Chapter 6: A Survey On MAC Protocols for Wireless Ad hoc Networks with Beamforming Antennas

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Outline

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- MAC Challenges with Beamforming Antennas
- MAC Protocol Classification
- Review of Random Access Protocols
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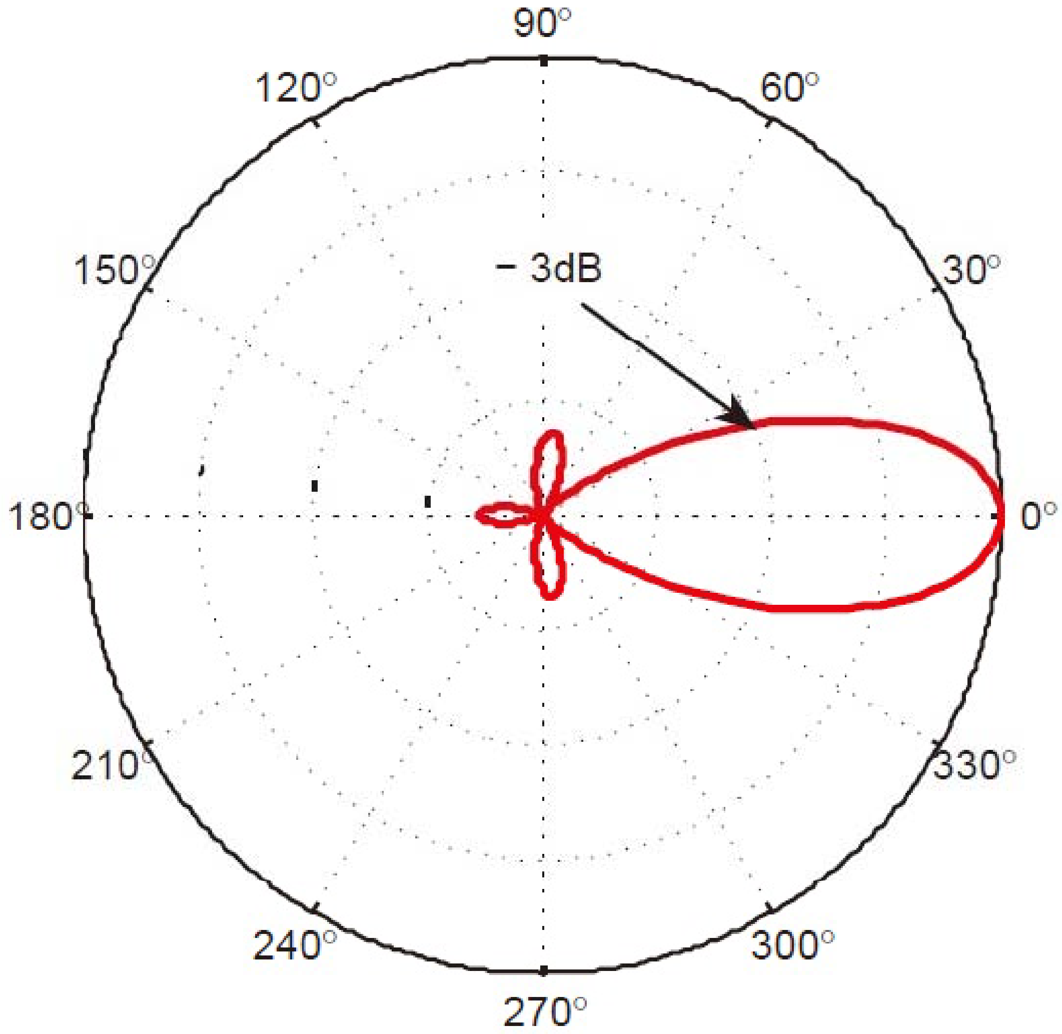
Abstract

- Beamforming antennas have the ability to increase the spatial reuse, improve the transmission reliability, extend the transmission range and/or save the power consumption.
- Traditional Medium Access Control (MAC) protocols fail to exploit the potential benefits due to the unique characteristics of wireless ad hoc networks with beamforming antennas.
- In this paper, we survey the literature on MAC protocols proposed for wireless ad hoc networks with beamforming antennas.
- We discuss the main beamforming-related challenges facing the medium access control in ad hoc networks. We present taxonomy of the MAC protocols proposed in the literature based on their mode of operation and the mechanisms used to address the challenges.

Introduction

- Antenna Basics and Types
- Benefits of Beamforming Antennas
- Medium Access Control (MAC)

Antenna radiation pattern with a main lobe pointing at 0º and side lobes with smaller gains.



Friss equation

$$P_r = \frac{P_t G_t G_r}{K r^{\delta}}$$

- P_r : received power
- P_t : transmission power
- r : distance
- G_t and G_r : transmitter and recevier gain
- δ : path loss exponent
- K : constant

Antenna Basics Types

- Directional antennas are often realized by means of antenna arrays.
- The "smart antennas" technology combines an antenna array with Digital Signal Processing (DSP) techniques that allow the antenna elements to transmit and receive in an adaptive, spatially sensitive manner.
- Beamforming antennas lie under the umbrella of "smart antennas" which also includes Multiple Input Multiple Output (MIMO) systems.
- DSP algorithms are used to estimate the Direction-of-Arrival (DoA) of the signal and use this information to calculate the weights applied to the signal at each antenna element that are responsible for changing the radiation pattern.
- Beamforming antennas are classified into switched beam systems and steered beam systems.

Switched Beam Antenna Systems

- In switched beam systems, the antenna array is combined with a fixed Beam Forming Network (BFN).
- BFN consists of a predetermined set of weight vectors, where the configuration of weights in a vector determines the direction in which the antenna radiation pattern is beamformed.
- Based on the direction-of-arrival estimation, the BFN chooses a weight vector to be applied to the signal received/transmitted by the antenna array.
- Switched beam antennas can provide most of the benefits of smart antennas at a small fraction of complexity and expense.

Switched Beam Antenna Systems (Cont.)

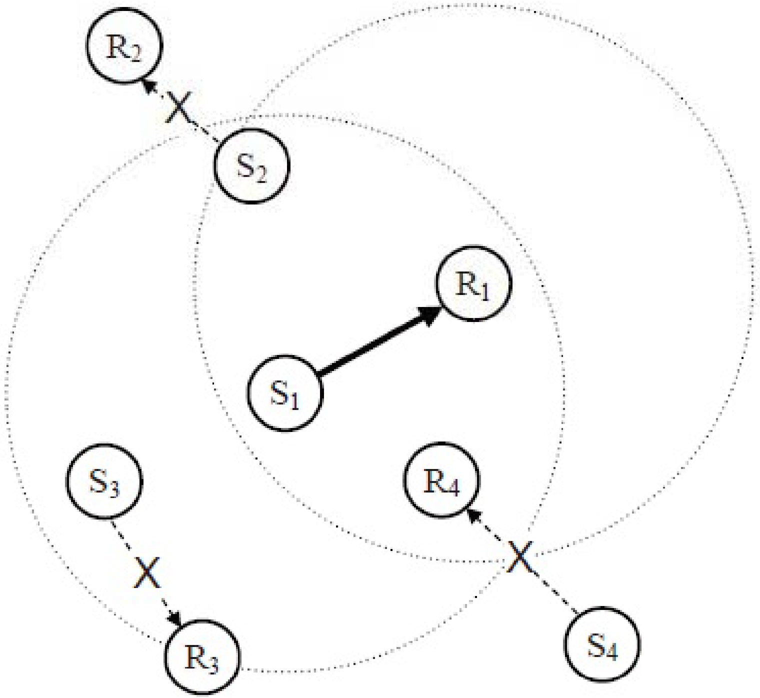
- Switched Beam Antenna Systems do not guarantee maximum gain due to scalloping.
- Scalloping is the roll-off of the antenna pattern as a function of the angle from the boresight. If the desired direction is not on one of the predetermined boresights, the transceiver will suffer from gain reduction.
- Switched beam antennas are not able to fully eliminate the interference outside the main lobe due to the absence of control on the side lobes.

Steered Beam Antenna Systems

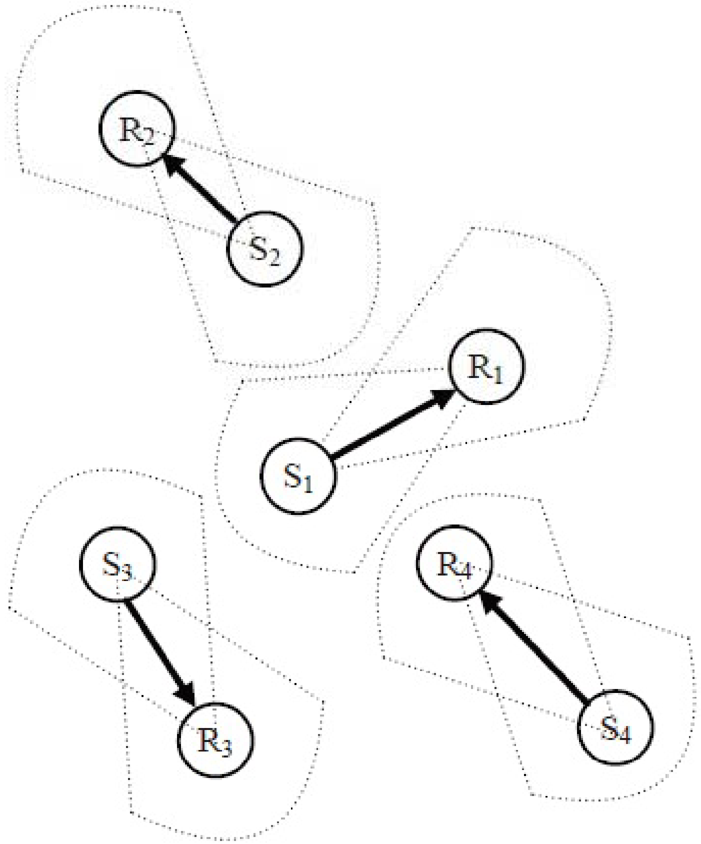
- They are also known as Adaptive Antenna Array (AAA) systems.
- Provide a high degree of flexibility in configuring the radiation patterns. Using a variety of sophisticated signal processing algorithms, the adaptive array antennas can adapt their weights in order to maximize the resulting Signal to Interference and Noise Ratio (SINR).
- The boresight of the main lobe can be directed towards the target using phase shifters.
- This type is known as phased antenna arrays.
- By increasing the complexity of the DSP algorithms, nulls can be additionally placed in the direction of interfering sources to suppress their interference.
- The need to continuously locate and track various types of signals complicates the signal processing task and results in a significant increase in the power consumption.

Benefits of Beamforming Antennas

- An illustrative example of the spatial reuse benefit of directional antennas.



(a) Omni-directional antennas.



(b) Directional antennas.

Benefits of Beamforming Antennas (Cont.)

- The directional reception and the ability of sophisticated beamforming antennas to completely suppress the reception from interfering directions can significantly reduce interference.
- The limited scope of the directional transmissions and receptions can increase the channel utilization significantly.
- The gain of the beamforming antenna results in focusing more energy in the intended direction which increases the Signal-to-Noise Ratio (SNR) for the same transmit power.
- This increase in the SNR improves the link reliability and robustness against fading.
- Better link quality could result in a higher transmission rate.

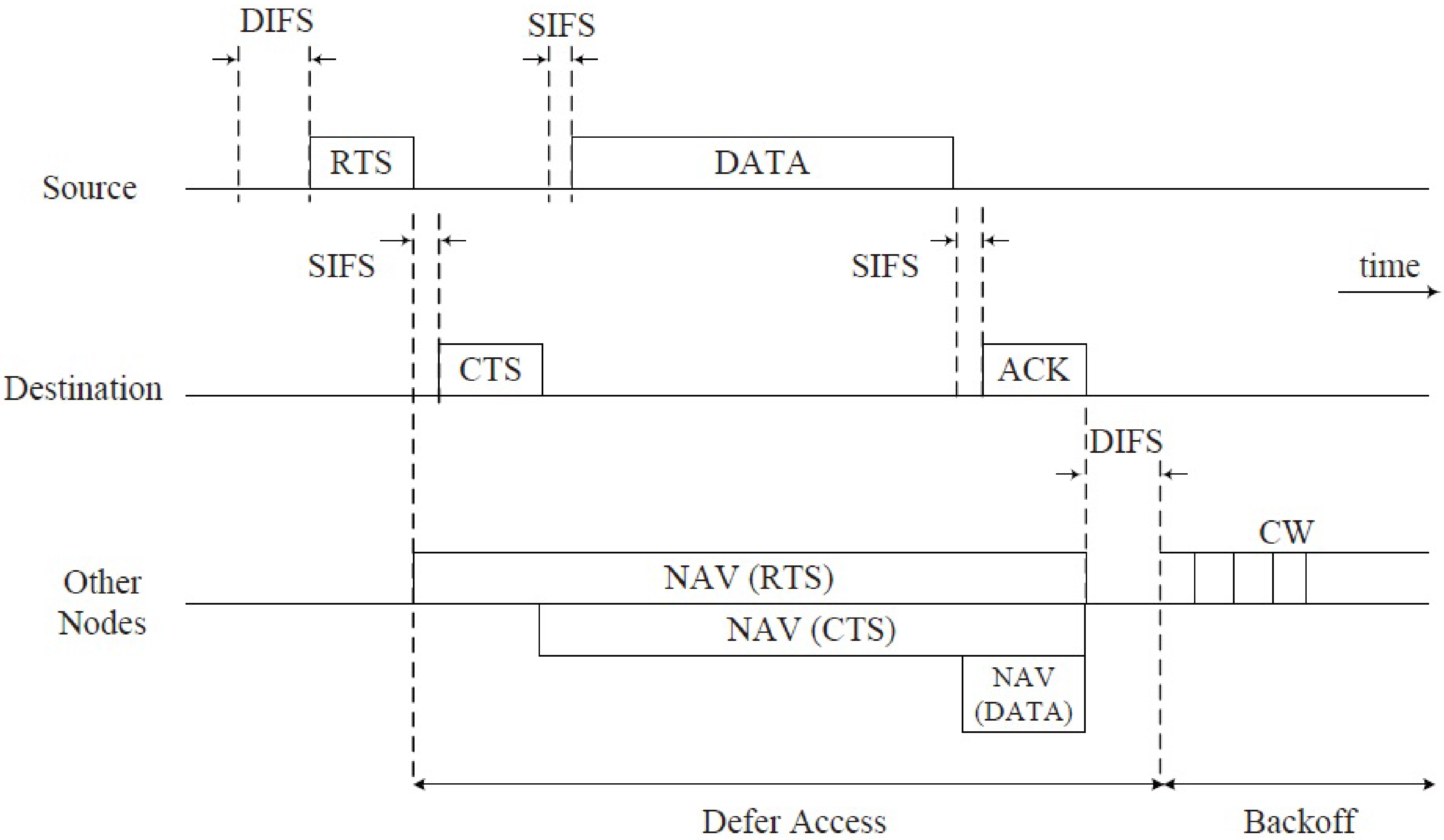
Benefits of Beamforming Antennas (Cont.)

- For the same transmit power as omni-directional antennas, the directional gain of beamforming antennas is translated to communication range extension.
- This extension may lead to fewer-hops routes and consequently a reduction in the end-to-end delay.
- Reductions in the power consumption can trade-off the benefit of range extension.
- For a specific pair of nodes, beamforming antennas are able to reduce the transmit power while maintaining the same wireless link quality as omni-directional antennas.
- Providing more secure wireless communication.

Medium Access Control (MAC)

- The goal of the MAC protocol is to set the rules in order to enable efficient and fair sharing of the common wireless channel.
- The MAC protocol typically needs to maximize the channel utilization by having as many simultaneous communications as possible.
- Medium access control protocols for wireless networks may be classified into two major categories:
  - contention-based MAC:
    - Nodes compete to access the shared medium through random access.
    - In case of conflict occurrence, a distributed conflict resolution algorithm is use to resolve it.
    - Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA).
  - contention-free MAC:
    - Based on a controlled access in which the channel is allocated to each node according to a predetermined schedule.

Channel reservation in IEEE 802.11 MAC



MAC Challenges with Beamforming Antennas

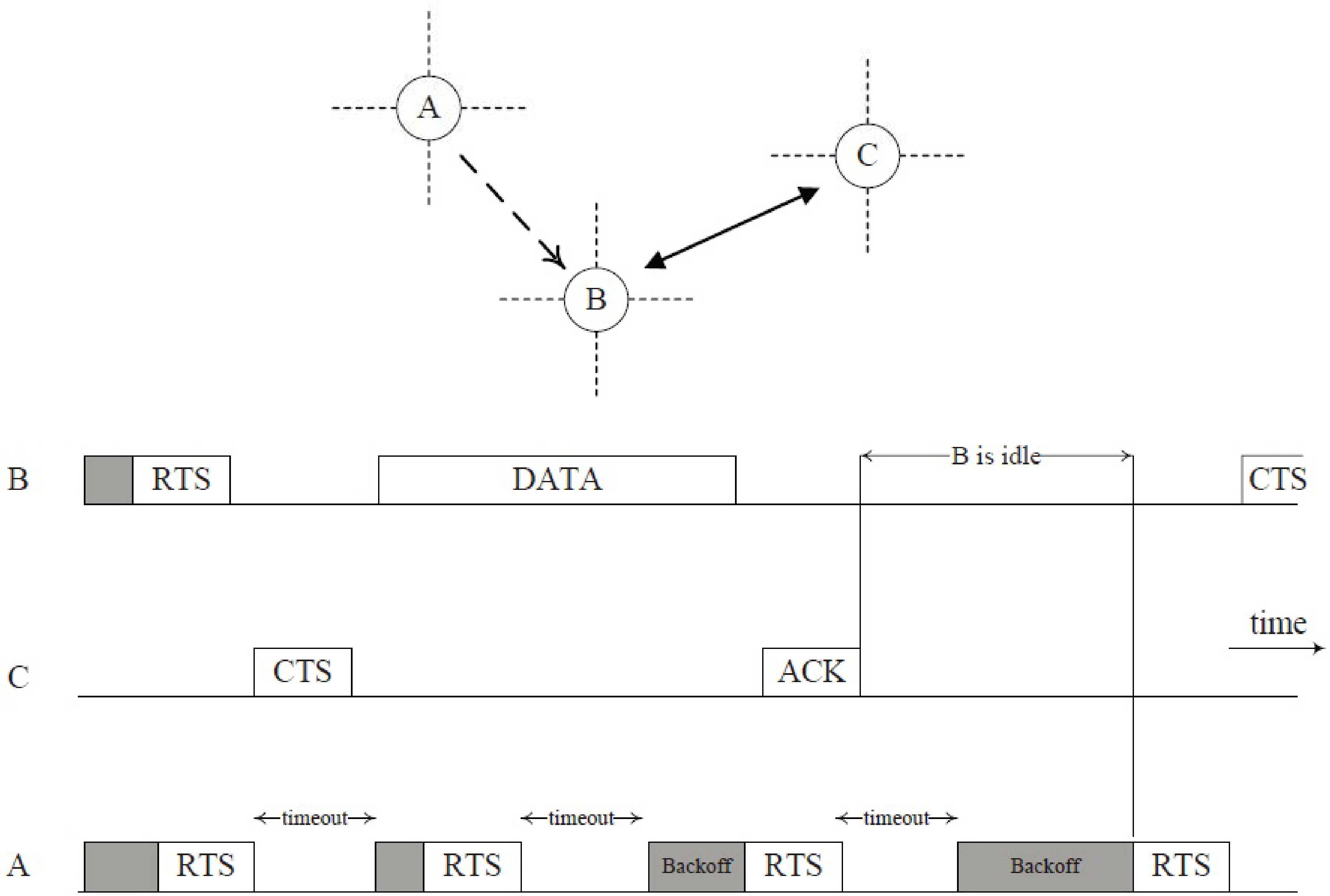
- Deafness
- New Hidden Terminals
  - Hidden Terminal Due to Asymmetry in Gain
  - Hidden Terminal Due to Unheard RTS/CTS
- Head-of-Line Blocking
- Communication Range Under-utilization
- MAC-layer Capture

Deafness

- Deafness occurs when a transmitter tries to communicate with a receiver but fails because the receiver is beamformed towards a direction away from the transmitter.

- Due to the characteristics of directional beamforming, the intended receiver is unable to receive the transmitter's signal and as a result appears deaf to the transmitter.

A scenario illustrating the deafness problem



New Hidden Terminals

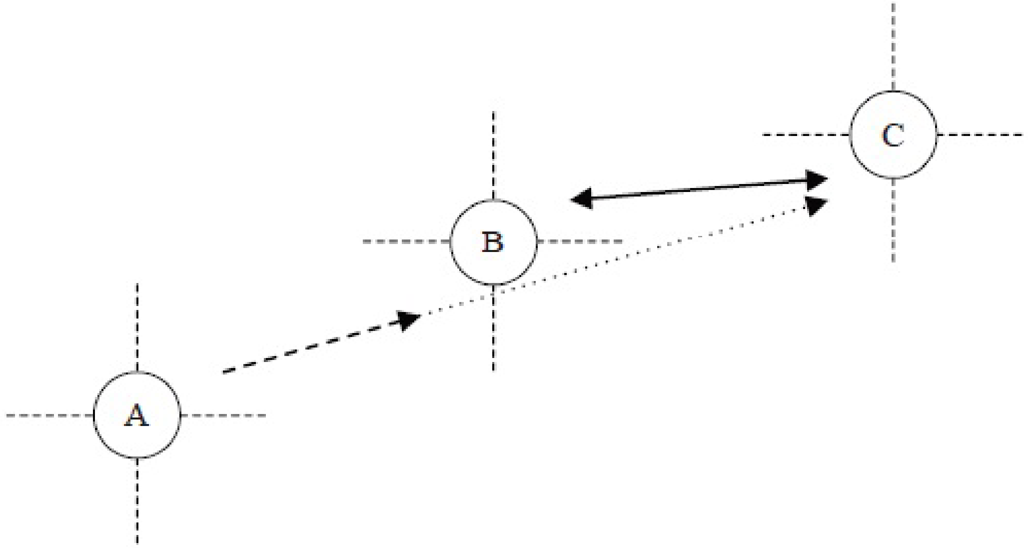
- In the context of beamforming antennas, the hidden terminal problem occurs when a potential interferer could not receive the RTS/CTS exchange due to its antenna orientation during the handshake and then initiates a transmission that causes collision.

- There are two new types of directional hidden terminal problems :
  - Hidden Terminal Due to Asymmetry in Gain
  - Hidden Terminal Due to Unheard RTS/CTS

Hidden Terminal Due to Asymmetry in Gain

- This problem is basically due to the fact that the antenna gain in the omni-directional mode (G_o) is smaller than the gain when the antenna is beamformed (G_d).

- If an idle node is listening to the medium omni-directionally, it will be unaware of some ongoing transmissions that could be affected with its directional transmission.

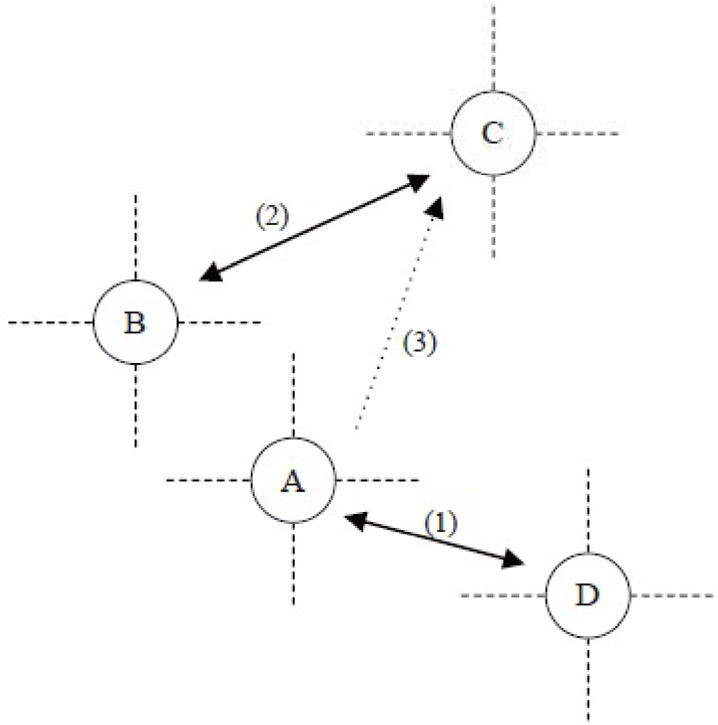


A scenario to illustrate the hidden terminal problem due to the asymmetry in gain.

- Assume that node A and node C are out of each other's range when one is transmitting directionally (with gain G_d) and the other is receiving omnidirectionally (with gain G_o).
- First, node B transmits RTS directionally to node C, and node C responds back with a directional CTS.
- Node A is idle (still in omnidirectional mode) so it is unable to hear the CTS.
- Data transmission begins from node B to node C with both nodes pointing their transmission and reception beams towards each other.

- While this communication is in progress, node A has a packet to send to node B.
- Node A beamforms towards node B (which is the same direction of node C) and performs the carrier sensing.
- The channel is sensed idle, node A sends a directional RTS to node B.
- Since node C is receiving data directionally using a beam pointed toward node B (and node A), the RTS from node A interferes with node B's data transmission at the receiver C causing collision.

A scenario to illustrate the hidden terminal problem due to unheard CTS.



- This type of hidden terminal problem occurs as a result of the loss in the channel state information during beamforming.
- When a node is involved in a directional communication, it would appear deaf to all other directions and important control packets may be lost during that time.

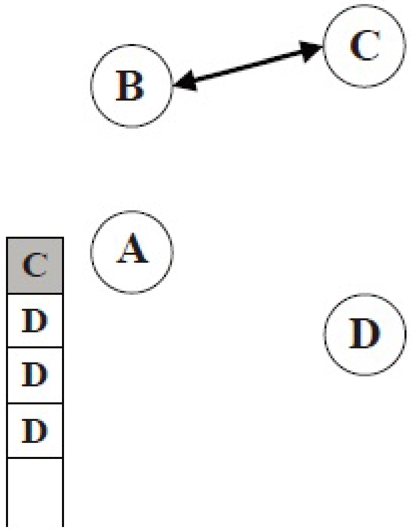
Hidden Terminal Due to Unheard RTS/CTS

- Suppose that node A is engaged in a directional communication with node D.
- While this communication is in progress, node B sends RTS to node C which in turns replies with CTS.
- Since node A is beamformed towards node D, it cannot hear CTS from node C.
- While the communication between node B and node C is in progress, node A finishes the communication with node D and now decides to transmit to node C.
- Since the DNAV at node A is not set in the direction of node C (due to the unheard CTS), node A transmits RTS to node C causing collision at node C.

Head-of-Line Blocking

- The Head-of-Line (HoL) blocking problem with directional MAC protocols was first identified in [45]. (IEEE LCN'04)
- It occurs as a result of the typically used First-In-First-Out (FIFO) queueing policy.
- If the medium is busy, no packets can be transmitted.
- In case of beamforming antennas, the medium is spatially divided and it may be available in some directions but not others.
- If the packet at the top of the queue is destined to a busy node/direction, it will block all the subsequent packets even though some of them can be transmitted

A scenario to illustrate the head-of-line blocking problem



■Using the FIFO queueing policy, although node A has packets that can be transmitted to node D, they are blocked by the packet destined to the busy node C.

■The HoL blocking problem is aggravated when the top packet goes into a round of failed retransmissions including their associated backoff periods.

Communication Range Under-utilization

- The operation of the directional MAC protocol may limit the full exploitation of the communication range extension offered by beamforming antennas.
  - If the protocol requires the omnidirectional transmission of control packets or the idle node to reside in an omni-directional mode, the communication range is limited.
  - It is possible for nodes to communicate over the extended range if both the transmitter and the receiver could agree to beamform towards each other at the same time which is a challenging issue in the presence of asynchronized medium access.

Three types of neighbors

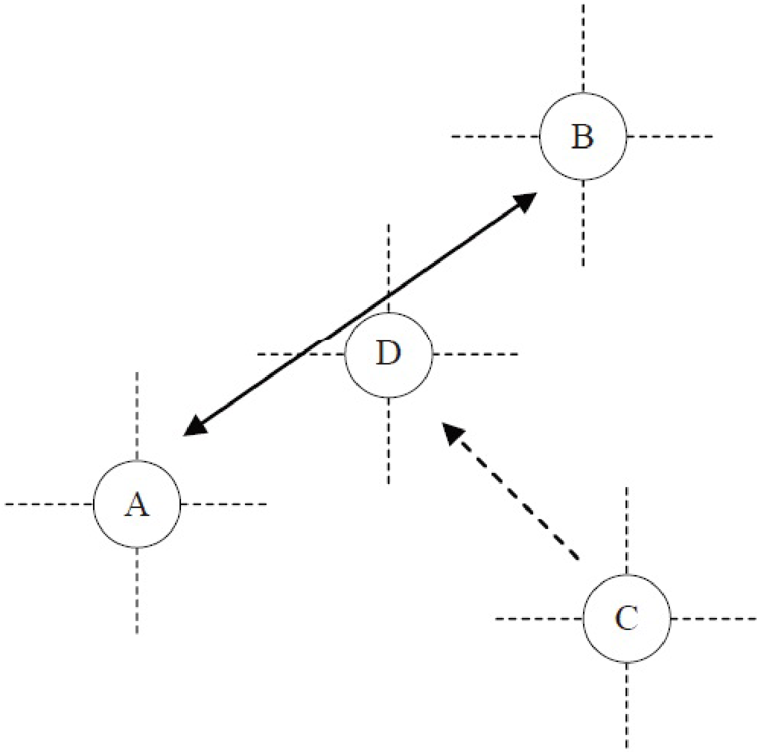
- The Omni-Omni (OO) neighbors:
  - Those are neighbors that can only receive the omni-directional transmissions of the node when they are listening in an omni-directional mode.
- The Directional-Omni (DO) neighbors:
  - Those are neighbors that can also receive the directional transmissions of the node when they are listening in an omni-directional mode.
- The Directional-Directional (DD) neighbors:
  - Those are neighbors that can receive the directional transmissions of the node only if they are already beamformed in the direction of the node.

- The challenge facing the MAC protocols is how to allow communication to occur between DD-neighbors.

MAC-later Capure

- Since a packet can be received from any direction, it is common that the antenna of an idle node resides in an omni-directional mode in order to be able to listen in all directions.
- When a signal is detected, the antenna will beamform towards the direction of maximum received power, receive the packet, decode it and pass it up to the MAC layer. If the packet is not destined to this node, the packet will simply be dropped.
- The time the node wastes in receiving packets, not intended to it, might refrain the node from transmitting/recieving useful packets to/from other directions thus resulting in channel underutilization.

A scenario to illustrate the MAC-layer capture problem

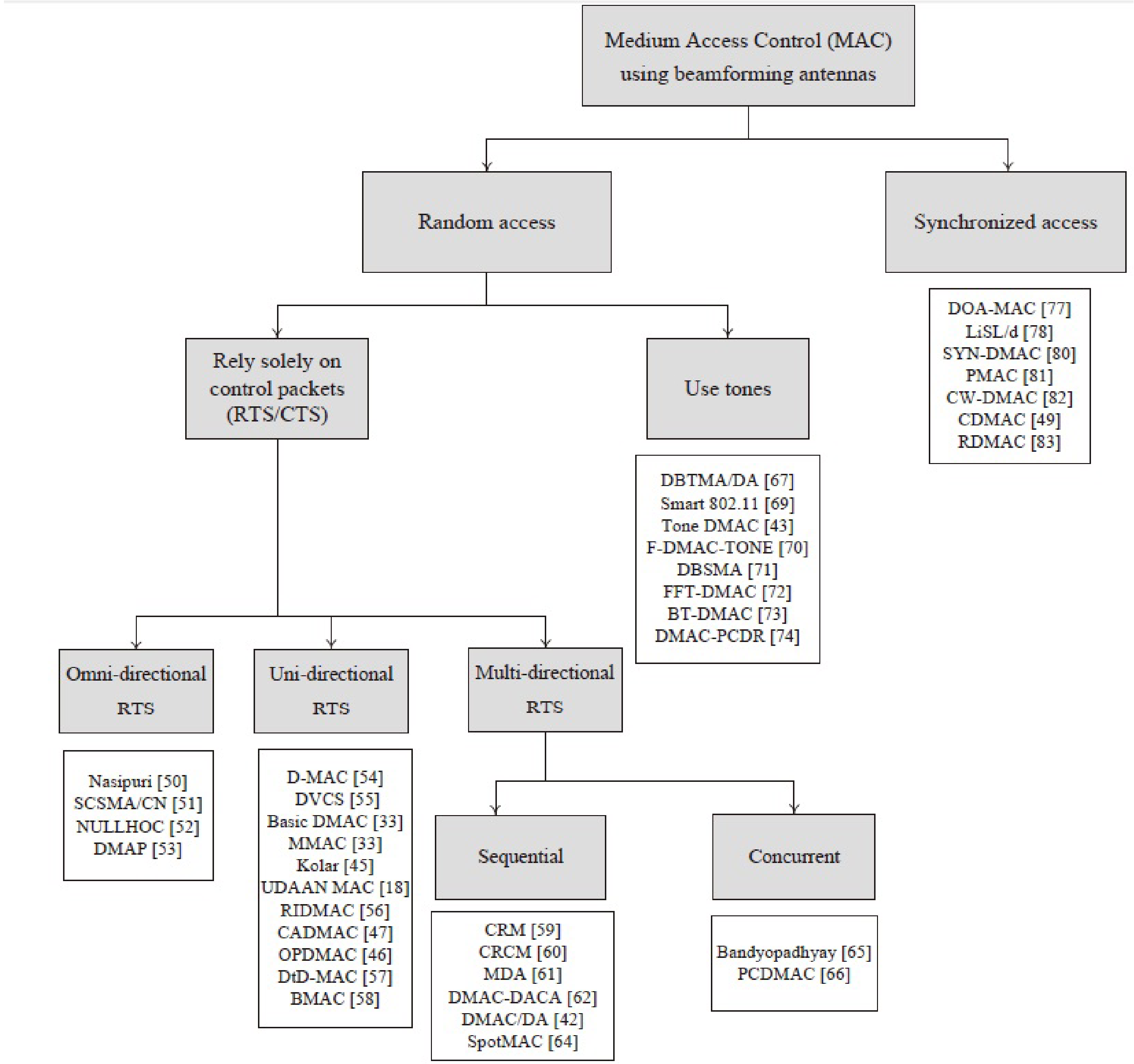


- In the context of beamforming antennas, the MAC-layer capture problem basically occurs when the node does not perform any intelligent control of the underlying antennas when it is idle.

MAC Protocols Classification

- The MAC protocols can be broadly classified into random access protocols and synchronized access protocols.
- Random access protocols allow the stations to access the shared medium randomly through contention with each other.
- Synchronized access protocols allow the stations to access the medium based on a predetermined schedule which can be achieved through local and/or global synchronization.

A taxonomy of MAC protocols for wireless ad hoc networks with beamforming antennas

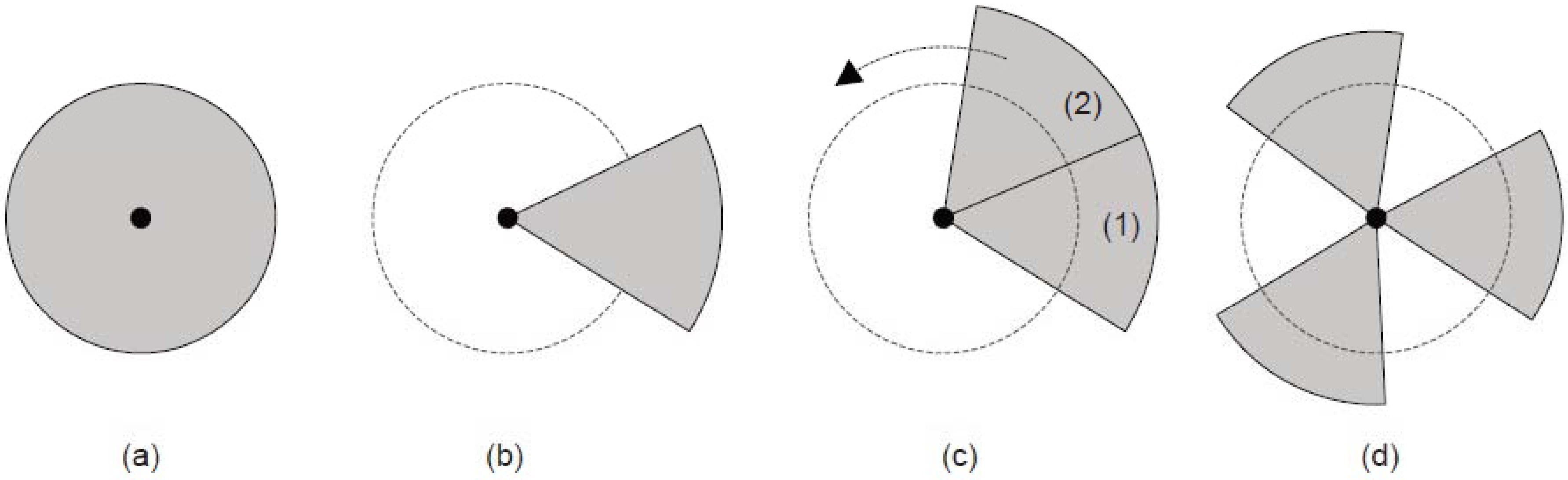


MAC Protocols Classification

- Most random access protocols rely on the concept of Carrier Sensing Multiple Access (CSMA) in which physical carrier sensing is performed before initiating transmission.
- Random access protocols can be further classified into sub-categories according to the tool(s) used to handle MAC main challenges such as deafness and hidden terminals.
- The first sub-category of directional MAC protocols rely solely on control packets in particular RTS/CTS packets traditionally used for collision avoidance.
- The second sub-category employs busy tones that are usually transmitted on a dedicated control channel.

The coverage range of different tranmission modes.

- The protocols that rely on the control packets can be further classified based on how the initial control packet (i.e RTS packet) is transmitted.



- (a) Omni-directional.
- (b) Uni-directional.
- (c) Multi-directional Sequential.
- (d) Multi-directional concurrent.

MAC Protocols Classification

- Some directional MAC protocols that belong to the category of synchronized access protocols, the basic idea is to coordinate conflict-free transmissions to occur simultaneously.

- Time is usually divided into frames and each frame consists of sub-frames which are simply a group of time slots.

- In one sub-frame, channel contention is usually used to perform a schedule for contention-free data transmission in the rest of the frame.

- Since achieving global synchronization is considered difficult in multi-hop wireless networks, recent protocols have chosen to rely on local coordination between neighboring nodes.

Review of Random Access Protocols

- RTS/CTS-base protocols
  - Protocols that use omni-directional RTS
  - Protocols that use uni-directional RTS
  - Protocols that use multii-directional sequential RTS
  - Protocols that use multii-directional concurrent RTS

- Tone-base protocols

Nasipuri (IEEE, WCNC 2000)

- In this protocol, the authors propose that the data and its acknowledgement should be exchanged directionally in order to reduce the interference.

- they propose to send both RTS and CTS omni-directionally (ORTS/OCTS). Idle nodes listen to the surrounding medium in an omni-directional mode.

- When a node receives RTS for itself, it marks the beam from which it received the packet and responds with the omni-directional CTS.

- Upon receiving the CTS in response, the sender node also knows the direction of the intended receiver.

Nasipuri (Cont.)

- Each neighboring node that receive either the RTS or CTS, begin an off-the-air period for the duration specified in the RTS/CTS packet similar to IEEE 802.11 NAV.
- Increase in the total throughput.
- The communication range is limited by the omni-directional gain. Also, the spatial reuse is severely affected by the need to transmit the RTS/CTS omni-directionally.

SCSMA/CN (IEEE WCNC'04)

- The Selective CSMA with Cooperative Nulling (SCSMA/CN) protocol for ad hoc network stations with adaptive antenna arrays.
- They propose to transmit all the packets omni-directionally and exploit the nulling capabilities of the receiving antenna to dynamically null potential future interfering packet transmissions.
- After the exchange of RTS/CTS packets, the source node along with all of the nodes that received the CTS packet simultaneously transmit a short Cooperative Nulling (CN) packet so that the beamforming weights at the destination node are calculated.
- The beamforming antenna attempts to maximize the desired signal and null those interfering transmissions.
- Following this, The destination node and all of the neighbors of the source node send CN packets in the same fashion so beamforming can be performed at the source node.
- The performance of the protocol is limited to the available degrees of freedom of the antenna array.

NULLHOC (IEEE GLOBECOM'04)

- In the NULLHOC protocol, the total bandwidth is divided into two orthogonal channels: a Data Channel (DC) and a Control Channel (CC).
- The source sends RTS packet that contains the antenna weights the node will use for receiving the ACK. If the destination is able to involve in this communication, it responds with CTS packet that contains the receiving and transmitting antenna weights.
- Then, the source reserves the access right to the DC by sending a Data-Send (DS) control packet that contains the antenna weights that the node will use while transmitting the DATA packet.
- The throughput gains tend to saturate as the number of antennas increase due to increased control overhead.

DMAP (IEEE GLOBE'04)

- A Directional MAC with Power control (DMAP)
- Use separate control and data channels to solve hidden terminal problem due to unheard RTS/CTS messages at the expense of additional sophisticated hardware.
- Idle nodes listen omni-directionally to the data and control channels.
- When a node has a packet to send, it first sends the RTS omni-directionally with a common fixed power. Upon reception, the intended receiver estimates the Angle-of-Arrival (AoA), calculates a power control factor and encapsulates it in the Directional CTS (DCTS) sent to the source node.
- The source node uses the power control factor to calculate the sufficient transmit power needed to transmit the data packet.

DMAP (Cont.)

- The power of the DCTS is scaled by a powerscaling factor that ensures that every potential interferer listening omni-directionally can hear the DCTS.
- Transmission of DCTS from minor lobes of the receiver at scaled power would also prevent potential interferers located in other directions.
- DMAP improves the network throughput and reduces the energy consumption at the same time.

D-MAC (IEEE INFOCOM 2000)

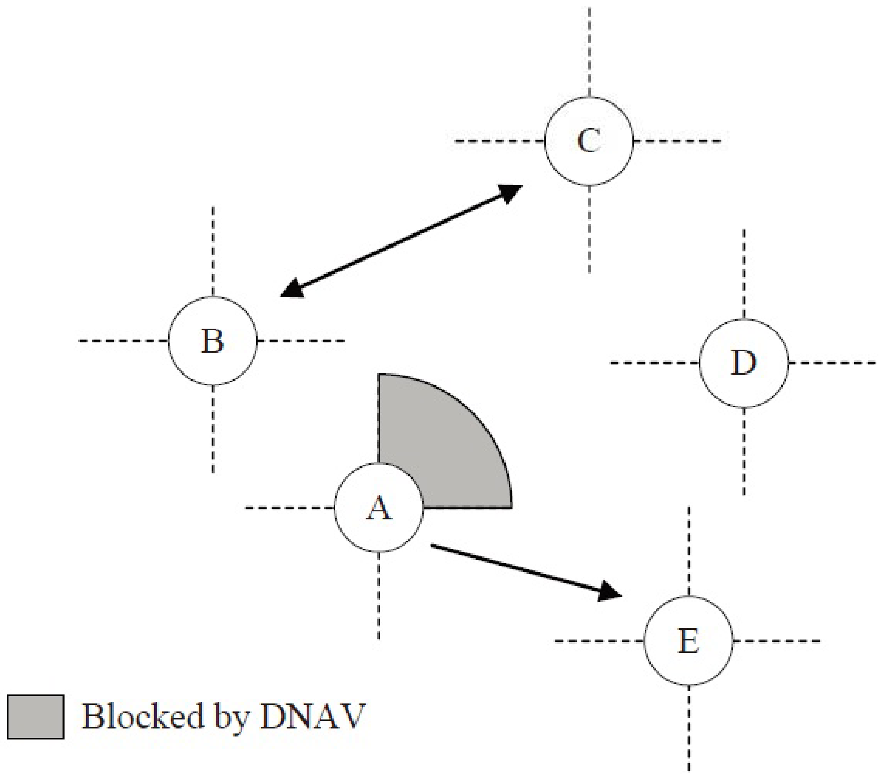
- They assume packets can be transmitted directionally or omni-directionally but packet reception can be done omni-directionally only.
- They propose the D-MAC protocol in which RTS is sent directionally (DRTS) towards the intended receiver to avoid unnecessary waiting time if one of the other directions is blocked.
- The basic assumption here is that each node knows the location information of each of its neighbors by means of Global Positing System (GPS) and each node transmits based on the direction derived from the physical location information.
- To avoid collisions at the receiver, omnidirectional CTS is sent followed by directional DATA and ACK exchange.

- The simulation results show performance improvement due to the increase in the number of concurrent transmissions in the network.

DVCS (IEEE GLOBECOM'04)

- Directional Virtual Carrier Sensing (DVCS) for contention based MAC protocols to make effective use of directional antennas.
- First, each node caches estimated AOAs from neighboring nodes when it hears any signal.
- Using the AOA cache, a source node can transmit DRTS without the need of additional hardware.
- Second, when a node receives an RTS from a neighbor, it adapts its beam pattern to maximize the received power and locks the pattern for the rest of the communication.
- Also, the source node locks its beam pattern after CTS reception. Beam locking prevents the nodes from being distracted by signals from other directions.
- The third and main capability to support DVCS is the use of directional NAV (DNAV). Each node maintains a DNAV table which can consist of multiple DNAVs each has its own direction, width and expiration time.

A scenario to illustrate the DNAV mechanism



Basic DMAC (ACM Mobicom'02)

- Basic DMAC is considered the benchmark for directional medium access control protocols.
- The authors assume that an upper layer is aware of the neighbors of a node and is capable of supplying the transceiver profiles required to communicate with each of these neighbors.
- The MAC layer receives these transceiver profiles along with the packet to be transmitted.

- In Basic DMAC, RTS/CTS/DATA/ACK are all transmitted directionally.
  - An idle node listens to the channel omni-directionally but when it receives a signal, its antenna system is capable of determining the Direction-of-Arrival (DoA) of this incoming signal.
  - The receiving node locks onto that signal and receives it.
  - The physical carrier sensing and the backoff phase are performed while the antenna is in a directional mode.
  - Basic DMAC performs DVCS using DNAV tables.

Basic DMAC (Cont.)

- The results show that directional communication has the potential to improve the performance in terms of aggregate throughput and end-to-end delay.
- The performance mainly depends on the topology and flow pattern in the network.
- Random topologies with unaligned flows perform much better than aligned topologies since the spatial reuse can be exploited.

MMAC (ACM Mobicom'02)

- The MMAC protocol aims to transmit the data packet over the longest possible hops.
- Since the idle nodes reside in omni-directional mode, they propose to propagate the RTS over multiple hops to inform the DD-neighbors to beamform towards the transmitter.
- In MMAC, the MAC layer receives a packet from an upper layer containing the DO-neighbor route to the next DDneighbor.
- A special RTS packet contains the DO-neighbor route is transmitted to the next neighbor on that route.
- Nodes along that route forward the RTS according to the encapsulated route.

MMAC (Cont.)

- The special RTS gets highest priority and is forwarded with a preceding backoff.
- Once the RTS is received by the DD-neighbor, CTS, DATA and ACK are transmitted over the single long hop.
- MMAC outperforms Basic DMAC in terms of aggregate throughput.
- The limitations of this protocol include the long delay of RTS propagation and the risk of losing RTS over multiple hops.
- Also, the intermediate multi-hop paths for RTS propagation may not always be available.

Kolar (IEEE LCN'04)

- The authors propose a new greedy queuing policy that can be implemented within the DMAC protocol.
- Based on the DNAV table, the authors propose using the least wait time to pick a packet for transmission.
- The simulation results show that the new queueing policy outperforms the existing one in terms of overall throughput and end-to-end delay.
- However, the proposed scheme does not consider the effect of deafness, which may cause the DNAV entries to be invalid.

UDAAN-MAC (IEEE J. Sel. Areas Commu. , 2005)

- The UDAAN-MAC protocol has two features that differentiate it from previous approaches which are a new backoff mechanism and the integration of power control.
- The authors propose a new backoff algorithm (called forced idle) in which the duration and the window adjustment mechanism depend on the type of event causing the backoff.
- The RTS contains the transmitted power and the source node's current receiver threshold.
- The UDAAN-MAC protocol performs power controlled DVCS.
- The DNAV table contains the duration, the direction and the allowed power.

RIDMAC (IEEE ICC'06)

- Receiver-Initiated Directional MAC (RIDMAC) protocol.
- Each node maintains a polling table and uses the information in the header of the data frame to update its table.
- After exchanging the DATA/ACK frames, the transmitter and the receiver check their own polling table whether potential deafness nodes exist or not.
- If more than one node is registered in the polling table, the least recently transmitting node is polled using a directional Ready-To-Receive (RTR) packet.
- Once RTR is received, the polled node, that was possibly suffering from deafness, transmits the data frame.

CADMAC (IEEE SECON'07)

- A Capture-Aware Directional MAC (CADMAC) to address the MAC-layer capture problem.
- The CADMAC protocol aims to prevent a node susceptible to capture from operating in the omnidirectional mode while idle.

- CADMAC assumes time is divided into cycles with each cycle subdivided into ON and OFF durations.

  - During the ON duration, the MAC layer records every received packet and the beam used to receive it.
  - If a beam proves to be the receiver of only capture traffic, then the beam is black-listed.
  - At the end of the ON duration, CADMAC decides to turn off all black-listed beams for the next OFF duration.

OPDMAC (IEEE ICC'08)

- An Opportunistic Directional Medium Access Control (OPDMAC) protocol.

- The OPDMAC protocol aims to grasp the transmission opportunities offered by beamforming antennas by eliminating the use of the over-conservative binary exponential backoff algorithm commonly used by most directional MAC protocols.

- In OPDMAC, the node is not forced to undergo idle backoff after a transmission failure but can rather take the opportunity of transmitting other outstanding packets in other directions.

- This novel mechanism minimizes the idle waiting time, increases the channel utilization, reduces the impact of the deafness and prevents the head-of-line blocking.

OPDMAC (Cont.)

- After each successful transmission, the node is forced to remain idle for a random period of time called the Listening Period (LP) even if it has packets outstanding for transmission

- The listening phase is needed to reduce the transmission failures due to deafness and to allow each node to update its channel state information.

DtD-MAC (IEEE Trans. Veh. Technol 2009)

- Directional-to-Directional MAC (DtD-MAC) protocol
- DTD-MAC performs directional idle listening through continuous directional scanning to sense all directions.
- Using DtD-MAC, communication is possible with DD-neighbors and the hidden terminal problem due to asymmetry in gain is alleviated.
- The problem of deafness is aggravated and the probability of collision is increased.
- To address these issues, the sender transmits multiple DRTS packets towards the receiver in order to capture the continuously scanning idle receiver.

DtD-MAC (Cont.)

- DtD-MAC requires the carrier sensing to be greater than the DATA period to avoid collisions.
- Large control overhead and excessive delay limit the performance of the protocol when the number of beams increases.

BMAC (EURASIP Journal 2009)

- BMAC performs joint channel gathering and medium sharing.
- The channel acquisition is performed proactively through a periodic training sequence.
- The channel to the corresponding node is estimated and the channel coefficients and the node identifier are saved in a channel table.
- When there is data ready to be sent, the source node sends a Beamformed RTS (BRTS) to maximize the power at the destinations and make nulls towards the potentially interfering neighbors.
- When receiving the BRTS, the destination node calculates the exceeded power for further transmitted power correction and then it sends an Omni-directional CTS (OCTS) packet containing this correction factor.

CRM (ACM MobiHoc'03)

- Circular RTS MAC (CRM) protocol in [59] which is the first protocol to employ the multi-directional sequential transmission of the RTS packet.
- The rationale is to inform all the neighbors about the upcoming communication using directional transmissions only and hence the protocol is able to achieve communication range extension as well.
- In CRM, the directional RTS is transmitted consecutively in a circular way until it scans all the area around the transmitter.
- The transmitter does not need to know the direction of the receiver.
- The receiver replies with a directional CTS after the conclusion of the circular RTS.

CRCM (IEEE PIMRC'05)

- Circular RTS and CTS MAC (CRCM) protocol that requires circular RTS and circular CTS packets prior to data transmission. Similar to CRM.
- The sender transmits circular directional RTS packet to all directions and the receiver sends a directional CTS towards the sender.
- Different from CRM, CRCM requires the receiver to circularly transmit CTS to inform un-aware neighbors about the imminent communication.
- Unaware neighboring nodes are those nodes that are in the coverage range of the receiver but not in that of the transmitter.
- The CRCM protocol protects the ACK reception from collision and hence handles the hidden terminal problem due to the asymmetry in gain at the expense of additional delay and large control overhead.

MDA (IEEE GLOBECOM'05)

- MAC protocol for Directional Antennas (MDA) that also employs the circular directional RTS/CTS transmissions simultaneously after successfully exchange a single directional RTS/CTS.
- To avoid coverage overlap of the circular RTS/CTS, MDA employs a Diametrically Opposite Directional (DOD) procedure.
- In MDA, the overhead associated with the DOD RTS and CTS packets is optimized by sending these packets only through those directions where neighbors are found.
- Another new feature in MDA is the use of an Enhanced DNAV (EDNAV) mechanism that differentiate between collision avoidance and deafness avoidance.

MDA (Cont.)

- The EDNAV consists of two components:
  - A DNAV table which is modified when the node receives the first directional RTS/CTS packets.
  - A Deafness Table (DT) that is modified when a node receives a DOD RTS/CTS.

- The simulation results show that MDA performs better than IEEE 802.11, Basic DMAC and CRM protocols.

DMAC-DACA (IEEE ISWPC'06)

- DMAC protocol with Deafness Avoidance and Collision Avoidance
- In this protocol, the basic directional RTS/CTS exchange is followed by sweeping RTS/CTS counterclockwise to inform all the neighbors about the upcoming communication.
- Deafness is avoided using a deafness neighbor table that use the sweeping RTS/CTS to record the deafness duration of neighboring nodes.
- The location information, retrieved by GPS, is added to the RTS/CTS frames.
- Using this information, the node that receives RTS/CTS can update the record in its deafness neighbor table if any of the neighbors is in the coverage area of the upcoming transmission.

DMAC-DACA (Cont.)

- The DMAC-DACA protocol performs collision avoidance through the DNAV mechanism.
- A node updates its DNAV if the transmitter or the receiver node is a DD-neighbor of this node.

DMAC/DA (IEEE GLOBECOM'07)

- Directional MAC with Deafness Avoidance (DMAC/DA) to address the tradeoff between deafness avoidance using additional control frames and the excessive overhead associated with them.
- In DMAC/DA, Wait-To-Send (WTS) frames are transmitted by the transmitter and the receiver after the successful exchange of directional RTS and CTS similar to MDA [61].
- However, WTS frames are transmitted only to the directions where potential transmitters are located in order to reduce the control overhead.
- The potential transmitter is selected either based on the history of previous communications or by means of explicit next packet notification if possible.

SpotMAC (IEEE ICCCN'07)

- SpotMAC protocol that is based on the use of pencil (narrow) beams.
- Pencil beams provide high spatial reuse and constrain the hidden terminal problem to a linear topology.
- SpotMAC uses an additional inverted RTS/CTS exchange to overcome the hidden terminal problem.
- The use of pencil beams increases the probability of deafness significantly.
- Whenever a failure is encountered, SpotMAC allows the sender to contend for the channel quickly by backoffing for a random period of time derived from a constant contention window.

SpotMAC (Cont.)

- This reduces the effect of deafness. If the number of failures exceeds a threshold, the contention window is increased exponentially.
- The results show that pencil beams can achieve very high spatial reuse in non-deafness scenarios.

Bandyopadhyay (IEEE GLOBECOM'01)

- Bandyopadhyay et al. in [65] propose an adaptive MAC protocol for wireless ad hoc networks using a kind of adaptive antenna arrays known as ESPAR.

- Each node periodically collects its neighborhood information and forms an Angle-SINR Table (AST).
- The AST specifies the strength of radio connection from each node to its neighbors at different particular directions.

- Using these information, a Neighborhood-Link-State Table (NLST) at each node is formed to determine the best possible direction of communication with any of its neighbor.

- RTS and CTS packets are sent selectively multidirectional to avoid interfering with known ongoing communications.

PCDMAC (Elsevier Journal of ad hoc Networks 2008)

- Power-Controlled Directional MAC (PCDMAC) protocol for wireless mesh networks with adaptive antennas.

- PCDMAC is the transmission of the RTS and CTS packets concurrently in multiple directions with a tunable power per direction that is adjusted to avoid interference with ongoing transmissions.

- This is done to inform the maximum number of neighbors of the new transmission. PCDMAC employs a DNAV that has an additional entry specifying the minimum power gain to reach an active node.

- After the successful exchange of RTS/CTS packets, the DATA and ACK packets are transmitted directionally with the minimum required power to reduce the interference and increase the spatial reuse.

Tone-based protocols

- A tone is a pure unmodulated sinusoidal wave transmitted at a particular frequency.
- Tones do not contain any information and hence do not need decoding but only need to be detected.
- In traditional ad hoc networks, tones (known as busy tones) are typically transmitted by busy nodes on separate dedicated channels (narrow bands) to inform all the nodes in their neighborhood about the ongoing transmission and hence protect them from collisions.
- The disadvantages of using tones are the bandwidth offset and the additional required hardware.

DBTMA/DA (IEEE Milcom'02)

- Dual Busy Tone Multiple Access (DBTMA) [68] for the case of Directional Antennas (DBTMA/DA).

- In the proposed protocol, the channel is split into a data channel for data frames and a control channel for control frames with the two busy tones, transmit busy tone (BTt) and receive busy tone (BTr), are assigned two separate single frequencies in the control channel.
  - When a node has data to send and it cannot sense BTr, the node transmits an omni-directional RTS since the receiver direction is not known.
  - When the RTS is received and the receiver does not sense BTt, it responds with a directional CTS and turns on the directional BTr.
  - Upon receiving the CTS, the source nodes transmits the data frame directionally and turn on the directional BTt until the data transmission is completed.

Smart 802.11 (IEEE ICC'04)

- When a node has a packet to send, it beamforms towards the intended receiver and transmits a short sender-tone to initiate communication.
- All idle nodes that receive the sender-tone beamform towards the sender and enter a random defer phase before transmitting the receiver-tone.
- When the sender receives the receiver-tone, it transmits its packet and waits for the receipt of an ACK.
- If there is no ACK, it enters backoff as in IEEE 802.11. Since the proposed protocol does not take care of hidden terminals

ToneDMAC (IEEE ICNP'04)

- In ToneDMAC, the backoff phase is performed in an omni-directional mode to alleviate the possibility of deadlocks and prolonged periods of deafness.

- ToneDMAC uses a tone-based notification mechanism that allows the neighbors of a node to distinguish congestion from deafness and react appropriately.

F-DMAC-TONE (IEEE ISWPC'07)

- Fragmentation-based Directional MAC with TONE (FDMAC- TONE) protocol that does not assume separate data and control channels.

- F-DMAC-TONE uses a combination of three features to solve the problem of hidden terminals due to unheard RTS/CTS.

  - When a node returns from directional to omni-directional mode, it undergoes a pause period before attempting transmission in another direction.

  - A second feature in F-DMAC-TONE is the fragmentation of packets into smaller chunks transmitted individually but acknowledged collectively.

  - The third feature is the use of a short TONE signal in between fragments to inform other nodes capable of causing collisions with the ongoing transmission.

DBSMA (IEEE PIMRC'05)

- Directional Busy Signal Multiple Access (DBSMA) protocol that relies on the use of busy tones.
- In DBSMA, all the transmissions, receptions, and idle listening are performed directionally to achieve better connectivity.
- When a node is in an idle state, its directional antenna sweeps continuously to cover the whole region.
- When a node wants to transmit, the node transmits an out-of-band invitation signal which is long enough to capture an idle sweeping receiver.
- The invitation signal is followed by an RTS packet.

DBSMA (Cont.)

- The invitation signal locks sweeping antennas in one direction to receive the RTS and the intended receiver responds with a CTS packet.
- While in the reception mode, the receiver continuously transmits a busy signal to alleviate any possibility of collision from the hidden terminals.
- In DBSMA, if the sender senses a busy signal or busy channel in one direction, it may choose to communicate with another node in another direction.
- Moreover, DBSMA uses a separate backoff counter for each direction in order to adapt independently to the traffic conditions in different directions.

FFT-DMAC (IEEE GLOBECOM'07)

- Flip-Flop Tone directional MAC (FFT-DMAC) protocol that utilize two pairs of tones to solve the deafness and hidden terminal problems.
- The first pair of tones are transmitted omni-directionally to announce the start and end of a communication, therefore, overcoming the deafness problem.
- The second pair of tones are sent directionally by the receiver towards the sender to solve the hidden terminal problem and to acknowledge the receipt of both RTS and DATA packets.
- In FFT-DMAC, each node maintains a "deafness nodes" list and "ongoing transmission nodes" list that are updated with the reception of tones.

BT-DMAC (IEEE GLOBECOM'07)

- Busy Tone Directional MAC (BTDMAC) protocol for wireless ad hoc networks using directional antennas in [73].
- BT-DMAC combines the use of two busy tones with the DNAV table to solve the deafness and hidden terminal problems.
- When the transmission is in progress, the transmitter and the receiver turn on the transmitting busy tone BTt and the receiving busy tone BTr, respectively.
- Each tone is transmitted omni-directionally and is pulse-modulated with the node ID and the beam used for communicating.
- Any node hearing the busy tones learns the node IDs and the beam numbers from the tones and whether the potential sending will interfere with the current transmission.

DMAC-PCDR (IEEE WTS'08)

- Directional MAC protocol with Power Control and Directional Receiving (DMACPCDR) that mitigates the interference caused by directional hidden terminals and minor side lobes.

- DMAC-PCDR employs directional idle receiving through the continuous rotation of the antenna beam while the node is idle.

- Directional receiving eliminates the hidden terminal problem due to asymmetry in gain and the interference caused by the reception through the side lobes.

- In order to enable an idle receiver to receive the signal, each control packet (RTS or CTS) is transmitted with a preceding tone that is long enough for an idle node to hear it.

DMAC-PCDR (Cont.)

- The node which receives the preceding tone stops the rotation and receives the packet.
- On the other hand, DMAC-PCDR improves spatial reuse of the wireless channel and extends the communication range through transmission power control.

DOA-MAC (IEEE PIMRC'03)

- DOA-MAC protocol for nodes equipped with adaptive antenna array in ad hoc network.

- DOA-MAC is based on the slotted ALOHA with each slot broken into three minislots.
  - In the first minislot, all transmitters transmit a simple tone towards their intended receivers.
  - The receivers then run a DOA algorithm to identify the direction of the transmitters.
  - The second minislot is the packet transmission minislot.
  - After receiving the packet, the receiver rejects the packet if it is not the intended destination.
  - Otherwise, the receiver responds with an ACK in the last minislot.

LiSL/d (IEEE ICC'05)

- TDMA-based directional MAC protocol called LiSL/d in [78].
- The LiSL/d protocol performs link scheduling through pure directional transmission and reception.
- Time is divided into frames and each frame is divided into three sub-frames.
  - Devoted for neighbor discovery which is performed through scanning and three-way handshakes.
  - Reassurance and reservation are made at the second sub-frame when the two nodes point towards each other with their beams and exchange another three-way handshakes.
  - The third sub-frame is for data transmission.

SYN-DMAC (IEEE MILCOM'05)

- The timing structure of SYN-DMAC consists of three time phases in each cycle which are: Random access, DATA and ACK phases.

- The random access phase serves as channel contention for data transmission. Multiple RTS/CTS packets are exchanged and multiple data transmissions can be scheduled.
  - The later scheduled data transmissions should not collide with previous scheduled transmissions.

- In the DATA phase, parallel contention-free data transmission is achieved .

- In the ACK phase parallel contention-free ACK packets are sent.

PMAC (IEEE Trans. Wireless Commu. 2007)

- In this protocol, the time is divided into contiguous frames and each frame is divided into three segments: search, polling and data transfer.
  - In the search segment, each node searches for new neighbors by transmitting or receiving pilot tones directionally.
  - If two nodes discover each other, they exchange a list of the available slots in their corresponding polling segments.
  - The polling slot allows the nodes to schedule data transfers in the third segment of the frame and also allows them to keep track of the direction of each other that may change due to mobility.
  - In the data transfer segment, multiple data transfers take place according to the schedules formed in the polling segment.

CW-DMAC (IEEE COMSWARE' 07)

- Contention Window Directional MAC (CW-DMAC) protocol to address the deafness and hidden terminal problems using single channel and single radio interface.

- The idea is to separate the transmission of control and data packets in time without the need of network-wide synchronization.

- When a node receives an RTS but cannot send the CTS due to beam blockage it instead sends a Negative CTS (NCTS) to inform the sender that the data transmission cannot happen without interfering with the already reserved transmissions.

CW-DMAC (Cont.)

- Upon receiving the NCTS, the sender sends a TC (Transmission Cancel) packet omni-directionally to inform neighbors that the current transmission transmission has been canceled.

- At the end of the control window, the directional DATA packets are transmitted simultaneously followed by concurrent transmission of ACK packets.

CDMAC (Springer Wireless Networks 2009)

- Coordinated DMAC (CDMAC) protocol that also requires local synchronization only.

- The timing structure of CDMAC consists of a contention period in which control packets are exchanged followed by two contention-free periods for parallel DATA and ACK transmissions.
- CDMAC does not require the neighbor directions to be known a priori.
- Different from CW-DMAC, CDMAC use three control packets (RTS/CTS/confirmed-RTS) for channel reservation, all transmitted omni-directionally.
- The beam indices to be used to transmit DATA/ACK packets are included in the CTS and confirmed-RTS packets.
- The master node-pair, those who first win the channel contention, specify the duration of the contention and contention-free periods.

RDMAC (IEEE ICC'09)

- Reservation Directional MAC (RDMAC) for multi-hop wireless networks with directional antennas.

- The RDMAC protocol operates in sessions with each session comprising a reservation period and a transmission period.
  - In the reservation period, the first node to transmit the RTS defines the start and end time of the transmission period.
  - The neighboring nodes that receive the ORTS/OCTS packets, estimate the direction of arrival and point their antennas towards the sender/receiver to receive the remaining control packets.
  - The reserving nodes transmit directional RTS/CTS packets so the neighbor nodes can update their DNAV taking into consideration any possible interference caused by minor lobes.

Directional MAC Protocols Features Comparsion Part 1

Protocol	Packet transmission			Idle Listening	Tones transmission	Backoff		Channel(s)	Power control
	RTS	CTS	DATA/ACK			Antenna	Mechanism		
Nasipuri [50]	Omni	Omni	Dir	Omni	-	Omni	BEB	Single	No
SCSMA/CN [51]	Omni	Omni	Omni	Omni	-	Omni	BEB	Single	No
Nullhoc [52]	Omni	Omni	Dir	Omni	-	Omni	Constant CW	Multi	No
DMAP [53]	Omni	Dir	Dir	Omni	-	Omni	BEB	Multi	Yes
D-MAC [54]	Dir	Omni	Dir	Omni	-	omni	BEB	Single	No
DVCS [55]	Dir	Dir	Dir	Omni	-	Omni	BEB	Single	No
Basic DMAC [33]	Dir	Dir	Dir	Omni	-	Dir	BEB	Single	No
MMAC [33]	Dir (along DO route)	Dir	Dir	Omni	-	Omni	BEB	Single	No
Kolar [45]	Dir	Dir	Dir	Omni	-	Omni	BEB	Single	No
UDAAN D-MAC [18]	Dir	Dir	Dir	Omni	-	Omni	Event-based CW	Single	Yes
RIDMAC [56]	Dir	Dir	Dir	Omni	-	Omni	BEB	Single	No
CADMAC [47]	Dir	Dir	Dir	Multi-dir	-	Multi-dir	BEB	Single	No
OPDMAC[46]	Dir	Dir	Dir	Omni	-	Dir	Opportunistic	Single	No
DtD-MAC [57]	Dir	Dir	Dir	Dir	-	Dir	2 constant CW (Alternate)	Single	No
BMAC[58]	Dir	Omni	Dir	Omni	-	Omni	BEB	Single	Yes

Directional MAC Protocols Features Comparsion Part 1(Cont.)

CRM [59]	Multi-dir sequential	Dir	Dir	Omni	-	Omni	BEB	Single	No
CRCM [60]	Multi-dir sequential	Multi-dir sequential	Dir	Omni	-	Omni	BEB	Single	No
MDA [61]	Multi-dir sequential	Multi-dir sequential	Dir	Omni	-	Omni	BEB	Single	No
DMAC-DACA [62]	Multi dir sequential	Multi dir sequential	Dir	Omni	-	Omni	BEB	Single	No
DMAC/DA [42]	Multi-dir sequential	Multi-dir sequential	Dir	Omni	-	Omni	BEB	Single	No
SpotMAC [64]	Multi-dir sequential	Dir	Dir/Multi-dir sequential	Omni	-	Omni	BEB	Single	No
Bandyopadhyay [65]	Multi-dir concurrent	Multi-dir concurrent	Dir	Multi-dir	-	-	-	Single	No
PCDMAC[66]	Multi-dir concurrent	Multi-dir concurrent	Dir	Omni	-	Omni	BEB	Single	Yes

Directional MAC Protocols Features Comparsion Part 1(Cont.)

DBTMA/DA [67]	Omni	Dir	Dir	Omni	dir/dir	Omni	MILD	Multi	No
Smart 802.11b[69]	-	-	Dir	Omni	dir/dir	Omni	BEB	Single	No
Tone DMAC [43]	Dir	Dir	Dir	Omni	omni	Omni	prempted BEB	Multi	No
F-DMAC-TONE [70]	Dir	Dir	Dir	Omni	dir	Omni	BEB	Single	No
DBSMA [71]	Dir	Dir	Dir	Dir	dir/dir	Dir	BEB for each beam	Multi	No
FFT-DMAC[72]	Dir	-	Dir	Omni	omni/dir	Omni	BEB	Multi	Yes
BT-DMAC [73]	Dir	Dir	Dir	Omni	omni/omni	-	-	Multi	No
DMAC-PCDR [74]	Dir	Dir	Dir	Dir	dir	-	-	Single	Yes
DOA-MAC[77]	-	-	Dir	-	dir	-	-	Single	No
LiSL/d [78]	-	-	Dir	-	-	-	-	Single	Yes
SYN-DMAC [80]	Dir	Dir	Dir	Omni	-	Omni	BEB	Single	No
PMAC [81]	Dir	Dir	Dir	Dir	dir	-	-	Single	No
CW-DMAC [82]	Omni	Omni	Dir	Omni	-	-	-	Single	No
CDMAC [49]	Omni	Omni	Dir	Omni	-	Omni	BEB	Single	Yes
RDMAC [83]	Omni	Omni	Dir	Omni	-	Omni	BEB	Single	No

Directional MAC Protocols Features Comparsion Part 2

Protocol	Antenna used			Neighbors		MAC challenges addressed			
	Type	Beam(s)	Nulling	Range	Beamfoming Information	Deafness	Hidden Terminals	HoL	MAC-layer Capture
Nasipuri [50]	Switched	Single	No	OO	DoA	No	No	No	No
SCSMA/CN [51]	Adaptive array	Single	No	OO	-	No	No	No	No
Nullhoc [52]	Adaptive array	Single	Yes	OO	Exchange antenna weights	No	Yes	No	No
DMAP [53]	Switched	Single	No	OO	AoA	Yes	Yes	No	No
D-MAC [54]	Switched	Single	No	OO	GPS	No	No	No	No
DVCS [55]	Adaptive array	Single	No	DO	AoA cache	No	No	No	No
Basic DMAC [33]	Adaptive array	Single	No	DO	Upper layer	No	No	No	No
MMAC [33]	Adaptive array	Single	No	DD	Upper layer	No	No	No	No
Kolar [45]	Switched	Single	No	DO	AoA cache	No	No	Yes	No
UDAAN D-MAC [18]	Switched	Single	No	DO	periodic heartbeats	No	No	No	No
RIDMAC [56]	Switched	Single	No	DO	Assumed available	Yes	No	No	No
CADMAC [47]	Switched	Multiple	No	OO	Assumed available	No	No	No	Yes
OPDMAC[46]	Switched	Single	No	DO	Upper layer	Yes	Yes	Yes	No
DtD-MAC [57]	Switched	Single	No	DD	AoA cache	Yes	Yes	No	No
BMAC[58]	Adaptive array	Single	Yes	OO	Periodic Training Sequence	Yes	Yes	No	No

Directional MAC Protocols Features Comparsion Part 2 (Cont.)

CRM [59]	Switched	Single	No	DO	DoA	Yes	Yes	No	No
CRCM [60]	Switched	Single	No	DO	DoA	Yes	Yes	No	No
MDA [61]	Switched	Single	No	DO	Upper layer	Yes	Yes	No	No
DMAC-DACA [62]	Switched	Single	No	DO	GPS	Yes	Yes	No	No
DMAC/DA [42]	Switched	Single	No	DO	Assumed available	Yes	Yes	No	No
SpotMAC [64]	Adaptive array	Single	Yes	DO	AoA cache	Yes	Yes	No	No
Bandyopadhyay [65]	Adaptive array	Multiple	Yes	OO	Periodic updates	No	Yes	No	Yes
PCDMAC[66]	Adaptive array	Multiple	No	DO	Assumed available	Yes	Yes	No	No
DBTMA/DA [67]	Switched	Single	No	OO	DoA	No	Yes	No	No
Smart 802.11b[69]	Adaptive array	Single	Yes	DO	Assumed available	No	No	No	No
Tone DMAC [43]	Switched	Single	No	DO	Assumed available	Yes	No	No	No
F-DMAC-TONE [70]	Switched	Single	No	DO	AoA cache	No	Yes	No	No
DBSMA [71]	Switched	Single	No	DD	Periodic updates	No	Yes	Yes	No
FFT-DMAC[72]	Adaptive array	Single	No	DO	Assumed available	Yes	Yes	No	No
BT-DMAC [73]	Switched	Single	No	DO	AoA cache	Yes	Yes	No	No
DMAC-PCDR [74]	Adaptive array	Single	No	DD	GPS	No	Yes	No	No

Directional MAC Protocols Features Comparsion Part 2 (Cont.)

DOA-MAC[77]	Adaptive array	Single	Yes	DO	Assumed available	No	No	No	No
LiSL/d [78]	Adaptive array	Single	No	DD	Scanning phase	No	No	No	No
SYN-DMAC [80]	Switched	Single	No	DO	Assumed available	Yes	Yes	Yes	No
PMAC [81]	Adaptive array	Single	No	DD	Search phase	Yes	Yes	No	No
CW-DMAC [82]	Switched	Single	No	OO	Assumed available	Yes	Yes	No	No
CDMAC [49]	Switched	Single	No	OO	AoA cache	Yes	Yes	No	No
RDMAC [83]	Switched	Single	No	OO	DoA	Yes	Yes	Yes	No

Comparison between different design MAC choices for beamforming antennas

Category	Design Choice	Advantages	Disadvantages
RTS transmission	Omni-directional RTS	– Informs neighbors in all directions about imminent communication – Reduces instances of deafness and directional hidden terminal problems	– Low Spatial reuse – Short Communication Range
	Uni-directional RTS	– Increases Spatial reuse – Extends communication range or decreases transmission power	– Increases instances of deafness and directional hidden terminal problems – Beamforming information is needed a priori
	Multi-directional Sequential RTS	– Eliminates the asymmetry of gain problem – Reduces instances of deafness significantly	– Large control overhead – Large delay
	Multi-directional concurrent RTS	– Reduces instances of deafness and directional hidden terminal problems without jeopardizing the spatial reuse	– Requires complex antenna systems
Tones	Using Tones	– Solves hidden terminal problem – Can be used to address deafness	– Requires complex hardware – Usually needs dedicated control channel
Synchronized Access	Global Synchronization	– Solves most challenges due to conflict-free scheduling	– Complex and not practical in wireless ad hoc networks
	Local Synchronization	– Simple to form conflict-free schedules	– Short Communication Range – Imperfect if nodes lie in different synchronized zones
Idle Listening	Omni-directional	– No deafness when the receiver is idle	– Cannot achieve full communication range extension – Susceptible to MAC- layer capture
	Directional	– Full communication range extension	– Increases instances of deafness

Comparison between different design MAC choices for beamforming antennas (Cont.)

Backoff mechanism	BEB	– Very popular (IEEE 802.11 standard)	– Increases impact of deafness and HoL blocking
	Constant CW	– Reduces impact of deafness and HoL blocking	– Increases collision and may result in deadlocks
	Opportunistic	– Minimizes impact of deafness and HoL blocking	– Works well with multiple flows at each node
Antenna type	Switched beam	– Simplicity	– Less flexible and no guarantee on maximum gain – Does not work well in multipath environment
	Adaptive array	– Provides maximum gain and nulling capability	– High Complexity and higher power consumption

Conclusion

- In this article, we presented a comprehensive survey of MAC protocols in wireless ad hoc networks with beamforming antennas.
- The directional MAC protocols were designed to exploit the benefits of beamforming antennas and overcome the beamforming-related challenges.
- This paper enlisted and discussed the main challenges facing MAC protocols in wireless ad hoc networks with beamforming antennas.
- This paper developed taxonomy of the existing MAC approaches and using that we discussed different basic design choices along with their associated tradeoffs.

Conclusion (Cont.)

- The omni-directional transmission of RTS/CTS reduces the instances of deafness and hidden terminal problem at the expense of reduced spatial reuse and shorter communication range.
- Uni-directional RTS/CTS handshakes achieve higher spatial reuse and longer communications range but aggravate the critical problem of deafness.
- To address this trade-off, the control packets (e.g. RTS and CTS) are sometimes transmitted circularly in all directions one at a time to avoid collision and/or deafness.
- The main drawback of this scheme is its large control overhead that can offset the benefits.

Conclusion (Cont.)

- Some directional MAC protocols use tones to mitigate deafness and/or directional hidden terminal problems. Tones are commonly transmitted on a dedicated control channel which requires extra bandwidth.

- Tone-based protocols require additional hardware that increases cost and complexity.

- A different MAC design choice is for the channel access to rely on synchronized access rather than random access. By separating the transfer of control and data packets in time, the location-dependent carrier sensing problems are alleviated.

- This paper investigated several opportunities for possible future work including the need for QoS-aware directional MAC protocols, accurate analytical modeling and MAC protocols for wireless ad hoc networks with heterogeneous antennas.

Homework #6:

1. What's benefits of beamforming atennas ?
2. What's MAC challenges with beamforming antennas ?