Traffic Stream (ADTTS) requests and ADDTS responses. Therefore, the reservation method used in EDCA/RR is similar to the one implemented in the four-way handshake. The difference is that EDCA/RR is QoS-aware and, therefore, it combines hidden node awareness with QoS provisioning. The ADDTS requests contain a Traffic Specification (TSPEC) field, which describes characteristics of traffic flows, e.g., data rate, delay bound. This is done in order to transfer the admission control and scheduling mechanisms designed for infrastructure networks into ad hoc networks. The operation of EDCA/RR is presented in Fig. 11. Node C defers its transmission after it is informed by node B about A’s transmission time.

2.10. AQMP (2009)

The Adaptive QoS MAC Protocol (AQMP) [18] proposes enhancements to DCF in order to make it QoS-aware. Traffic is divided into two categories: high and low priority. AQMP introduces the idea of Transmission License (TL) and implements a new adaptive backoff mechanism, which can help to decrease the probability of collisions (also those caused by hidden nodes) in the network.

In AQMP only stations with TL are allowed to participate in the contention phase. Initially, each station obtains the TL by default. Then, each node calculates its queue packet loss rate. The higher the loss rate the higher the network load. After exceeding a predefined maximum value of packet loss rate, the station loses its TL in order to decrease the contention in the network. Each traffic class has a different threshold value of the queue packet loss rate. Nodes with low priority have lower threshold values, therefore, they will likely lose their TL before high priority nodes. TL is automatically renewed after a fixed time in order to allow participation in channel contention again.

Another mechanism for supporting QoS is backoff differentiation. After an unsuccessful transmission stations use an adaptive backoff mechanism, in which CW increases proportionally to a Persistence Factor (PF). PF is a function of the queue packet loss rate. When the loss rate is above a predefined average, PF of high priority nodes is decreased and it is increased for low priority traffic. Otherwise, PF is increased for high priority nodes and decreased for low priority nodes. Both PF and CW have their minimum and maximum values, which are assigned dependently on traffic category.

In 2010 an extended version of AQMP was proposed – Adaptive QoS MAC Protocol (AMP) [19]. It combines AIFS differentiation with the previous scheme and, therefore, further decreases the probability of collisions. The idea is similar to the one used in the adaptive AQMP backoff procedure. When the loss rate is above a predefined average, the AIFS Number (AIFSN, defined for EDCA) of high priority node is decreased and it is increased for low priority traffic. Otherwise, AIFSN is increased for high priority nodes and decreased for low priority nodes. Different traffic categories have diverse sets of AIFSNmin and AIFSNmax values.

2.11. Fair QoS assured MAC protocol (2011)

The fair QoS assured MAC protocol [20] is based on DCF. It distinguishes three traffic classes. Each traffic class has a different set of CWmin and CWmax values. Frames are enqueued in three separate queues based on their types. Each node along the path from the source to the destination counts the number of successful frame transmissions, separately for each flow. If two frames of the same priority but from different flows are enqueued in a single queue the one which belongs to less served flow is dequeued. Such behavior is obtained by changing CW values according to a scaling factor, which is the ratio of the number of successful frame transmissions for the current flow to the
number of successful frame transmissions for any better served flow of the same priority. The proposed mechanism can help hidden nodes to transmit data because in most cases they will have poor ratio of successfully transmitted frames in comparison to unhidden nodes.

3. Busy tone signal-based protocols

Busy tone signal-based protocols take advantage of one or more busy tone signals. These signals are used to keep hidden nodes silent and are usually transmitted in the form of pulses of energy. Busy tone signal-based protocols can be divided into single and multiple channel-based. Single channel protocols use standard hardware and are partially or fully inter-operable with the IEEE 802.11 standard. Multiple channel-based protocols require more complex hardware. The main advantage of busy tone signal-based protocols is that busy tones can be recognized more easily (and can therefore be shorter) than traditional MAC frames. Additionally, several of these protocols support QoS.

3.1. RI-BTMA (1987)

The Receiver-Initiated Busy Tone Multiple Access (RI-BTMA) scheme [21] divides the total bandwidth into two channels – one for the transmission of data, and one for the transmission of the busy tone signal (Fig. 12). Prior to DATA transmission, the sender sends a preamble which identifies the intended destination on the data channel. The preamble can be sent only if the channel is idle and, thus, if the channel is busy the preamble transmission must wait a random time. After the preamble is successfully received, the destination immediately sends a busy tone signal. This signal informs the sender of a successful preamble transmission and reservation of the data channel. Such behavior prevents hidden nodes which overhear the busy tone signal from transmitting on the data channel. Then, the sender transmits its data, while the destination node keeps sending the busy tone on the dedicated channel to keep other nodes silent.

3.2. DBTMA (1998)

The Dual Busy Tone Multiple Access (DBTMA) protocol [22] was designed on the basis of two protocols: BTMA [11] (designed for infrastructure networks) and RI-BTMA [21]. The goal of DBTMA is to meet the needs and requirements of ad hoc networks. The authors show that the network utilization of DBTMA is about twice as that of the traditional RTS/CTS-based schemes.

DBTMA divides the single common channel into two sub-channels – a data channel and a control channel. No synchronization between nodes is required. DATA frames are transmitted on the data channel, while control frames (RTS and CTS) are transmitted on the control channel. Additionally, two narrow-band tones (Receive-Busy Tone – BTr and Transmit-Busy Tone – BTt) are added to the control channel. Both busy tones are sine waves at two different frequencies with appropriate spectral separation. A basic time diagram for the DBTMA protocol is presented in Fig. 13.

The protocol functions as follows. The sender may send its RTS only after it did not sense any BTr on the control channel. It must also keep on sensing the BTr signal during the transmission of its RTS frame (to check if other nodes did not send a BTr during this time). If it senses a BTr during this period it will defer its transmission even after
the reception of a CTS frame from the destination node. When the destination node receives the RTS frame, it senses BTt on the control channel. Every time when there is no BTt (i.e., other nodes in the destination node’s area do not transmit on the data channel) the destination replies with a CTS frame and turns on the BTr. Otherwise it keeps silent. After receiving the CTS frame the sender node turns on BTt for the duration of its data transmission.

The use of busy tones helps to avoid unwanted transmissions on the data channel as every node that senses BTr or BTt will not start its own transmission. In particular, the BTr signal helps prevent the simultaneous transmissions by hidden nodes. Additionally, since hidden nodes can reply to RTS requests they are allowed to use the channel together with unhidden nodes.

The main disadvantage of DBTMA is that it does not use ACKs and it is not backward compatible with the IEEE 802.11 standard. Furthermore, it requires additional transceivers and channels.

DBTMA is the basis of DBTMA/DA [23] which uses directional busy tone signals. This technique allows increasing network throughput because reservations of network capacity are more precise. However, it may be expected that its performance would degrade with node mobility.

3.3. PUMA (2002)

The Priority Unavoidable Multiple Access (PUMA) protocol [24] enhances DCF to support strict priority real-time transmission in ad hoc networks. In PUMA every active node measures SIFS, PIFS (Point Coordination Function IFS), and DIFS intervals \((SIFS < PIFS < DIFS)\) after the end of each frame transmission before starting its own transmission. If the medium is determined to be idle for a PIFS interval, the sender proceeds with a real-time transmission by sending a JAM signal of the length of one slot to inform other nodes about its planned transmission. The PIFS interval was selected in order to silence all legacy IEEE 802.11 ad hoc nodes which need to sense the wireless channel to be idle for DIFS before each transmission. Upon receiving JAM, in order to silence possible hidden nodes and reserve the wireless channel, the RTS/CTS exchange takes place. After the successful channel reservation, the sender transmits its DATA frame in a collision-free manner.

Fig. 14 illustrates a typical real-time frame transmission for PUMA. In order to increase the efficiency of PUMA in networks with high load and a large number of contending nodes, a Backoff scheme called Double Increment Double Decrement (DIDD) [25] is used as the default Backoff mechanism. In DIDD after each unsuccessful transmission the Contention Window (CW) is doubled and after each successful transmission it is divided by half. The DIDD mechanism is applied only to low priority flows. High priority flows use the traditional DCF Backoff procedure.

3.4. BusySiMon (2010)

Busy Signal-based Mechanism turned On (BusySiMon) [27] is a protocol which minimizes the probability of collisions of signaling frames and, therefore, decreases the negative impact of hidden nodes. To achieve this goal the channel reservation procedure consisting of the following two steps is proposed. First, fast preliminary reservation of the wireless channel is done using two short busy tone signals. Second, information about the transmission duration as well as the addresses of the sender and the destination nodes are distributed in RTS and CTS frames. This two step procedure is illustrated in Fig. 15.

The indisputable advantage of BusySiMon is that it resolves the problem of prioritizing traffic by the combination of the proposed reservation mechanism with the unchanged EDCA access parameters. This makes it compatible with EDCA and guarantees appropriate QoS support.

4. Power-aware protocols

The primary goal of power-aware protocols is to decrease the energy consumption of wireless nodes. They
can also be designed in order to minimize the probability of collisions of simultaneous transmissions, combined with busy tones, or take advantage of multiple channels in order to deal with the problem of hidden nodes in a precise way.

4.1. PAMAS (1998)

PAMAS [28] is a power-aware mechanism which is a combination of MACA (Section 2.1) and the idea of separating the signaling channel from the data channel. As a result, the protocol assumes that all the RTS/CTS exchanges are performed over the control channel while the transmission of DATA frames is performed over the data channel (Fig. 16). The separate control channel is used also in order to determine for how long the silent nodes may power off their transceivers.

The basic scheme of the PAMAS operation is given next. During data reception the destination node is obliged to start transmitting a busy tone signal over the signaling channel. All other nodes must listen on this channel in order to find out when they should power down their transceivers. They go to the off state when they do not have data to transmit and when they hear that the data channel is busy. The exact time of being turned off is given by a detailed set of rules [28].

It was shown that PAMAS successfully handles the hidden node problem in a four node line scenario in which, e.g., the MACA protocol fails [28]. The main drawback of PAMAS is that it does not consider the time needed to turn-around a transceiver which, in some cases, is significant and may lead to considerably worse system performance. Additionally, PAMAS should be extended by MAC layer acknowledgments.

4.2. PCMA (2001)

Power Controlled Multiple Access (PCMA) [29] uses two channels – one for busy tone transmissions and the second for the DATA and control frame transmissions. The operation of PCMA is presented in Fig. 17. First the sender and destination nodes exchange the Request-Power-To-Send (RPTS) and Acceptable-Power-To-Send (APTS) frames on the data channel. This is done in order to find the minimum

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2 The RPTS and APTS frames are similar to the RTS and CTS frames. The only difference is that they do not force hidden nodes to backoff.
transmit power which is required by the destination node to decode the transmitted frame. Then, the DATA and ACK frames are exchanged on the data channel and a busy tone is sent on the busy tone channel. The busy tone is transmitted by the destination node in the form of pulses of energy in order to advertise its tolerance to additional noise to other competing nodes. On the basis of this information, each potential transmitter can detect the upper bound of the transmit power for its DATA and control frames. This way of operation also reduces the interference range, and therefore, also the number of hidden nodes.

4.3. PCM (2005)

The Power Control MAC (PCM) mechanism [30] assigns transmit power levels according to frame type in order to save energy. Fig. 18 illustrates carrier sensing and transmission ranges for DATA/ACK and RTS/CTS frames used in the proposed power control scheme. The RTS and CTS frames are sent with the maximum available power level. This helps informing possible hidden nodes of the planned transmission. The DATA and ACK frames are sent with the minimum power required to assure communication between the sender and the destination nodes. Let us assume that in Fig. 18, node D wants to transmit its DATA frame to node E. Therefore, nodes D and E exchange the RTS and CTS frames with the maximum transmit power level. As a result, nodes B, C, F, G receive appropriate control frames and defer their transmissions for the duration of DATA-ACK transmission between nodes D and E. The carrier sensing ranges for the DATA and ACK frames are smaller than for the RTS and CTS frames. Therefore, nodes A and H cannot sense these transmissions. This may result in collisions because nodes A and H may start their own transmission with the maximum possible transmit power level. To solve this problem, the authors of PCM propose to periodically transmit DATA with the maximum power level.

The main drawback of PCM is that the constantly changing conditions of the wireless channel (caused by signal fading and/or shadowing) may degrade its performance [2]. Another difficulty is to implement frequent changes of the transmit power levels in the wireless hardware, proposed by the authors for DATA frames in order to prevent collisions, which may appear in the proposed scheme [2].
4.4. RICK (2004)

Random ID countdown with ACK (RICK) [31] is a protocol designed for ad hoc, sensor and mesh networks, which builds on MACP (Section 2.8). Instead of the traditional RTS and CTS frames RICK employs prohibiting signals so that nodes with smaller Competition Numbers (CNs) refrain from transmission. The prohibiting signals can be transmitted in a separate narrow-band control channel. The CNs are composed of two parts – random and ID. In order to support QoS and fairness, the random part is selected according to appropriate probability distributions. Typically, this results in larger CN values for high priority data. The ID part contains the identifier of a particular source-destination pair. Finally, by setting appropriate power levels of the prohibiting signals the overall network throughput can be improved, the number of collision-free transmissions within the same area can be increased, and the impact of hidden nodes can be minimized.

4.5. DRCE (2005)

The Dual-channel RTS/CTS/ETS (DRCE) protocol [32] is a scheme proposed for mobile ad hoc networks. It uses RTS, CTS and Ensure To Send (ETS) frames to reserve the wireless channel and silence possible hidden nodes. The CTS and ETS frames are used to inform about the final receiving and sending schedules, respectively. Therefore, upon receiving the RTS/CTS/ETS frames, every node makes appropriate reservations on the control and data channels (Fig. 19). DRCE uses additional Negative-ACK (NACK) frames to reschedule frame transmissions, e.g., when the wireless channel is busy.

A power-controlled version of DRCE was also proposed in [32]. It requires more complicated hardware, which measures the received signal strength and allows to control the transmission power of frames.

4.6. GMAC (2007)

GMAC [33] is a TDMA-based protocol. GMAC schedules transmissions not by control frames but based on the geographic position of nodes. GMAC operates as follows. Time is divided into super-cycles, which are divided into cycles and each cycle consists of slots. All stations in the network are synchronized. Each cycle can be represented by a circle composed of segments representing slots (Fig. 20).

Slot assignment is based on the geographic location of stations. In Fig. 21 n₁ is allowed to transmit data to n₂ in slot 3 and n₁ listens for that data in slot 3. Consequently, n₃ is allowed to send data to n₁ in slot 7, n₃ can send data to n₂ in slot 2, etc.

![Frame Exchange Sequence](image)

![Channel Reservations](image)

Fig. 19. DRCE operation [32].

Fig. 20. Slotting in GMAC and the circular representation of cycles [33].
to increase the overall network throughput, reduce the
delay and reduced frequency of RTS frame collisions.

5. Multiple channel-based protocols

Multiple channel-based protocols use several channels
to increase the overall network throughput, reduce the
number of collisions (including those caused by hidden
nodes), and decrease transmission delays. They can take
advantage of using busy tone signals and load balancing
to additionally improve their performance. There are three
categories of such protocols: with a common control chan-
el (CCC), without a common control channel, and hybrid.

5.1. MAC protocols with a common control channel

MAC protocols with a common control channel are pro-
posed as means to reduce collisions between different frame types by utilizing the separation of the signaling
and data channels. Usually less bandwidth is assigned to
the signaling channel than to the data channel. The trans-
mission of different frame types over different channels
can reduce the number of collisions.


Multi-Channel Variable-Radius Multiple Access (M-
VRMA) [35] is a power-controlled multi-channel MAC
scheme. It divides the wireless channel into \( m \) sub-chan-
nels – one public control channel and \( m − 1 \) data channels.
The RTS and CTS frames are transmitted on the control
channel. They are used to select an appropriate data chan-
el and reserve it for a DATA frame duration. CTS frames
are transmitted with low power levels which reduces their
transmission ranges and, consequently, increases the net-
work throughput. However, this way of operation reduces
the number of hidden nodes overhearing the CTS frames.
Additionally, Object-To-Sending (OTS) frames are used to
inform the sender of the RTS frame about already sched-
uled transmission (Fig. 22). After receiving OTS the sender
postpones its RTS transmission to a later time. The OTS
frames can be transmitted by a third-party node.

An advantage of M-VRMA is that nodes need to imple-
ment only a single transceiver. However, this solution
needs sufficient lag times in order to allow nodes to turn-
around their receivers and tune them to the frequency of
the selected channel.

5.1.2. DUCHA (2006)

The Dual-Channel MAC Protocol for Multi-hop Ad Hoc
Networks (DUCHA) [36] introduces the Negative CTS
(NCTS) frame and the Negative ACK (NACK) busy tone sig-
nal. NCTS is transmitted over the control channel and is
used to inform of the remaining time of the ongoing DATA
transmission. The NACK tone is sent by the destination
node on the busy tone channel to inform of a data trans-
mission failure. The protocol does not use ACK frames.
The basic time diagram of DUCHA is presented in Fig. 23.

DUCHA functions as follows. Before the transmission of
an RTS frame the control channel must be idle for at least a
DIFS period. If the channel is busy for a given time (i.e.,
equal to or longer than an RTS transmission) a node must
defer its transmission to avoid collision with a CTS frame.
Otherwise it transmits RTS. Then, if the data channel is idle,
the destination node of the RTS frame transmits the CTS
frame without checking the state of the control channel.
After correct reception of the CTS frame, if the control
channel is idle, the sender starts transmitting its data.
However, if both channels are busy upon the reception of

![Fig. 21. TDMA slot assignment in GMAC [33].](image-url)
the RTS frame, the destination node ignores the received RTS to avoid a collision. Finally, if the control channel has been idle for at least the duration of a CTS transmission and the data channel is busy, the destination node transmits NCTS. If the sender receives NCTS, it defers the data transmission for the time given in NCTS. Otherwise, it assumes a collision, defers the transmission, and doubles its Backoff window.

Every time a CTS frame is sent over the control channel the destination node must wait for a DATA frame. Whenever it starts receiving DATA it also transmits a busy tone over the busy tone channel in order to prevent possible hidden nodes from starting their transmissions on the data channel. The sender assumes a successful data transmission if there is no NACK sensed during the NACK period. Additionally, any node located in the carrier sensing range of the source or the destination node is not allowed to receive data during the NACK and data transmission periods.

**5.1.3. SAM-MAC (2008)**

The Self-Adjustable Multi-channel MAC (SAM-MAC) [37] divides available channels into one common channel and n data channels. In order to balance traffic over different channels each node is equipped with two transceivers. The common channel can be used for data transmission if it is not overloaded with traffic. Since SAM-MAC uses multiple channels to increase the overall network throughput it is especially attractive if the number of data channels is large [37].

Besides the standard frames (RTS, CTS, DATA and ACK), SAM-MAC introduces several new frames sent on the common channel: NCTS (sent when the destination node is unavailable), RTF/ATF (Request To Find/Acknowledgment To Find, to find the channel used by the destination node), RCT/ACT (Request To Change Traffic channel/Acknowledgment to Change Traffic channel, to change the traffic channel of the sender), NBC (NAV broadcast, transmitted to avoid the multi-channel hidden node problem which is described below).

Each node stores information about the traffic channels used by its neighbors. This information is exchanged on the common channel. If a particular source node knows which traffic channel is used by the destination node it transmits an RTS frame over this channel (Fig. 24a). Otherwise, it receives this information on the common channel after transmitting an appropriate query (Fig. 24b).

Multi-channel protocols introduce the multi-channel hidden node problem. An exemplary scenario illustrating the problem is presented in Fig. 25. Node A communicates with node B on a certain data channel. Node C, hidden to
node A, switches to this channel at time $t_1$ and misses the CTS frame. To face this problem, the NBC frame is exchanged on the control channel in order to inform node C about the NAV included in the missed CTS frame.

5.1.4. CCM-MAC (2009)

The cooperative CDMA-based multi-channel MAC (CACM-MAC) protocol [38] also divides the available channels into one control channel and $n$ data channels. However, each node is equipped with only a single transceiver. Control frames are transmitted using a specific common code. DATA frames are transmitted using a unique pseudo-random code. Additionally, each node maintains a channel status table with information about the busy data channels.

Nodes utilize the following frames during the wireless channel reservation procedure: RTS, CTS, DCTS (Decide Channel To Send), ITI (Information To Inform), and CFM (Confirm). DCTS informs of the selected channel, ITI is used by cooperating nodes to help the source/destination nodes in making decisions, and CFM informs neighbors of the receiver of the selected channel. A typical channel negotiation procedure is illustrated in Fig. 26. The CTS frame transmitted by node C informs the sender (node B) of the free data channels. The ITI frames carry additional information about the channel state. Utilizing information from A, B selects a particular data channel and informs C about its choice using the DCTS frame. If the selected channel is available, C returns the CFM frame to confirm the sender’s choice.
The advantages of CCM-MAC are the following. The protocol allows simultaneous transmissions on different channels. Additionally, it lessens the multi-channel hidden and exposed node problems with the use of information on the state of different channels gathered from cooperating nodes.

5.1.5. Self adjustable multi-channel MAC (2009)

Self Adjustable Multi-Channel MAC [39] operates using one or multiple transceivers. It modifies the RTS/CTS frames for multi-channel usage and divides the transmission frame into two periods: channel negotiation and data transmission. The modified Multi-channel RTS (MRTS) includes the control channel number as well as information on the available channels and their quality. The modified Multi-channel CTS (MCTS) also inform possible hidden nodes of planned transmissions. An additional frame, MCTS-R (MCTS Recognition), is used to confirm the channel reservation if the selected data channel (either primary or backup) is still free after the MCTS frame was received by the sender node. Otherwise, the MCTS-R frame informs about reservation failure.

5.1.6. MPCD-MAC (2011)

The Multi-channel Power-Controlled Directional MAC (MPCD-MAC) protocol [40] assumes that nodes are equipped with multiple interfaces with directional antennas. Its operation is based on (i) transmission of modified RTS and CTS frames on the control channel in all directions at the maximum power level and (ii) directional transmission of DATA and ACK frames on a chosen data channel at the minimum power required to assure successful reception of data. The transmission of the modified RTS and CTS frames in all directions is required to inform as many neighbors (including the hidden ones) of the source node as possible on the intended transmission. The modified RTS frame includes information on the chosen data channel. The modified CTS frame, among other things, informs of the availability of the chosen data channel at the receiver. MPCD-MAC implements two different NAVs: a NAV for the control channel (indicates the duration of the RTS/CTS exchange) and a Directional-NAV (D-NAV) for the data channel (which has entries for each data channel and for each antenna sector about the minimum transmission power level which can interfere with an ongoing transmission and the planned duration of this transmission). The information specified in D-NAV is used during the data channel and transmission power selection. Therefore, MPCD-MAC can limit the hidden node problem by reserving the data channels on a separate signaling channel without interfering with previously established connections.

5.1.7. CA-CDMA (2011)

The Controlled Access CDMA (CA-CDMA) [41] protocol uses two frequency channels (data and control). A common spreading code is used over the control channel and several node-specific codes are used over the data channel. The code used over the control-channel is orthogonal to other codes. CA-CDMA modifies the RTC/CTS frames, which are transmitted over a control channel at a fixed maximum power level. The modified RTS frame includes information on the maximum power level which can be accepted by the neighbors of the source node without disturbing their ongoing receptions. The modified CTS frame contains information on the additional noise power which can be accepted by the receiver node from each of its neighbors without affecting its current reception. Based on the information included in the modified RTS/CTS frames the transmission power of DATA frames can be dynamically adjusted to allow simultaneous transmissions in the neighborhood of the destination node. This way of operation allows to reduce interference caused by hidden nodes.

5.2. MAC protocols without a common control channel

MAC protocols without a common control channel, in contrary to the CCC solutions, arrange different channels for RTS, CTS, DATA, and ACK frame transmissions in a flexible way. The goal is to minimize the probability of collisions, including those caused by hidden nodes.

5.2.1. JMAC (2003)

The Jamming-based MAC (JMAC) protocol [42] divides the entire bandwidth into two sub-channels (S and R, Fig. 27) with a ratio of x: (1 – x) (the method of choosing x is given in [42]). Channel S is used for the transmission of RTS and DATA frames. Channel R is used for the transmission of ACK and CTS frames. One transceiver is used for each channel.

The basic access procedure of JMAC is presented in Fig. 27. The R channel must be sensed idle for a DIFS period before an RTS frame can be transmitted. Otherwise, it performs the Backoff procedure. After a successful transmis-
sion of the RTS frame, the sender node must wait for a CTS frame. After the reception of the RTS frame the destination node responds with a CTS frame and starts listening on the S channel for data. Then, after finishing the data transmission, the sender awaits for an ACK frame. While waiting for the CTS and ACK frames the sender node jams the S channel. This is done with the same purpose as the reservation mechanism in IEEE 802.11 (i.e., sending RTS). The main difference is that the medium is jammed as long as needed. On the other hand, the destination node during the reception of a DATA frame on the S channel jams the R channel in order to prevent other nodes from sending RTS frames on the S channel. The sender will stop jamming only after the RTS/CTS exchange fails and the destination node will stop jamming only when the data transmission appears unsuccessful. The presented mechanism helps to effectively block hidden nodes which are two-hops from the sender node.

5.2.2. ICSMA (2003)

The Interleaved Carrier Sense Multiple Access (ICSMA) protocol [43], like JMAC, divides the entire bandwidth into two sub-channels. It also employs a single transceiver for each channel. However, in contrary to JMAC, the channels are of equal bandwidth and the transmission may originate on either of the two channels. The destination node sends RTS and DATA on either channel while the destination node responds by sending ACK and CTS on the other channel. This way of operation not only allows to inform hidden nodes of planned transmissions but also reduces the overall number of frame collisions in comparison to protocols using a single wireless channel.

Fig. 28 presents the ICSMA procedure in the case of simultaneous transmissions between two nodes. In general, the ICSMA access procedure is similar to that of IEEE 802.11. The main difference is that ICSMA uses two channels. This prevents signaling frames from colliding with each other and, in some situations, allows for carrying two simultaneous transmissions (Fig. 28).

5.2.3. MMAC (2004)

In the Multi-channel Medium Access Control (MMAC) protocol [44] nodes utilize multiple channels by switching among them dynamically, using only one transceiver. Every node maintains a Preferred Channel List (PCL) which stores information about the usage of channels inside its transmission range. During an Ad hoc Traffic Indication Message (ATIM) window, PCL lists are transmitted by the

![Fig. 27. Basic access procedure of JMAC [42].](image)

![Fig. 28. Simultaneous transmissions with ICSMA [43].](image)
sender nodes within an ATIM frame in order to pass this information to the destination node (Fig. 29). On the basis of this information and its own PCL each receiver can choose an appropriate channel for data transmission. After the channel is selected, the destination node transmits an ATIM-ACK frame which includes information about the chosen channel. After the sender accepts the selected channel it replies with an ATIM-RES (ATIM-Reservation) frame. Then, on the chosen channel, the source and the destination nodes use the traditional four-way handshake mechanism to exchange data and inform possible hidden nodes of the intended transmission. Obviously, all nodes overhearing ATIM-ACK and ATIM-RES frames update their PCLs.

The authors of [44] claim that in comparison to IEEE 802.11 MMAC achieves higher throughput values and lower frame transmission delays. Additionally, because each node needs to implement only a single transceiver it does not need complex hardware. Finally, the authors stress that in order to save power, each node can change its state into doze mode if it did not transmit or receive frames for a predefined time. Unfortunately, MMAC is not suitable for multi-hop networks because it assumes full synchronization between nodes. Additionally, lack of an efficient channel selection algorithm may lead to poor performance [45]. Furthermore, MMAC may have large frame delays and may increase the number of exposed nodes [40].

TDMA-based MMAC (TMMAC [46]) is a modification of MMAC proposed in 2007. Similarly to MMAC it requires time synchronization and assumes beacon intervals of a fixed length (consisting of an ATIM window and a Communication window). However, in contrast to MMAC, TMMAC dynamically adjusts the ATIM window size depending on different traffic patterns. Additionally, in TMMAC the Communication window is divided into slots (of the length of the duration of a single frame transmission or reception) and TDMA is employed. In the ATIM window, nodes not only select the channels but also decide which slots will be used for their data transmissions.

5.3. Hybrid protocols

Hybrid multiple channel-based protocols temporarily use one of the data channels to act as a control channel.

5.3.1. MAC-SCC (2003)

The MAC with a Separate Control Channel (MAC-SCC) protocol [47] divides the available bandwidth into two sub-channels: control and data. The authors suggest that the two sub-channels may be created by using two codes with different spreading factors in Direct Sequence Spread Spectrum. To reduce the overall transmission time, the control frames (RTS and CTS) may be transmitted not only over the signaling channel but also over the data channel. Additionally, the protocol introduces two NAVs, one for each of the two sub-channels. Updating NAVs is similar to that in the IEEE 802.11 standard. The two NAVs allow for scheduling not only the ongoing but also the subsequent transmission which leads to backoff time reduction.

An exemplary operation of the MAC-SCC protocol is given in Fig. 30. In the presented scenario two source/destination pairs exchange their data. Channel A is initially the data channel while channel B is the signaling channel.

As can be seen, the Source 2/Destination 2 pair exchange their signaling data on Channel B without interfering with data transmission between the Source 1/Destination 1 pair on Channel A. Consequently, the DATA frame from Source 2 can be sent to Destination 2 imme-
ately after the Source 1/Destination 1 pair stops their frame exchange sequence. Therefore, in comparison to IEEE 802.11, with the use of MAC-SCC Source 2 will defer for a shorter time (it will not waste bandwidth by using the Backoff procedure). Thus, the channel utilization will be higher and the average throughput achieved by nodes will be increased.

Regarding the hidden node problem, it is not fully solved by MAC-SCC because, like many other protocols, the mechanism is mainly based on the RTS/CTS exchange. However, in a two-hop environment, the degrading impact on the network performance will be lessened thanks to the use of an additional channel which helps to increase the number of successful handshakes.

5.3.2. Hybrid protocol (2009)

In [48], the authors propose a hybrid MAC protocol which combines the advantages of a common control channel and a common control period. It also supports power management (i.e., each node can go into the sleep mode and wake up periodically at each ATIM window) and multi-rate transmissions. Furthermore, similarly to MMAC [44], the hybrid protocol uses ATIM, ATIM-ACK, and ATIM-RES frames to conduct channel negotiations (Fig. 31). However, unlike MMAC, the protocol uses two transceivers. Therefore, channel negotiations can be done on two separate channels. After the ATIM window, RTS, CTS, DATA, and ACK frames are exchanged on the chosen channels. The use of the RTS and CTS frames allows to minimize the number of collisions caused by the presence of hidden nodes.

6. Directional antenna-based protocols

Directional antenna-based protocols allow for simultaneous data transmission and reception in order to increase

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**Fig. 30.** MAC-SCC operation [47].

**Fig. 31.** Hybrid protocol operation [48].
spatial reuse. They minimize the probability of frame collisions (also caused by hidden nodes) and usually achieve higher network efficiency than IEEE 802.11.

6.1. DMAC (2002)

The basic Directional MAC (DMAC) protocol [49] assumes that the higher layers are aware of neighbors of a particular node and are able to provide transceiver profiles required to communicate with each neighbor. The operation of DMAC is based on the four-way handshake mechanism and it is the following. Nodes listen on the wireless channel omni-directionally and create Directional NAV (DNAV) tables to keep track of ongoing transmission directions and their corresponding durations. Channel reservation is done with directionally transmitted RTS and CTS frames preceded by the Backoff procedure. DATA and ACK frames are also sent directionally. The authors of DMAC admit that using directional RTS/CTS transmissions introduces two new kinds of hidden nodes – hidden nodes caused by asymmetry in gain (also called the directional hidden node problem) and hidden nodes caused by unheard RTS/CTS. Additionally, they mention deafness as another drawback of directional beam-forming. The deafness problem appears when a node does not hear RTS/CTS exchanges for new transmissions because it is engaged in its own directional transmission. The problem of node deafness is addressed in [50].

A variation of this protocol is DMAC with Power Control and Directional Receiving (DMAC-PCDR) [51]. The authors of DMAC-PCDR assume that each node is equipped with GPS and the location information is obtained at the MAC layer. Idle nodes rotate the directional receiving antenna beams, which solves the directional hidden node problem. Additionally, DMAC-PCDR includes three access modes. They are selected depending on the availability of the destination node’s location information. Finally, the protocol supports two transmission power controls (i.e., two different transmission power levels can be used to transmit frames of different types) in order to reduce the interference range and increase spatial reuse of the wireless channel.

6.2. CDR-MAC (2007)

The Circular Directional RTS MAC (CDR-MAC) [52] protocol supports neighbor discovery and tracking. CDR-MAC introduces consecutive directional transmission of RTS frames in directions 1 to \( m \) (Fig. 32) to inform neighbors about its planned transmission. The circular directional transmission is achieved thanks to antennas with a predefined number of beams. After overhearing the RTS frame, the destination node transmits a directional CTS frame for which the sender listens omni-directionally. The transmissions of DATA and ACK frames are also directional.

To resolve the problem of neighbor’s locations each node maintains a Location Table, with information about beams from which the transmitter received a frame and by which the destination node transmitted a frame. This allows for maintaining pairs of beams used for direct transmissions. The Location Table is updated every time a node receives a frame.

Thanks to the circular directional transmissions of RTS frames and Location Tables the protocol alleviates the hidden node and the deafness problems. The performance of CDR-MAC can be, however, degraded by long DIFS intervals, RTS collisions and interference from minor lobes [53]. Additionally, CDR-MAC has a large signaling overhead [54].

6.3. CDMAC (2009)

The Coordinated Directional MAC (CDMAC) [54] allows for parallel directional DATA/ACK transmissions. Additionally, it uses omni-directional RTS/CTS transmissions to minimize the deafness problem. It is assumed that each node has a single transceiver but it can dynamically switch from directional to omni-directional transmission and reception.

Parallel DATA/ACK transmissions are possible thanks to a coordinated MAC timing-structure in which, in order to reserve the wireless channels and silence possible hidden nodes, multiple omni-directional RTS/CTS frame exchanges take place before any DATA transmission. In addition to RTS/CTS frames the CDMAC protocol uses an omni-directional Confirmed RTS (CRTS) frame. CRTS is transmitted by the sender node to confirm the reservation and inform other nodes about the channel which will be used for the scheduled data transmission.

The timing structure of CDMAC is illustrated in Fig. 33. Firstly, a local Master Node (MN) is selected. Then, Slave Nodes (SNs) are selected to transmit their DATA and ACK frames in a contention-free manner. This is done in order to alleviate the exposed node problem. The RTS/CTS/CRTS handshake is used for both SN and MN contention.

6.4. RDMAC (2009)

Reservation-Based Directional MAC (RDMAC) [53] operates in sessions comprising of two periods – reservation and transmission. The reservation period consists of two phases – probing and beam-indication (Fig. 34). In the
probing phase, nodes transmit the RTS and CTS frames using omni-directional antennas (denoted ORTS and OCTS, respectively). In the beam-indication phase and in the transmission period, nodes transmit either the RTS and CTS frames or the DATA and ACK frames using directional antennas. In this case the RTS and CTS frames are called DRTS and DCTS, respectively. Additionally, similarly to DMAC (Section 6.1), each node maintains a DNAV table, which is checked during the probing phase and is updated during the beam-indication phase. This way of two-step channel reservation allows to reduce the interference among nodes.

The authors of RDMAC explore location-dependent carrier sensing and the problem of interference caused by the minor lobes of antennas, which in many previous directional antenna-based protocols was considered to be known a priori. Another advantage of RDMAC is that it allows for simultaneous directional transmissions. This technique allows to increase the overall network throughput and decrease transmission delay. Finally, it gives better results in comparison with CDR-MAC and DCF [53].

6.5. MCDA (2009)

In the Multi-Channel MAC protocol with a Directional Antenna (MCDA) [55] each node is equipped with a single antenna and has to switch between the data and control channels. Therefore, to cope with the channel collision problem (i.e., situation in which the control channel information cannot be heard because a node is tuned to a data channel) the authors adopt the channel switch sequence (CSS) mechanism. CSS enables direct switching to the next data channel without negotiation. Additionally, MCDA implements RTS/CTS/DATA/ACK exchange. RTS frames are transmitted omni-directionally on the control channel and directionally on the data channels. All CTS/DATA/ACK frames are transmitted directionally.

MCDA operates in three phases: negotiation, communication, and block. In the first phase the source-destination pair exchanges RTS/CTS frames on the control channel to select the data channel. In the communication phase, the nodes exchange RTS/CTS frames on the selected data channel to avoid the hidden node problem. If the source-destination pair succeeds in RTS/CTS negotiations it can exchange DATA/ACK frames on the data channel in the communication phase. The block phase is used in overload situations. If a pair of communicating nodes stays in the block phase it switches to a single data channel and waits for the channel to become idle. This prevents nodes from inefficient switching to busy data channels.

6.6. MARS (2009)

Multiple Access Scheme with Sender driven and Reception first for Smart antenna (MARS) [56] is a protocol which changes RTR frames into Ready To Receive and Transmit (RTRT) frames. RTRT frames include addresses of the source and destination nodes. A node transmits an RTRT frame when it has data to send (middle node in Fig. 35). Because the RTRT frame includes the transmitter address, the neighbors of the middle node can adjust their antennas to its direction and transmit their RTS frames. If a particular neighboring node does not have data to send it sets the size of data to zero. Upon reception of the RTS frames the middle node adjusts the gain pattern of its antenna and transmits all corresponding CTS frames. Then, the directional DATA and ACK frames transmissions take place. This way of operation allows to reduce polling overhead and interference in comparison to the IEEE 802.11 standard. After the successful reception of data from its
neighbors the middle node reserves the wireless channel and transmits its own DATA frame. Such behavior, however, may be undesirable for delay sensitive traffic.

7. Comparison

The main advantages and disadvantages of the different MAC protocol categories presented in this paper are gathered in Table 1. Table 2 contains an additional detailed comparison of most of the presented protocols sorted by their publication date. Selected column headers can be commented as follows: required change (subjective evaluation of the number of changes introduced to the IEEE 802.11 standard), modification (proposed modifications in comparison to the IEEE 802.11 standard), hardware (complexity of the required hardware), overhead (subjective evaluation of the signaling overhead in comparison to the IEEE 802.11 standard), reservation method (frames used for channel reservation), reservation time (subjective evaluation of the entire channel reservation time required before each DATA frame transmission), QoS (support for Quality of Service), and hidden node support (whether this was the primary goal of the protocol). The remaining column headers are self-explanatory. Studying the two tables gives the reader a deeper understanding of the progress made in the area of alleviating the hidden node problem.

8. Future research directions

As described in this paper, significant research has already been performed in the area of hidden nodes. However, a number of issues remain unresolved or not completely addressed. Therefore, this chapter contains speculation on future research challenges.

Designing a new protocol resilient to hidden nodes requires careful consideration. This is because the problem

<table>
<thead>
<tr>
<th>Protocol type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>Pure contention-based (e.g., MACA, four-way handshake, EDCA/RR)</td>
<td>Standard hardware, interoperability with IEEE 802.11 if standard RTS and CTS frames are used</td>
<td>Medium/large signaling overhead, slow/very slow channel reservation, often not suitable for delay sensitive traffic</td>
</tr>
<tr>
<td>Single channel busy tone-based (e.g., PUMA)</td>
<td>Standard hardware, easy recognition of busy tones, partial or full interoperability with IEEE 802.11. QoS support, fast channel reservation possible</td>
<td>Signaling overhead may be increased in comparison to IEEE 802.11, legacy nodes may be assigned a lower priority</td>
</tr>
<tr>
<td>Multiple channel-based (e.g., DBTMA, SAM-MAC, CCM–MAC)</td>
<td>Separation of data and control traffic to reduce collisions, possibility of load balancing and use of busy tones, simultaneous transmissions in the same region without interference, higher network efficiency than IEEE 802.11</td>
<td>Assignment of separate channels must be done in real-time, nodes must sometimes be synchronized, hardware complexity because of additional channels and transceivers, channel gain of data and control channels may be different, nodes with a large number of transceivers (e.g., one per channel) are expensive while nodes equipped with a single transceiver are inefficient, difficult interoperability with IEEE 802.11, large signaling overhead, slow channel reservation, difficulty in optimal spectrum division between the control and data channels, spectral separation between data and control channels are required to avoid inter-channel interference, no QoS support.</td>
</tr>
<tr>
<td>Power-aware (e.g., PCM, SSPC)</td>
<td>Decreased energy consumption, can be combined with busy tones or can take advantage of multiple channels</td>
<td>Signal fading may degrade performance, reducing the power of ACK transmission may lead to increased number of collisions due to decreased carrier sensing range, large signaling overhead, slow channel reservation</td>
</tr>
<tr>
<td>Directional antenna-based (e.g., RDMAC, MARS, MCDA, DMAC)</td>
<td>Simultaneous data transmission and reception increases spatial reuse, minimized probability of collisions, can take advantage of multiple channels, higher network efficiency than IEEE 802.11</td>
<td>New kinds of hidden nodes, higher directional interference and deafness, performance decreases with node mobility, additional hardware complexity, in most cases large signaling overhead and slow channel reservation, performance strongly dependent on network topology, performance can be deteriorated by the side-lobe problem, no QoS support.</td>
</tr>
<tr>
<td>Protocol name</td>
<td>Required change</td>
<td>Modification</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------</td>
<td>--------------</td>
</tr>
<tr>
<td>FAMA-NCS [10]</td>
<td>Small</td>
<td>Long CTS frames</td>
</tr>
<tr>
<td>Four-way handshake [12]</td>
<td>None</td>
<td>–</td>
</tr>
<tr>
<td>PCMA [29]</td>
<td>Large</td>
<td>Noise and interference level measurement, busy tone signals determine the maximum possible transmit power level</td>
</tr>
<tr>
<td>DBTMA [22]</td>
<td>Large</td>
<td>Out-of-band signaling, busy tones, no ACK frame</td>
</tr>
<tr>
<td>DMAC [49]</td>
<td>Large</td>
<td>Frames are transmitted using directional antennas, medium is sensed using omni-directional antennas, each node maintains a directional NAV table</td>
</tr>
<tr>
<td>PCM [30]</td>
<td>Medium</td>
<td>RTS/CTS frames sent using maximum transmit power, ACK sent with minimum transmit power level</td>
</tr>
<tr>
<td>PUMA [24]</td>
<td>Medium</td>
<td>Additional JAM signal for isochronous traffic, modified control frames, modified Backoff mechanism</td>
</tr>
<tr>
<td>AA [13]</td>
<td>Small</td>
<td>Extended RTS/CTS frames</td>
</tr>
<tr>
<td>M-VRMA [35]</td>
<td>Medium</td>
<td>Extended RTS/CTS frames, additional signaling frame</td>
</tr>
<tr>
<td>MACP [15]</td>
<td>Large</td>
<td>Additional level of channel access competition based on DMBC</td>
</tr>
<tr>
<td>RICK [31]</td>
<td>Large</td>
<td>Changed Backoff control and countdown competition, additional power control</td>
</tr>
<tr>
<td>DRCE [32]</td>
<td>Medium/ Large</td>
<td>Additional signaling frames, transmission power control, two separate channels</td>
</tr>
<tr>
<td>EDCA/RR [17]</td>
<td>Small</td>
<td>Extended RTS/CTS frames</td>
</tr>
<tr>
<td>CDR-MAC [52]</td>
<td>Large</td>
<td>Circular directional transmission of RTS, directional antennas with predefined number of beams, multiple RTS transmissions, each node maintains location table</td>
</tr>
<tr>
<td>DMAC-PCDR [51]</td>
<td>Large</td>
<td>Each node equipped with GPS, smart usage of omni-directional and directional antennas, rotation of receiving antenna beams</td>
</tr>
<tr>
<td>SAM-MAC [37]</td>
<td>Large</td>
<td>Balances traffic over multiple channels, two transceivers for each node, additional signaling</td>
</tr>
<tr>
<td>CCM-MAC [38]</td>
<td>Medium</td>
<td>Additional control frames: decide-channel-to-send (DCTS), information-to-inform (ITI), confirm (CFM)</td>
</tr>
<tr>
<td>MARS [56]</td>
<td>Large</td>
<td>Additional signaling (ready-to-receive-and-transmit frame), changed RTS frame format, smart antennas</td>
</tr>
<tr>
<td>RDMAC [53]</td>
<td>Large</td>
<td>Smart usage of directional and omni-directional antennas, additional signaling</td>
</tr>
</tbody>
</table>
of hidden nodes can be seen from several different angles. For example, there are protocols which calculate the maximum signal strength which can be used for a new data transmission without interfering with ongoing transmissions (Section 5.1.7). In this case, the definition of a hidden node is different than the traditional one. Other protocols utilize multiple channels, but then have to address the multi-channel hidden node problem described in Section 5.1.3. This problem also appears in cognitive networks [57], which are currently receiving increased attention. Additionally, if directional antennas are used, two new kinds of hidden nodes may appear (Section 6). Finally, to our best knowledge in the literature there is no survey which elaborates on the complexity of the hidden node problem in detail.

Furthermore, not all protocol categories presented in this paper support QoS (Table 1). However, it would be ideal if future hidden node-aware solutions would include some sort of QoS provisioning. Especially because of the growth of the number of delay-sensitive and bandwidth-consuming services. Therefore, it can be expected that future wireless networks will require QoS-aware solutions. It should also be kept in mind that it is difficult to provide an appropriate level of QoS (i.e., hard QoS guarantees) if the protocol operates only at the MAC layer [58]. Ideal solutions require admission control, traffic policing, adequate bandwidth allocation and reservation, etc. Therefore, future hidden node-resilient QoS-aware mechanisms will most likely require cross-layer interactions.

Another very important issue, directly related to QoS, is fairness. Studies have shown (e.g., [59–62]) that the current IEEE 802.11 standard does not assure a fair share of resources if hidden nodes are present in the network. Therefore, future research should focus on the problem of fairness in multi-hop networks, with special attention paid to multi-hop flows [63]. New protocols should additionally avoid starvation of flows as well as take care of meeting the deadlines of real-time frames.

There are several extensions to IEEE 802.11 currently under development (IEEE 802.11aa, IEEE 802.11ac, IEEE 802.11ad, IEEE 802.11ae, IEEE 802.11af, IEEE 802.11s). They define new channel access mechanisms, wider channel bands, new frequencies, etc. Therefore, it is important to verify if these new technologies can be impacted by the problem of hidden nodes. Preliminary research has already been done with respect to the MCF Coordinated Channel Access (MCCA) defined in IEEE 802.11s [64]. In [65], it was stressed that MCCA prevents interference from hidden nodes by advertising reservation periods in the two-hop neighborhood of both the sender and destination nodes. Unfortunately, the operation of MCCA can be severely affected by interference from outside the two-hop neighborhood.

Importantly, many MAC protocols assume fixed carrier sensing/transmission/collision ranges which, however, may dynamically change, e.g., due to shadowing or multi-path fading.

Additionally, the proposed solutions are in most cases not tested in real environments. Therefore, future studies should rather be devoted to real implementations than just simulations. Only such an approach can ultimately verify a protocol’s usefulness in future wireless networks.

Also the use of PHY/MAC/Network layer measurements could be of great help. It would be ideal if future protocols knew which parts of the network are impacted by which
transmissions, could predict possible topology changes (e.g., caused by the mobility of nodes) and overload situations, and were aware of the availability of network resources. Such up-to-date information, if used well, would certainly improve the overall network performance and would facilitate spatial reuse of the wireless channels.

Furthermore, networks with hidden nodes can frequently be affected by the presence of exposed nodes [60]. In the literature not enough interest has been paid to this problem. Therefore, future hidden node-aware solutions should pay attention to the problem of exposed nodes as well.

Finally, it should be kept in mind that each protocol is a trade-off between complexity, signaling overhead, level of QoS provisioning, etc. It is within the remit of the protocol designer to find the best consensus, which in most cases, is a very challenging task.

To summarize, all open issues described in this section are gathered in Fig. 36. However, the list is still open because other research challenges will certainly appear due to the continuous emergence of new wireless technologies.

9. Conclusions

This paper has given a detailed overview of the following five types of MAC protocols proposed in the literature, which alleviate the hidden node problem: (i) Pure contention-based mechanisms which can be divided into three groups: sender-initiated, receiver-initiated, and hybrid. The sender-initiated mechanisms need a sender node to reserve the wireless channel before any data transmission may take place. In the case of the receiver-initiated mechanisms a destination node invites the sender node to transmit a DATA frame. The hybrid MAC protocols use either the sender- or the receiver-initiated channel access methods depending on current network conditions. (ii) Busy tone signal-based protocols which take advantage of one or more busy tone signals to keep hidden nodes silent during an ongoing transmission. (iii) Power-aware mechanisms which reduce transmit power levels of certain frames sent on the wireless channels to avoid collisions. (iv) Directional antenna-based protocols which implement directional transmissions to avoid interference with neighboring nodes. (v) Multiple channel-based protocols which can be divided into three groups: with a common control channel, without a common control channel, and hybrid. The protocols with a common control channel exploit the advantage of separation of the control and signaling channels to reduce the number of collisions between frames of different types. The protocols without a common control channel arrange the channels in a flexible way to transmit frames in a collision-free manner. Finally, hybrid protocols combine the advantages of both approaches.

Additionally, separate sections have been devoted to protocol comparison and future research directions. The former summarizes the advantages and disadvantages of the described protocol categories as well as changes made to the IEEE 802.11 standard. This was done to give a straightforward view on the progress made in the area of hidden nodes. The latter aimed at speculating about expected challenges to give research ideas to future protocol designers.

References

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