ABSTRACT

Title of Thesis: AN ADAPTIVE MAC PROTOCOL FOR WIRELESS MULTI-HOP NETWORKS WITH MULTIPLE ANTENNAS

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Radio links that use multiple antennas at both transmitter and receiver sides are referred to as Multiple-Input Multiple-Output (MIMO) links. MIMO links are known to provide multiplicative increase in capacity and spectral efficiency by simultaneously transmitting multiple independent data streams in the same channel. However, current medium access control (MAC) protocols can't fully exploit the bandwidth and capacity of the MIMO links. In this thesis, we present a new MAC protocol, Achieving Maximum Transmit Antenna MAC (AMTA-MAC), which can fully utilize the feature of MIMO links to achieve better performance in terms of fairness and throughput. We implement the AMTA-MAC protocol in the network simulator ns-2 for a system with two antennas. Simulation results show that the AMTA-MAC outperforms the throughput of IEEE 802.11 and MIMA-MAC and mitigates the unfairness problem of IEEE 802.11.

AN ADAPTIVE MAC PROTOCOL FOR WIRELESS MULTI-HOP NETWORKS WITH MULTIPLE ANTENNAS

By

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2005

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Acknowledgements

I would like to thank my advisor Dr. Virgil D. Gligor for his advice, support and encouragement. I would also like to thank Dr. Gang Qu and Dr. Steven A. Tretter for being my committee member and correcting my thesis.

Also I would like to thank my friend Dr. Gang Lu for assisting in the programming. I would like to thank all the friends to give the support and happiness. I would like to thank my family for endless love. I would like to thank Xin for sharing every moment with me.

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Chapter 1. Introduction

Multiple-Input Multiple-Output (MIMO) is a promising technology for the next generation wireless systems because of its ability to enhance capacity and robustness of the link. It refers to radio links with multiple antennas at the transmitter and the receiver side. The sender splits data stream into M parallel lower rate streams, with each data stream transmitted over one transmit antenna. The receiver then receives a superposition of the transmit signals and separates and detects the M data streams via Spatial Multiplexing (SM) technique. With the specific techniques, MIMO allows: 1. Multiplicative increase in capacity and spectral efficiency; 2. Dramatic reductions of fading; 3. Increase system capacity (number of users); 4. Improve resistance to interference [9, 10].

However, as the wireless channel is shared among all wireless stations, a medium access control (MAC) protocol is needed to avoid collision. Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) is widely used in today's wireless MAC protocols. In CSMA/CA, every node first senses the carrier before transmission. If the channel is busy, the node defers its transmission; otherwise, it begins transmission. However, the CSMA/CA suffers from the hidden node problem [1]. If two nodes can’t sense each other and both of them send information to the same receiving node, a collision will occur at the receiving node. To solve this problem, IEEE 802.11 employs an RTS/CTS/DATA/ACK protocol which exchange RTS/CTS control packets before data transmission and ACK packet after data transmission. But the hidden node problem is not completely solved [2, 3]. It has been shown that IEEE

802.11 has hidden node and exposed node problems, which lead to throughput decrease and unfairness. A new MAC protocol to solve those problems is expected.

With spatial multiplexing in MIMO, it becomes possible to transmit a data packet over two or more antennas within a broadcast domain, as long as the receiver is able to separate them. However, current MAC protocols are not work well over MIMO channel, such as IEEE 802.11 and MIMIA-MAC. They can not fully exploit the bandwidth and capacity of the MIMO channel. We propose an adaptive MAC protocol, AMTA-MAC, which can fully utilize the feature of MIMO to achieve better performance both in term of fairness and throughput. With the proposed AMTA-MAC protocol, we can achieve the maximum transmission rate. And based on different network topologies, it can choose the optimal way to distribute channels to all the nodes.

We have simulated and evaluated the throughput and fairness of the AMTA-MAC protocol by using network simulator ns-2 [4]. The simulation was performed under two scenarios: same direction traffic (SDT) and opposite direction traffic (ODT). By comparing the results with IEEE 802.11 and MIMA-MAC, our results show that the proposed AMTA-MAC outperforms the throughput of MIMA-MAC and mitigate the unfairness problem of IEEE 802.11.

This thesis consists of seven chapters. The rest of the thesis is organized as follow. In Chapter 2, we introduce the MIMO channels and the properties of it, Array Gain, Diversity Gain, Spatial Multiplexing and Interference Reduction. In Chapter 3, we present the current MAC protocols, specify the IEEE 802.11 MAC protocol, and point out the hidden node and exposed node problems with it. In Chapter 4, we introduce the different scenarios in using MIMO links. Chapter 5 proposes the new adaptive MAC protocol, AMTA-MAC, and presents the basic structure, operation and analysis under different situations. In Chapter 6, we simulate the proposed AMTA-MAC protocol, and compare the results with IEEE 802.11 MAC protocol and MIMA-MAC protocol. In Chapter 7, we present conclusions.

Chapter 2. MIMO Wireless Networks

In communication theory, MIMO wireless systems refer to radio links with multiple antennas at the transmitter and the receiver sides.

In 1994, Paulraj and Kailath [5] first proposed a technique for increasing the capacity of wireless link using multiple antennas at both the transmitter and the receiver. The goal is to approach performance limits and to explore efficient but easy to realize coding and modulation schemes for wireless links using multiple antennas.

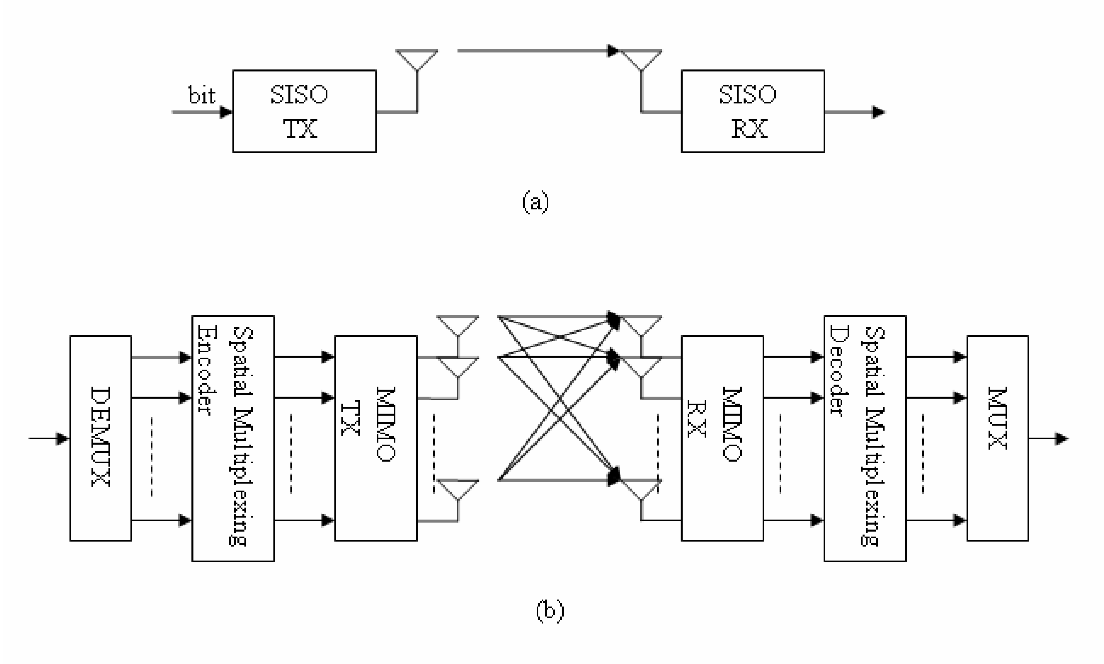


Figure 1. Overview of SISO and MIMO systems [6]

Figure 1 shows a simple example of the Single-Input Single-Output (SISO) wireless system and MIMO wireless system. The major difference between the SISO and MIMO system is the additional signal and information processing in the transceiver design. Spatial Multiplexing (SM) [7] is a technique maximizing the average date rate over the MIMO system. The bit stream to be transmitted is demultiplexed into M (the number of antennas) sub-streams with 1/M rate. Those sub-streams are modulated and transmitted simultaneously from each antenna. The spatial signatures of these signals induced at the receive antennas are separated. The receiver, having knowledge of the channel, can differentiate between the M co-channel signals, after which demodulation yields the original sub-streams that can now be combined to yield the original bit stream. Thus SM increases transmission rate proportionally with the number of transmit-receive antennas. However, to successfully differentiate M independent data streams, the number of receive antennas should be larger or equal to M [7], and channel state information (CSI) for all the propagation paths between the transmitter and receiver have to be provided to the receiver. However, these two requests are not necessary. From the research of Ahlen et al [21], it is possible differentiate the M data streams without CSI and less receive antennas. In order to get the best performance, in this thesis, we define that CSI is needed and the number of transmit antennas less than or equal to the number of receive antennas.

Several properties of multiple antennas in wireless can be exploited for better performance, such as array gain, diversity gain, spatial multiplexing and interference reduction.

- Array gain refers to the average increase in SNR at the receiver that arises from the coherent combining effect of multiple antennas in receiver or transmitter or both. Consider a SIMO channel. Signals arriving at the receive antenna have different amplitude or phase. The receiver can combine the signals coherently so that the resultant signal is enhanced.

The average increase in signal power at the receiver is proportional to the number of the receive antennas. In channel with multiple antennas at transmitter, array gain exploitation requires channel knowledge at the transmitter.

- Diversity Gain. In wireless channels signal power fades. When the signal power drops significantly, the channel is said to be in a fade. Diversity is used in wireless channels to compensate fading. Receive antenna diversity can be used in SIMO channels. The receive antennas receive independently faded version of the same signal. The receiver combines these signals so that the resultant signal exhibits considerably reduced amplitude fading in comparison with the signal at any one antenna. Transmit diversity is applicable to MISO channels. Suitable design of the transmitted signal is required to extract diversity in such channels. ST (space time) diversity coding [8] is a transmit diversity technique that relies on coding across space (transmit antennas) to extract diversity. Utilization of diversity in MIMO channels requires a combination of the receive and transmit diversity described above. The diversity order is equal to the product of the number of transmit and receive antennas, if the channel between each transmit-receive antenna pair fades independently.
- Spatial Multiplexing. We have described SM in some detail above. Besides MIMO channels, SM can also be applied in a multiuser format (MIMO-MU, also known as space division multiple access or SDMA). Consider two users transmitting their individual signals, which arrive at a base-

station with two antennas. The base station can separate the two signals to support simultaneous use of the channel by both users. This allows a capacity increase proportional to the number of antennas at the base-station and the number of users.

- Interference Reduction. Co-channel interference appears due to frequency reuse in wireless channels. When multiple antennas are used, the differentiation between the spatial signatures of the desired signal and co-channel signals can be exploited to reduce the interference. Interference reduction can also be implemented at the transmitter, where the goal is to minimize the interference energy sent towards the co-channel users while delivering the signal to the desired destination.

The following chapters will explain why the current IEEE 802.11 MAC protocol is not optimal for MIMO multi-hop wireless networks. A new MAC protocol is proposed to improve the throughput and fairness in MIMO wireless networks.

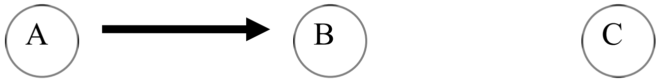
Chapter 3. Current Wireless MAC Protocol

Wireless media can be shared and any nodes can transmit at any point in time. This could result in possible contention over the common channel. If channel access is probabilistic, then the resultant attainable throughput is low. A MAC protocol is a set of rules or procedures to allow the efficient use of a shared medium [11], such as wireless. We define a *node* as any host that is trying to access the medium. The *sender (or transmitter)* is a node that is attempting to transmit over the medium. The *receiver* is a node that is the recipient of the current transmission. The MAC protocol is concerned with per-link communications, not end-to-end.

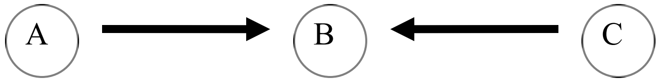
3.1 CSMA/CA MAC Protocol

Carrier Sense Media Access with Collision Avoidance (CSMA/CA) is widely used in today's wireless MAC protocols. In CSMA/CA, every node first senses the carrier before transmission. If the channel is busy, the node defers its transmission; otherwise, it begins transmission. However, the CSMA/CA suffers from the hidden node problem.[1]

Figure 2 shows a scenario of hidden node problem. Because node A and node C can’t sense each other (out of signal range), they are said to be hidden from one another. When both of them attempt to send information to the same receiving node, node B in this case, a collision of data occurs at the receiver node.



(a) A transmits to B (C does not hear this)



(b) C transmits to B --- Collision!

Figure 2. The hidden node problem

3.2 IEEE 802.11 MAC Protocol

In wireless networks, interference is location based. Thus, the hidden node problem may happen frequently. Resolving hidden node problem becomes one of the major design considerations of MAC protocols. IEEE 802.11 Distributed Coordination Function (DCF) is the most popular MAC protocol used in both wireless LANs and mobile ad hoc networks (MANETs) [2]. To solve the hidden node problem in CSMA/CA MAC protocol, IEEE 802.11 MAC protocol employs a new handshake protocol which exchanges RTS/CTS control packets before data transmission and ACK packet after data transmission. However, the hidden node problem is not completely solved. To help understand the problems of the IEEE 802.11 MAC protocol, we first describe its basic structure and operation.

3.2.1 An Overview of the IEEE 802.11 MAC Protocol

The design of the 802.11 MAC protocol is based on a CSMA/CA with RTS/CTS protocol [12, 13]. To avoid collisions, all of the receiver's neighboring nodes need to be informed that the channel will be occupied. This can be achieved by reserving the channel using a handshake protocol. An RTS (Request To Send) message can be used by a node to indicate its wish to transmit data. The receiving node can allow this transmission by sending a grant using the CTS (Clear To Send) message. Because the broadcast nature of these messages, all neighbors of the sender and receiver will be informed that the medium will be busy, thus preventing them from transmitting and avoiding collision.

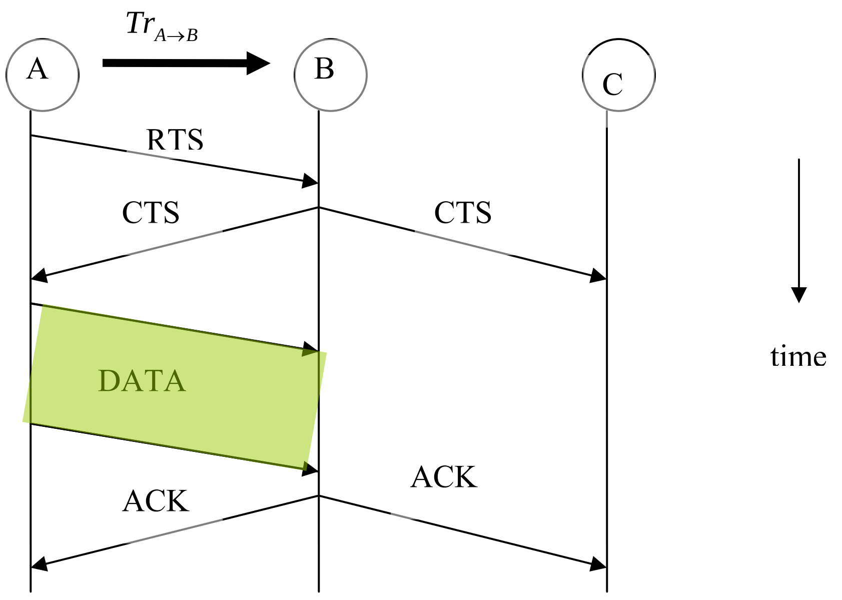


Figure 3. The basic operation of the IEEE 802.11 MAC protocol

Figure 3 shows a basic operation of the IEEE 802.11 MAC protocol. If node A wants to transmit data to node B, it first sends an RTS packet to node B, then node B replies with a CTS packet to both A and C. Since node C can decode the CTS transmitted from node B, node C remains silent until the end of the A-B dialog when the ACK message is received. Therefore, node A can transmit the DATA packet to node B without any interference from node C, which solves the hidden node problem. Finally, receiver B replies with an acknowledgement (ACK) packet back to transmitter A to indicate that it has received the DATA packet successfully. One thing to notice here is that CSMA/CA is based on the assumption that there can be only one date transmission at any time in one broadcast domain, which eventually limits the capacity of the network.

3.2.2 Operation of IEEE 802.11 MAC Protocol

In this section, we describe the operation of IEEE 802.11 MAC protocol in detail for better understanding the simulation results later. IEEE 802.11 employs a fragmentation/defragmentation mechanism. To increase reliability, IEEE 802.11 will partition the data units into smaller MAC protocol data units (MPDU) automatically, and recombine those MPDU into the original data units. The length of MPDU is much smaller than original data units, in order to increase the probability of successful transmission.

The time interval between frames is called the inter-frame space (IFS). There are four types of IFS defined: short inter-frame space (SIFS), PCF (point coordination function) inter-frame space (PIFS), DCF inter-frame space (DIFS), and extended inter-frame space (EIFS). Because SIFS and PIFS were used in PCF, we only concern with DIFS and EIFS, which are used in distributed coordination function (DCF). Figure 4 [12] describes the relationships among IFS. They are list in order, from the shortest to the longest.

A node can begin to transmit only after it senses that the channel is idle for a DIFS interval. If the channel is busy, the node will wait until the channel is idle again.

If channel is busy and a node can decode the ongoing transmission, the node can transmit after the transmission is finished and a new DIFS interval starts. Or if the ongoing transmission can't be decoded, the node can transmit after the finish of the current transmission when an EIFS interval, which is much longer than DIFS, starts.

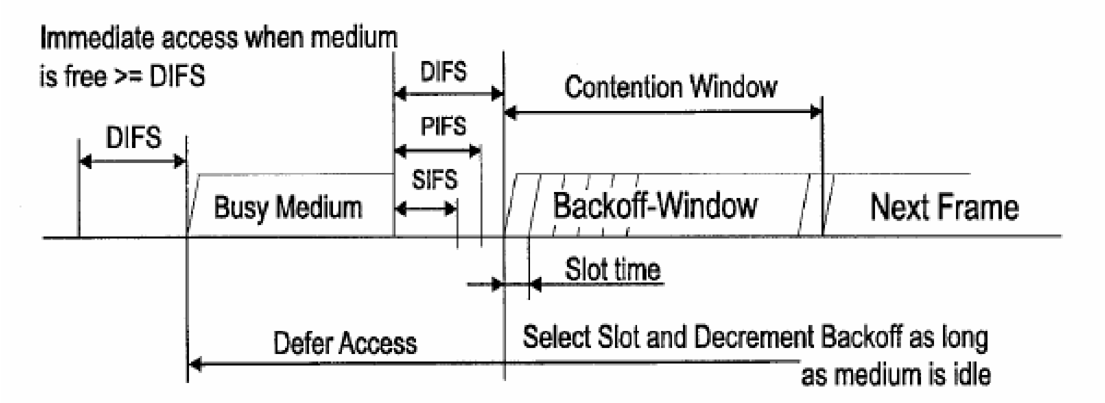


Figure 4. IFS relationship [12]

In addition, a node will defer a random backoff time after DIFS or EIFS to reduce the probability of collision. If two nodes try to send data to the same node, the node that have small backoff time will win. The backoff time equals the product of a slot time and a random number. The random number is uniformly chosen from contention window (CW) parameter, which takes value from aCWmin to aCWmax. Each time the transmission fails, the value of aCWmin will be doubled until it reaches aCWmax. After a successful transmission, the aCWmin value will change to the initial aCWmin value.

3.2.3 Hidden Node Problem in IEEE 802.11 MAC Protocol

The RTS/CTS handshake of IEEE 802.11 does not work as well as we expected in theory. It cannot prevent hidden node problems completely. In this section, we explain this through a theoretical analysis. For better explanation, we first review the three radio ranges: namely transmission range (R_{TX} **),** carrier sensing range (R_{CS}) and interference range (R_I) [2].

- Transmission Range (R_{TX}) represents the range within which a packet can be successfully received if there is no interference from other radios. The transmission range is mainly determined by transmission power and radio propagation properties (i.e., attenuation).
- Carrier Sensing Range (R_{CS}) is the range within which a transmitter can apply carrier sense. This is usually determined by the antenna sensitivity. In IEEE 802.11 MAC, a transmitter only starts a transmission when it senses that the media is free.
- Interference Range (R_I) is the range within which nodes in receive mode will be "interfered with" by an unrelated transmitter and thus suffers a loss.

Consider a wireless network consisting of three nodes in Figure 5. If node A (transmitter) transmits packets to node B (receiver), the shaded area represents the interference range within which node B will be interfered by other unrelated transmitter, such as node C. Nodes within the interference range of a receiver are usually called the “hidden nodes”. When the receiver is receiving a packet, if a hidden node also tries to start a transmission concurrently, collisions will happen at the receiver.

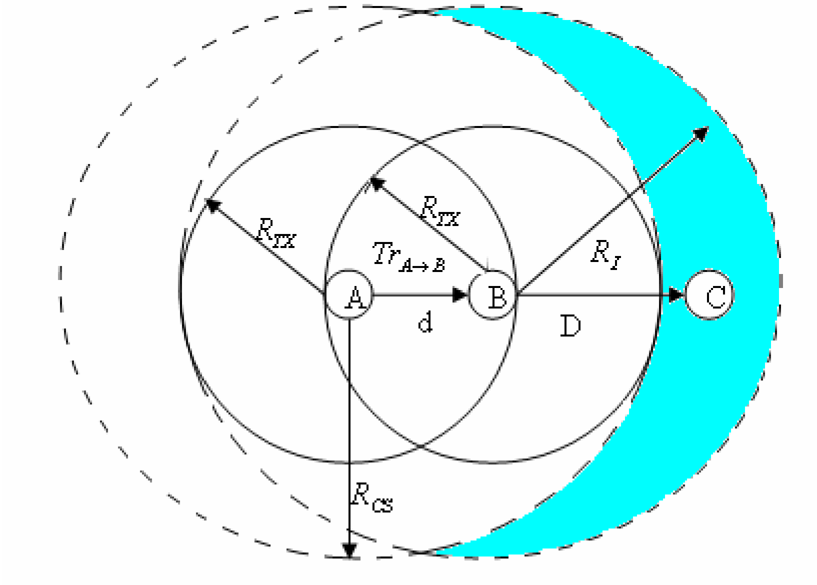


Figure 5. Review of the three radio ranges

According to Rappaport [14], the receiving power P_r of a signal at the receiver can be modeled as equation (1).

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^2} \qquad (1)$$

Here P_t is the transmission power, G_t and G_r are antenna gains of transmitter and receiver respectively, h_t and h_r are the heights of the two antennas, and d is the distance between the transmitter and the receiver. We assume that all the radio parameters are the same at each node. A signal arriving at the receiver is considered to be valid if the Signal-to-Noise Ratio (SNR) is above a certain threshold (SNR-threshold). Now, we assume that a transmission is going from a transmitter to a receiver and at the same time, an interfering node, D meters away from the receiver, starts another transmission. Let P_r denote the receiving power of signal from transmitter and P_i denote the power of interference signal at the receiver. Then, SNR is given as SNR= P_r / P_i. From equation (1), we get

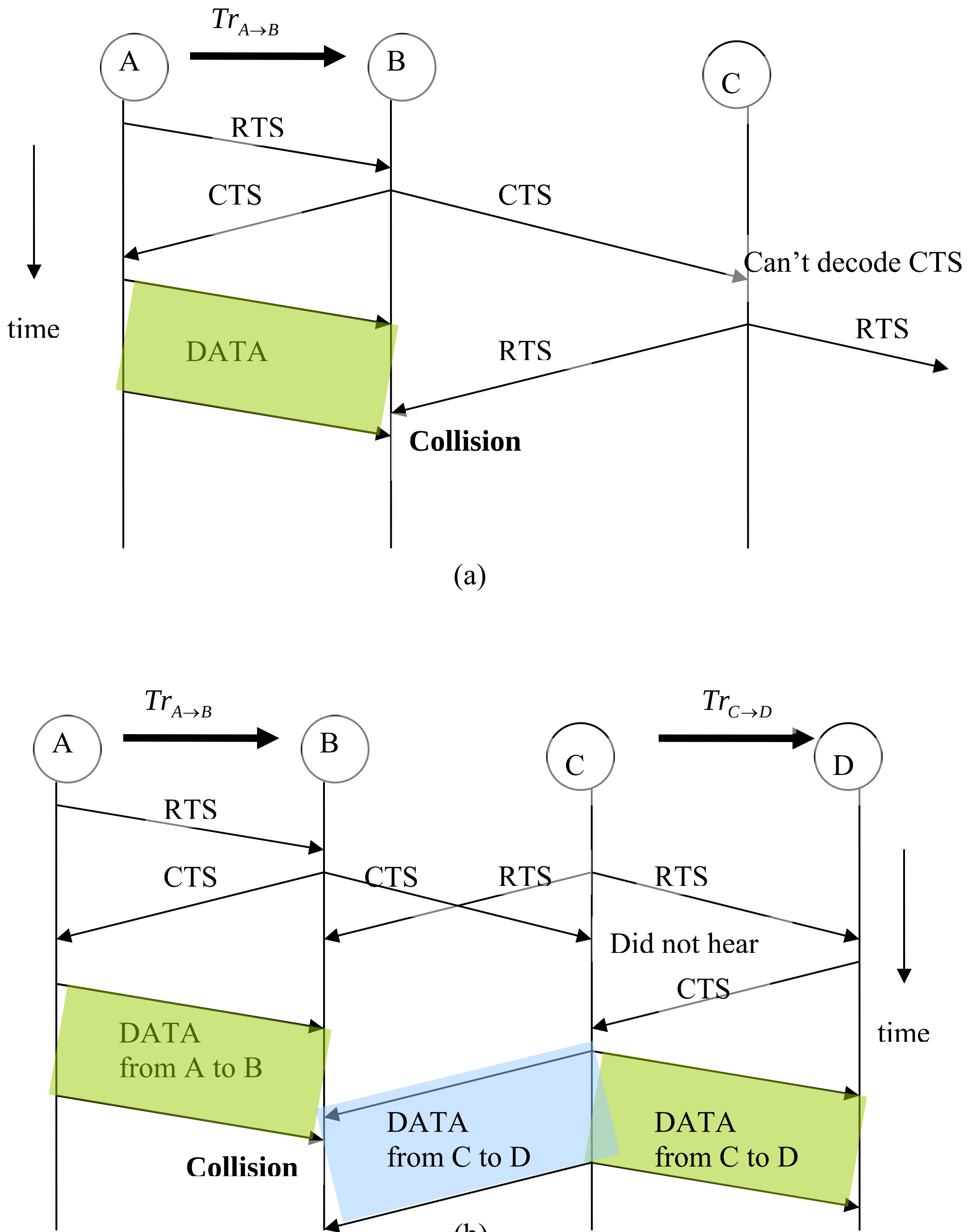
$$SNR = \frac{P_r}{P_i} = \left(\frac{D}{d}\right)^2 \geq SNR\_threshold \qquad (2)$$

$$D \geq \sqrt{SNR\_threshold} * d \qquad (3)$$

From equation (3), to get valid signals at receiver, the interference nodes must be $\sqrt{SNR\_threshold} * d$ meters away from receiver, which is the interference range we mentioned above. In practice [14], the SNR-threshold is always set to be 10. Then we get R_I

$$R_I = \sqrt{10} * d = 3.16d \qquad (4)$$

Let's consider the Figure 5 again. D is the distance between node B and node C. When node A starts to transmit, all the nodes within R_{CS} of node A defer their transmission until the end of the transmission. However, node C is outside R_{CS} of node A but within R_I of node B. It can not sense the transmission from node A to node B. So it will not defer its transmission. Because node C is outside R_{TX} of node B, it can't decode the CTS from node B. So it will not be blocked by the CTS. If node C tries to access channel before the end of transmission from node A, a collision will occur at node B. Figure 6a illustrates this situation. In Figure 6b, there is another hidden node problem. Node C sends RTS, and at the same time, node B sends a CTS to node A. Thus node C misses the CTS from node B. The collision happens when both node B and node C send data packet. Thus, the hidden node problem still remains in IEEE 802.11 MAC protocol.



(a)

(b)

Figure 6. Hidden node problems in IEEE 802.11

3.2.4 Exposed Node Problem

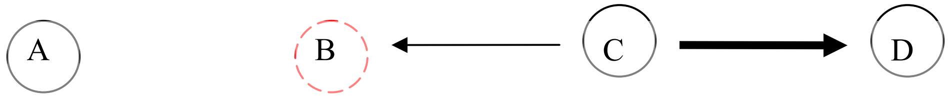
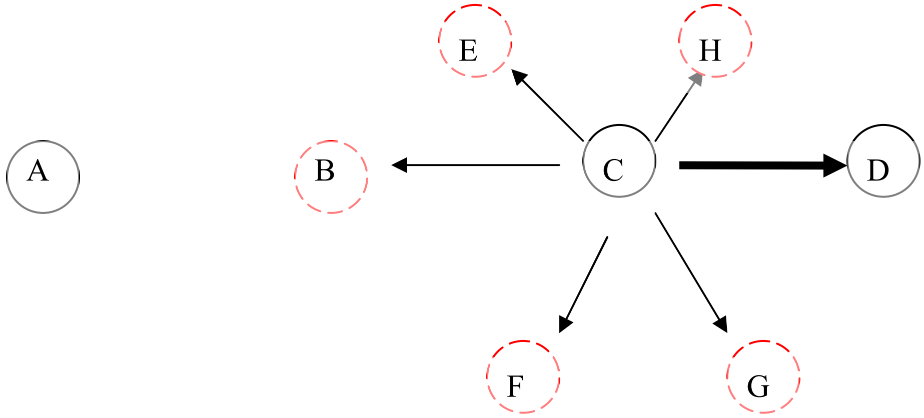


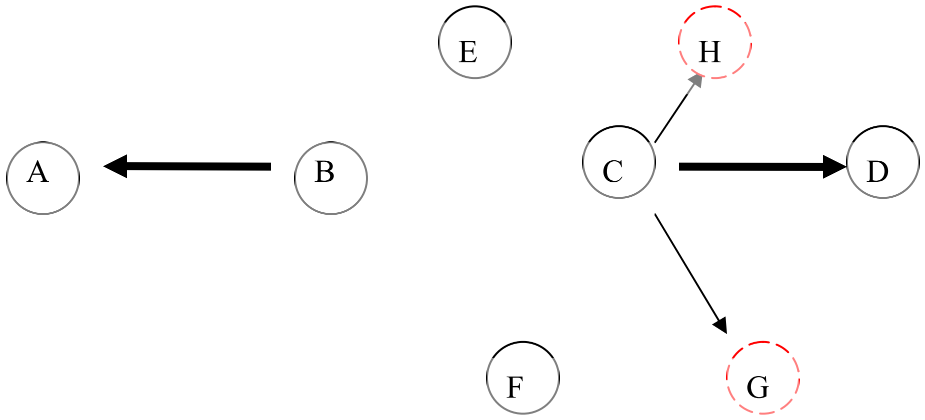
Figure 7. Exposed node problems

Overhearing a data transmission from neighboring nodes can keep a node from transmitting to other nodes. This is known as the exposed node problem. An exposed node is a node in range of the transmitter, but out of range of the receiver. Figure 7 illustrates this problem. Node B was blocked because node C is sending data packet to node D, although B wants to transmit to A. It is a waste of bandwidth.

A solution to the exposed node problem is the use of directional antennas [11].



(a) Omni-directional antenna used



(b) Directional antenna used

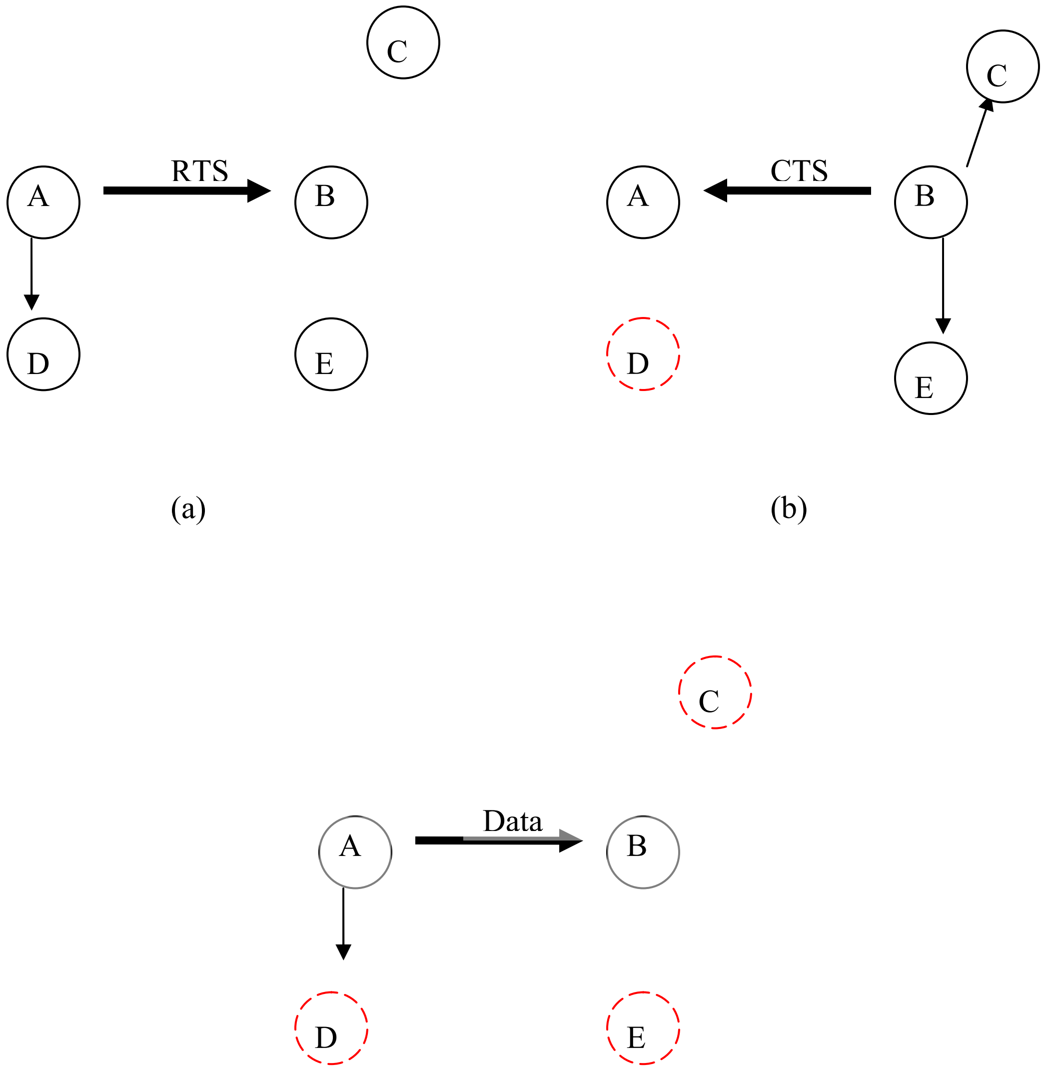
Figure 8. Using a directional antenna to resolve the exposed node problem

Figure 8 shows the comparison of the using omni-directional antenna and directional antenna. With omni-directional antenna, all the neighbors suffer from the exposed node problem. And when C is transmitting, all the neighbors are blocked (the node with broken line in Figure 8a). By using directional antenna in Figure 8b, node C can only interfere with nodes H and G, but node B is able to transmit data safely. And in Figure 8b, only nodes H and G suffer from the exposed node problem.

3.3 Other Existing Ad Hoc MAC Protocol

3.3.1 Multiple Access with Collision Avoidance (MACA)

The Multiple Access with Collision Avoidance protocol (MACA), proposed by Karn [15]**,** solves the hidden node problem and outperforms CSMA in a wireless multi-hop network. As shown in Figure 9, MACA uses a three-way handshake, RTS-CTS-Data.



(a)

(b)

(c)

Figure 9. Operation of MACA

In Figure 9a, sender A first sends an RTS to receiver B to reserve the channel. This procedure blocks sender's neighboring nodes from transmitting. Receiver B then sends CTS to sender A to grant transmission in Figure 9b. This procedure results in blocking the receiver B's neighboring nodes from transmitting, thereby avoiding collision. The sender can proceed with data transmission now.

Collision does occur in MACA, especially during the RTS-CTS phase. There is no carrier sensing in MACA. Each node basically adds a random amount of time to the minimum interval required to wait after overhearing an RTS or CTS message. If two or more nodes transmit an RTS at the same time, a collision may happen. Then these nodes will wait for a randomly chosen interval and try again. Because both of the RTS and CTS message carry the information of the amount of data that sender plans to send, when a node overhears an RTS or CTS addressed to other node, it can inhibit its own transmission long enough for other node to send data. Thus, compared to CSMA/CA, MACA reduces the chances of data packet collision. Since RTS and CTS are much smaller in size than data packets, the chance of collision is also smaller.

3.3.2 MACA-BI (by Invitation)

All the MAC protocols that we have described so far can be categorized to the Sender-Initiated MAC protocols, whereby the sender first contacts the receiver to claim that it has data to send. Now we will look at another class of MAC protocols, Receiver-Initiated MAC protocols. In contrast with the Sender-Initiated MAC protocol, in the Receiver-Initiated MAC protocol, receiver will first contact sender to claim that it is ready to receive data. MACA-BI (Multiple Access with Collision Avoidance by Invitation) is an example of Receiver-Initiated MAC protocol.

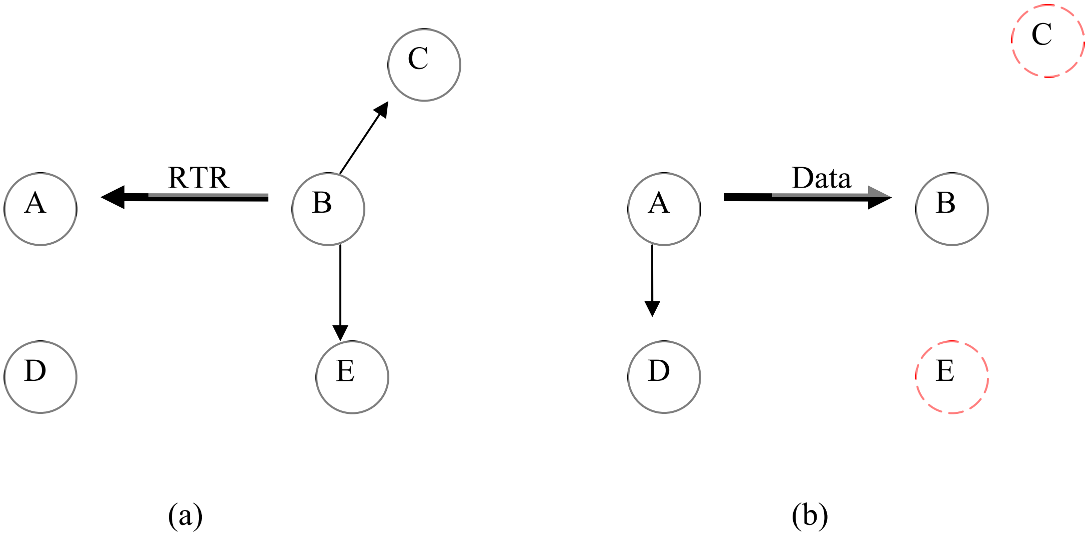


Figure 10. Operation of MACA-BI

MACA-BI, a simplified version of MACA with only a "two-way" handshake, was proposed by Fabrizio Talucci [16]. Figure 10 shows the operation of the MACA-BI MAC protocol. There is no RTS message in MACA-BI, and instead of the CTS message of MACA, here a new message RTR (Ready to Receive) is sent to indicate the readiness to receive a certain number of data packets. Node B in Figure 10 first sends out an RTR message to inform node A that it is ready to receive data packets, and at the same time it blocks the other neighbors who are not invited. Node A then begins sending data packet to node B. However, the receiver (Node B) must estimate the queue length and average arrival rate [16] to regulate the transmission. To make this possible, the author suggests that each data packet carries the information about the backlog in the transmitter (Node A in this case). From the backlog notification and from previous history, B can decide how many packets to invite. Then Node A replies with the requested packets, including the new backlog information. Hence, for the constant bit rate (CBR) traffic, MACA-BI will show high performance due to the reduced contention period and correct prediction for queue length and arrival rate. When the traffic is non stationary, however, the prediction is unreliable. The performance of MACA-BI will drop dramatically.

To enhance the performance under non-stationary traffic situations, a node may still transmit an RTS if the queue length or packet delay has exceeded a given threshold before an RTR is received from the intended destination. So the MACA-BI is turning to MACA now.

In summery, MACA-BI preserves the function of MACA. It is a data collision free protocol like MACA, but is less likely to suffer from the control packet corruption, since it requires only half of the control packets that MACA does. The receiver-initiated mechanism of MACA-BI automatically provides traffic regulation, flow control and congestion control (by simply withholding the “invitation”).

Chapter 4. MAC over MIMO

4.1 IEEE 802.11 MAC Protocol over MIMO

The IEEE 802.11 MAC protocol can be simply extended to MIMO links and provides M fold improvement in throughput performance through spatial multiplexing [17]. However, IEEE 802.11 MAC protocol is not the optimal choice for MIMO wireless network. Besides the unsolved hidden node problem and exposed node problem we described above, it also suffer from unfairness problems. Figure 11 shows how to use IEEE 802.11 MAC protocol on MIMO channels. For simplicity, we will use 2 antennas in the following chapters but the discussion can be easily extended to M antennas. Because 802.11 is based on the assumption that there can be only one data transmission at any time in one broadcast domain, when the transmission $Tr_{0\rightarrow1}$ is ongoing, Node 2 is blocked as long as Node1 and Node 2 are close (within carrier sensing range) . Node 2 can start to transmit only after $Tr_{0\rightarrow1}$ finishes.

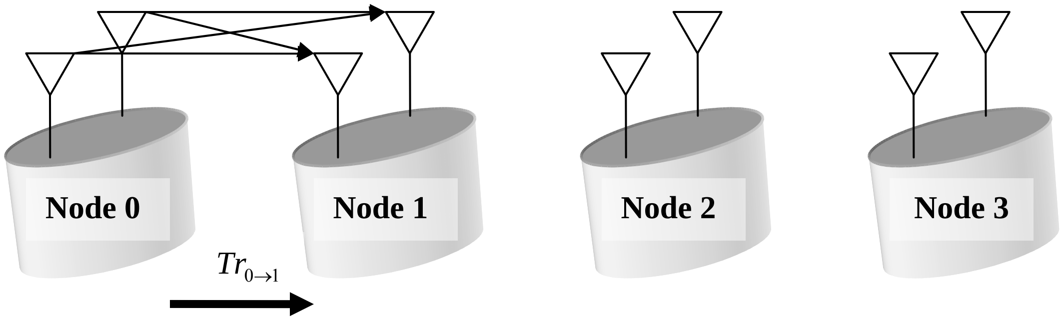


Figure 11. The IEEE 802.11 MAC protocol over MIMO

4.2 MIMA-MAC Protocol

By MIMO links, two or more data stream transmissions can happen at the same time, as long as the receiver is able to separate them. In [18], the authors propose a new MAC protocol, named Mitigating Interference using Multiple Antennas MAC (MIMA-MAC), that can mitigate unfairness and improve the throughput of IEEE 802.11 MAC protocol. In MIMA-MAC, each node can use at most one antenna to transmit data packet. Figure 12 shows the implementation of MIMA-MAC over MIMO channel. Because both the Node 0 and Node 2 transmit data packets with single antenna, those data can be separated by the receiver with two antennas by using spatial multiplexing. So the transmission $Tr_{0\rightarrow 1}$ and $Tr_{2\rightarrow 3}$ can happen simultaneously, although Node 1 is interfered by Node 2. Note that the number of receiving antennas must be larger than or equal to the number of transmitting antennas [7], in order to successfully differentiate data packets.

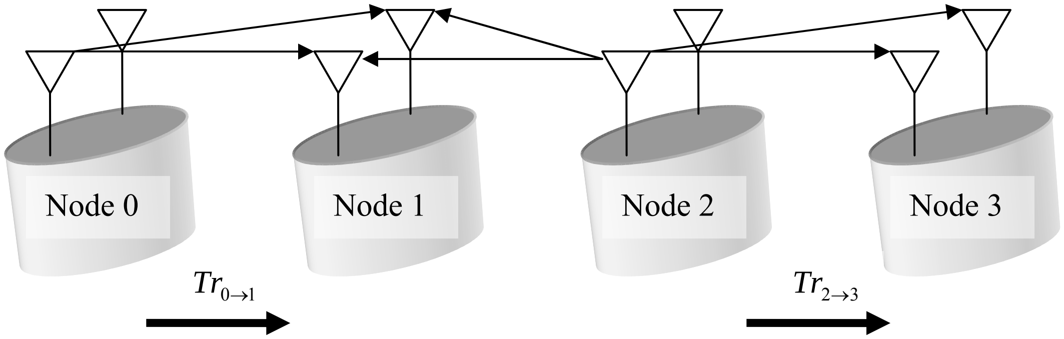


Figure 12. The MIMA-MAC protocol over MIMO

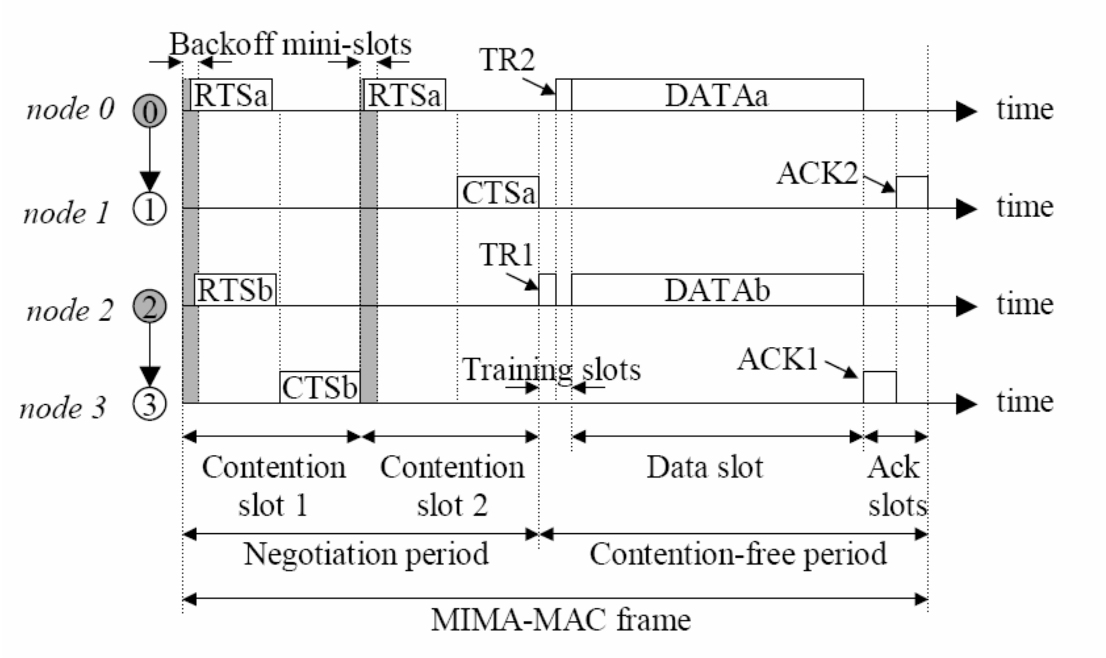


Figure 13. Operation of MIMA-MAC [18]

MIMA-MAC is an extension from IEEE 802.11 with two sets of RTS/CTS/ACK. Figure 13[18] shows the operation of MIMA-MAC in the scenario of Figure 12. Within the first contention slot, Node 2 gets CTS from Node 3 successfully. So it does not send any message in the second contention slot. Thus, in the second contention slot, Node 1 will not have collision and Node 0 can get the CTS from Node 1. After sending a training sequence to inform the receiver the Channel State Information (CSI), Node 0 and Node 2 send data packets simultaneously. This protocol guarantees that there will be only one transmission granted in one contention slot, so the total transmission will not exceed two. However, this protocol also limits the number of transmit antennas to one, which restricts the throughput on single channel.

Telatar [19] shows that by using multiple antennas on both ends of transmitter and receiver, the theoretical capacity of the link increases linearly as min $\{M_r, M_t\}$, where M_r and M_t are the number of receive and transmit antennas, respectively. In MIMA-MAC, in order to avoid interference, any transmitter can only use one antenna to transmit data packet. So the condition $M_r \geq M_t$ on any node is always satisfied. Because the min $\{M_r, M_t\}$ is always equal 1, we can't expect a multiplicative increase in throughput performance with MIMA-MAC protocol. In contrast with the IEEE 802.11 MAC protocol, MIMA-MAC can successfully mitigate interference. However, it can't fully exploit the performance limits of MIMO links. Our purpose is to develop a MAC protocol which can freely choose scenario in Figure 11 or Figure 12.

Chapter 5. The Proposed AMTA-MAC Protocol

5.1 Motivation

As described above, there are two scenarios in MIMO application. Let's denote the scenario in Figure 11 as scenario 1, and the scenario in Figure 12 as scenario 2. Under scenario 1, we can get maximum transmission rate by using two antennas, but that will keep all the neighbors from transmission due to exposed node problem of IEEE 802.11. Under scenario 2, in contrast, fairness is guaranteed. However, we can never get maximum transmission rate on any single channel with the restriction of MIMA-MAC, which allow only one transmit antenna for each node.

In heavy traffic situations or high nodes density, we would like most channels to be working and maximum nodes to participate to improve the average throughput and fairness. Scenario 2 is ideal under this condition, since scenario 1 will cause many nodes to be blocked by their neighbors. But if there are few transmission requests in the network or most nodes are far apart, scenario 1 is better in obtaining maximum single transmission rate. Thus, in different environments, the requirement of the transmission model is different. If we use MIMA-MAC in scenario 1 however, if only few nodes need to transmit data and can only use one transmit antenna, the bandwidth of MIMO link is wasted. So we propose an adaptive MAC protocol that can freely choose between scenario 1 and scenario 2 to satisfy different requirements.

In the following section, we will come up with a new adaptive MAC protocol, Achieving Maximum Transmit Antenna MAC protocol (AMTA-MAC), which guarantees fairness and achieves the maximum transmit antennas number adaptively based on different environment.

5.2 Basic Structure

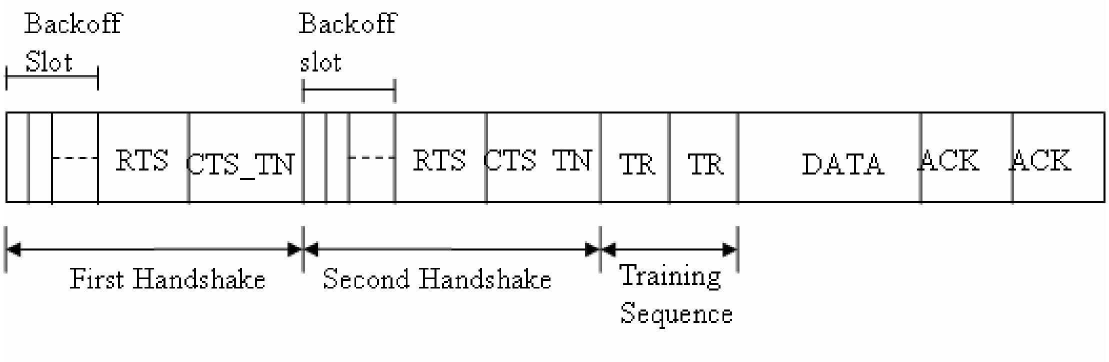


Figure 14. The frame structure of proposed AMTA-MAC protocol

The structure of proposed adaptive MAC protocol is shown in Figure 14, which is based on MIMA-MAC[18]. It can be viewed as a combination of two IEEE 802.11 MAC protocols, which contain two sets of RTS/CTS/ACK message.

In the proposed AMTA-MAC protocol, we set the default number of transmit antennas to two in all the transmitters. That is all the transmitters are ready to use two antennas to transmit data packets, if they are permitted to transmit, unless explicit notice of a decreased number of transmit antenna is received. We will describe this in detail in next paragraphs. As mentioned in Chapter 2, in spatial multiplexing requests data streams are transmitted simultaneously. To satisfy this, we require that all the frames in the proposed AMTA-MAC protocol have fixed size and are synchronized. Using a global positioning system (GPS) can make this possible.

Because the number of receiving antennas is two in this scheme, we can apply at most two transmissions at the same time in an interference range. The CTS/RTS handshake protocol in 802.11 MAC protocol can ensure that at most one transmission happen. So here we use two handshakes protocol to ensure that at most two transmissions can take place. Note the two transmissions may come from two transmit antennas on the same node, which is the major difference from MIMA-MAC which can only use one transmit antenna.

The RTS message remains the same except that there are some backoff time slots in the header of RTS. To avoid collision, we refer to the random backoff time mechanism in 802.11 MAC protocols [12]. Before the transmission of RTS packet starts, it first defers some number of backoff time slots. The number of the backoff time slots is chosen from contention window (CW), which is uniformly distributed from aCWmin to aCWmax. Here the value of aCWmin is doubled every time the collision happens until it reaches to the value aCWmax. If transmission is successful, the value of aCWmin will be set to initial value of aCWmin. Because the size of the RTS slot is fixed, we can only apply limited number backoff time slots. The collision may still happen for dense node environment. So here we apply the algorithms in Sundaresan et al and Ingram et al [17, 20] to set up a transmission probability parameter P to every node. That is, the node has probability P to transmit data. The initial value is 1, if a transmission failed, we decrease P to $P*(1-\beta)$ until it reach the lowest value P_{lowest}. On the other hand, if the transmission is success, we will increase P to $P+\alpha$ until it reaches 1. Parameters α and β usually take value between 0.1 and 0.5. In this thesis, we use $\alpha = 0.5$, $\beta = 0.2$ and $P_{lowest} = 0.2$.

A new message was used to reply the RTS message. Clear to Send with Transmission Notice (CTS_TN) informs the node who sent RTS that it is safe to transmit a data packet in next data slot. Other nodes that received CTS_TN are informed that there is a transmission within the interference range that will take place in the next data slot. If a transmitter receives an unexpected CTS_TN message, that is the CTS_TN sent to reply other node's RTS, the transmitter will decrease its transmit antenna number to one. A transmitter will also decrease the antenna number if it does not receive the expected CTS_TN message that is the CTS_TN sent to reply for its RTS. A node can transmit only if it receives the expected CTS_TN. This procedure assures that the transmitter uses the most antennas allowed. We will specify its operation on next section. From the theoretical view, a node can receive an unexpected CTS_TN only if there is a transmission in process not related to it. This transmission will collide with the transmission of the node if the total transmit antenna number exceeds the number of receive antennas. Because the transmit number in the node is already the maximum number, the node has to decrease its own transmit number. If a node does not get the expected CTS_ TN, it must be that some other nodes within interference range also want to transmit. To prevent collision in the future, that node should decrease the transmit antenna number. If neither of these two things happen, it must be that there is no other transmission around, that node can use the maximum number of the transmit antenna.

By the requirement of spatial multiplexing, channel state information (CSI) is needed to differentiate different transmissions. A known training sequence (TR) is provided in the protocol for this purpose. To ensure the correct CSI, the TR must not be interfered with, so only one transmission is allowed when the TR is transmitting.

To increase reliability, we also apply the fragmentation/defragmentation mechanism as in IEEE 802.11 described in Chapter 3. This partitions the data units into smaller MAC protocol data units (MPDU) automatically, and recombines those MPDU into the original data units. The length of MPDU is much smaller than original data units, in order to increase the probability of successful transmission. This mechanism can also help the protocol fast switch transmission model between scenarios 1 and scenario 2. We will discuss it in next chapter. As in the IEEE 802.11 MAC protocol, the ACK message is used to inform transmitter the data packet was received correctly. There are two ACK sent to the two transmitters separately. To get the correct ACK at a transmitter, the two ACK can't be sent simultaneously.

This scheme can be easily extended to M antennas. However, with the increase of the number of antennas, more handshake steps are needed, and this will lead to a large header of the frame structure.

5.3 Operation of the Proposed AMTA-MAC

An example of the operation of the proposed AMTA-MAC is shown in Figure 15. In scenario 2, Node 0 transmits data packet to Node 1, and Node 2 transmits data packet to Node 3 simultaneously. In first handshake slot, Node 0 does not get expected CTS_TN message from Node 1 due to the collision at Node 1. So it decreases its own transmit antenna number to one. Node 2 gets the expected CTS_TN message successfully, so it can transmit its data packet. Note here that Node 2 is ready to transmit its data packet with two antennas now. In the second handshake slot, Node 0 also gets the expected CTS_TN, so it can also transmit its data packet. But here Node 2 get the unexpected CTS_TN from Node 1, and Node 2 have to decrease its transmit antenna number to one. Because Node 2 gets the expected CTS_TN in first handshake slot, it will send TR on first TR slot. Node 0 will send its TR on second TR slot. In the data slot, node 0 and node 2 will send data packet simultaneously, and will not interfere each other because the receiver have the exact channel state information. At last, node 3 and node 1 send ACK message to node 2 and node 0 separately.

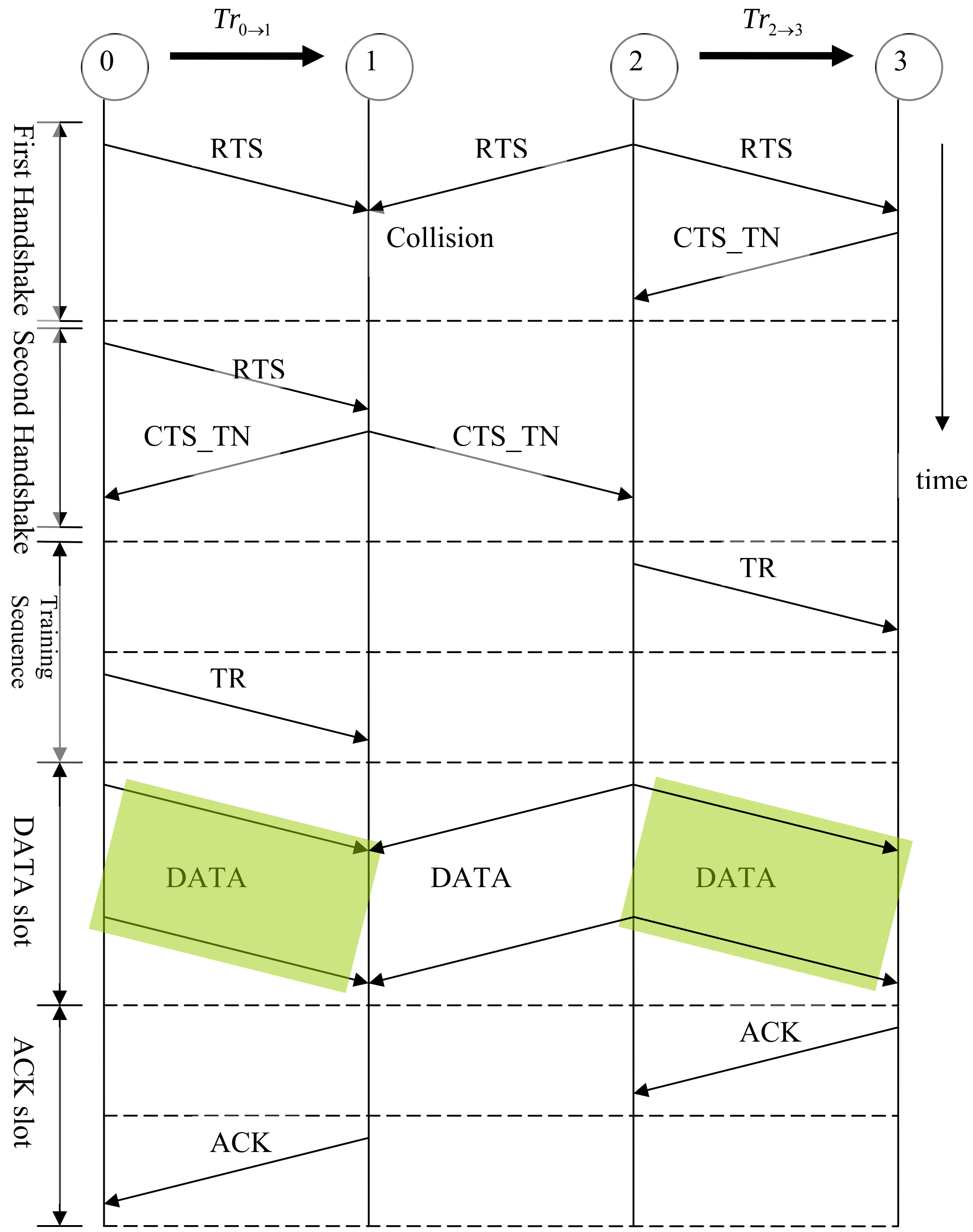


Figure 15. Operation of proposed AMTA- MAC protocol in scenario 2

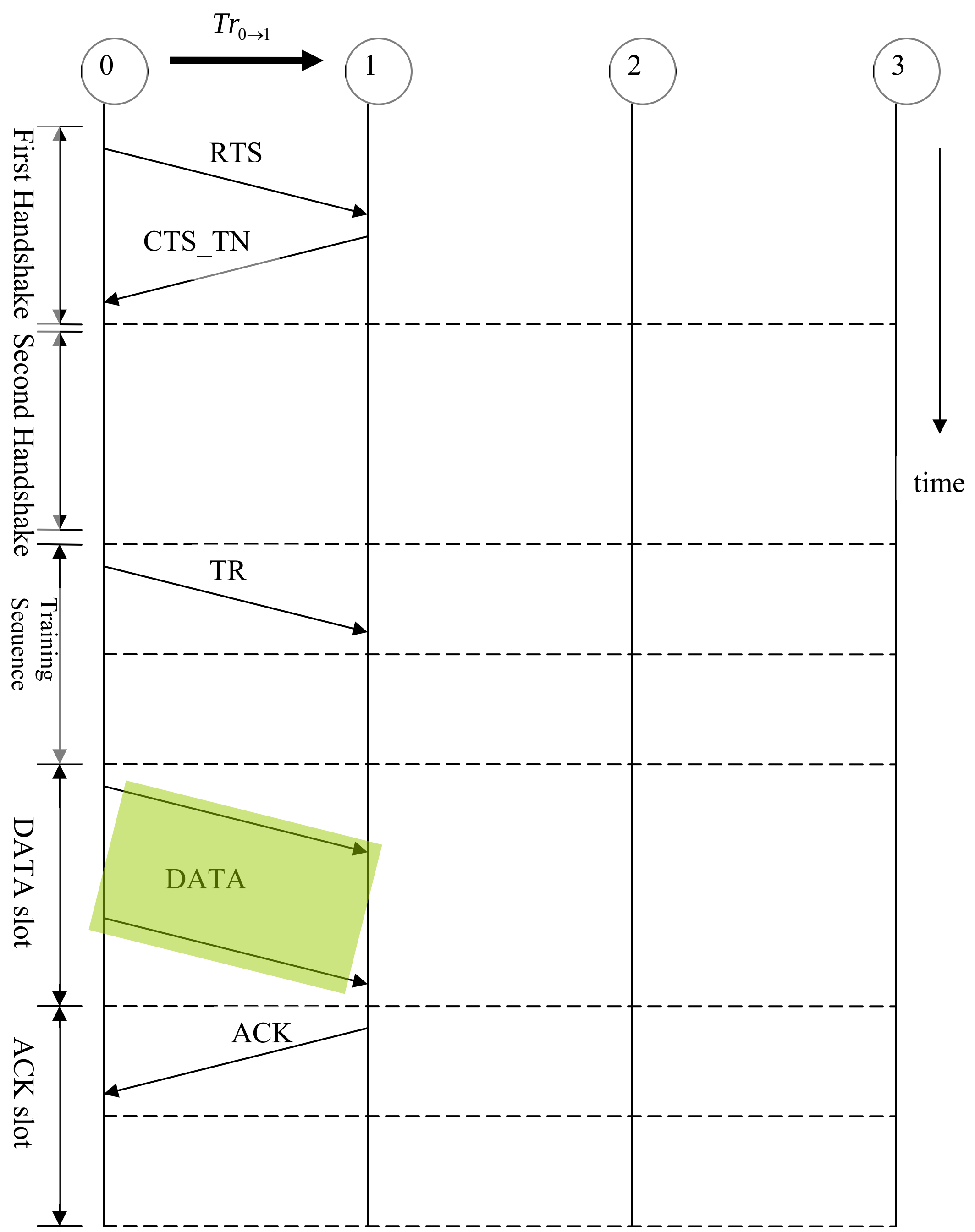


Figure 16. Operation of proposed AMTA-MAC protocol in scenario 1

Now consider the scenario 1. The operation was shown in Figure 16. Because there are no transmission on neighbor nodes, the transmitter can use maximum number of transmit antennas without worry about collision. In Figure 16, Node 0 gets the expected CTS_TN in first handshake slot and nothing in second handshake slot. So it knows there is no other transmission around and it can transmit data packet with maximum number of transmit antennas.

If Node 2 of Figure 16 wants to transmit a data packet to Node 3 at the same time $Tr_{0\to1}$ is ongoing, it will wait for the start of the next frame and send an RTS at same time with Node 0. Thus, Figure 16 has changed to scenario 2 now, and both Node 0 and Node 2 can be granted to transmit with one antenna as described in Figure 15. If Node 2 finished all the data packet transmissions and does not send RTS in next frame, that moves at Node 2 is the changing from scenario 2 to scenario 1. In the next frame, Node 0 will get permission for two antenna transmissions as described in Figure 16. So the proposed AMTA-MAC can switch between scenario 1 and scenario 2 automatically to utilize the maximum number of transmit antennas. Because we apply the fragmentation/defragmentation mechanism, the frame size is much smaller than the original one. So it is fast to switch between scenario 1 and scenario 2 at the happening or end of transmission $Tr_{2\to3}$. The switch happens in the next frame start.

As described above, the proposed AMTA-MAC protocol can automatically switch between scenario 1 and scenario 2 to achieve the maximum transmit antennas in the broadcast domain. Within a dense node environment, it can also ensure most nodes get transmit permission. So the proposed AMTA-MAC protocol can fully utilize the features of the MIMO channel to achieve better performance with respect to fairness and throughput than IEEE 802.11 and MIMA-MAC. We will compare them in the next section.

5.4 Does the Proposed AMTA-MAC perform well

As described in Chapter 3, the IEEE 802.11 MAC protocol suffers from the hidden-node and exposed-node problem. In this section, we will see whether the proposed AMTA-MAC protocol solves the problems in IEEE 802.11 MAC protocol.

Consider the hidden-node problem presented in chapter 3. Both in Figure 6(a) and Figure 6(b), we can see that the problem arises because the RTS and CTS are not sent in a fixed time slot. That is, in IEEE 802.11, one node's RTS may sent at the same time with other node's CTS. Due to the asynchronism of the IEEE 802.11 protocol, the hidden node problem is inevitable. If a node sends RTS/CTS at the same time, the hidden-node problem will not arise. The proposed AMTA-MAC protocol is based on the assumption all the frames are fixed and synchronized. So the hidden-node problem does not exist in the proposed AMTA-MAC protocol. Let's consider the exposed node problem in Figure 7. Node B was blocked by node C because node C is going to send data packet. In the proposed AMTA-MAC protocol, the RTS message do not block any unrelated node, and thank to the MIMO technique, we can transmit data packet from node B to node A and node C to node D at the same time, which fully exploit the bandwidth and capacity of the wireless network. From this analysis, it seemed be intuitively clear that the proposed AMTA-MAC protocol do not suffer from the problems in IEEE 802.11 MAC protocol, and have better performance both in throughput and fairness.

In Chapter 4, we have described the greatest shortcoming of the MIMA-MAC is the restriction placed on the transmit antenna number. With fixed transmit antenna number, MIMA-MAC can't fully exploit the performance limits of MIMO links

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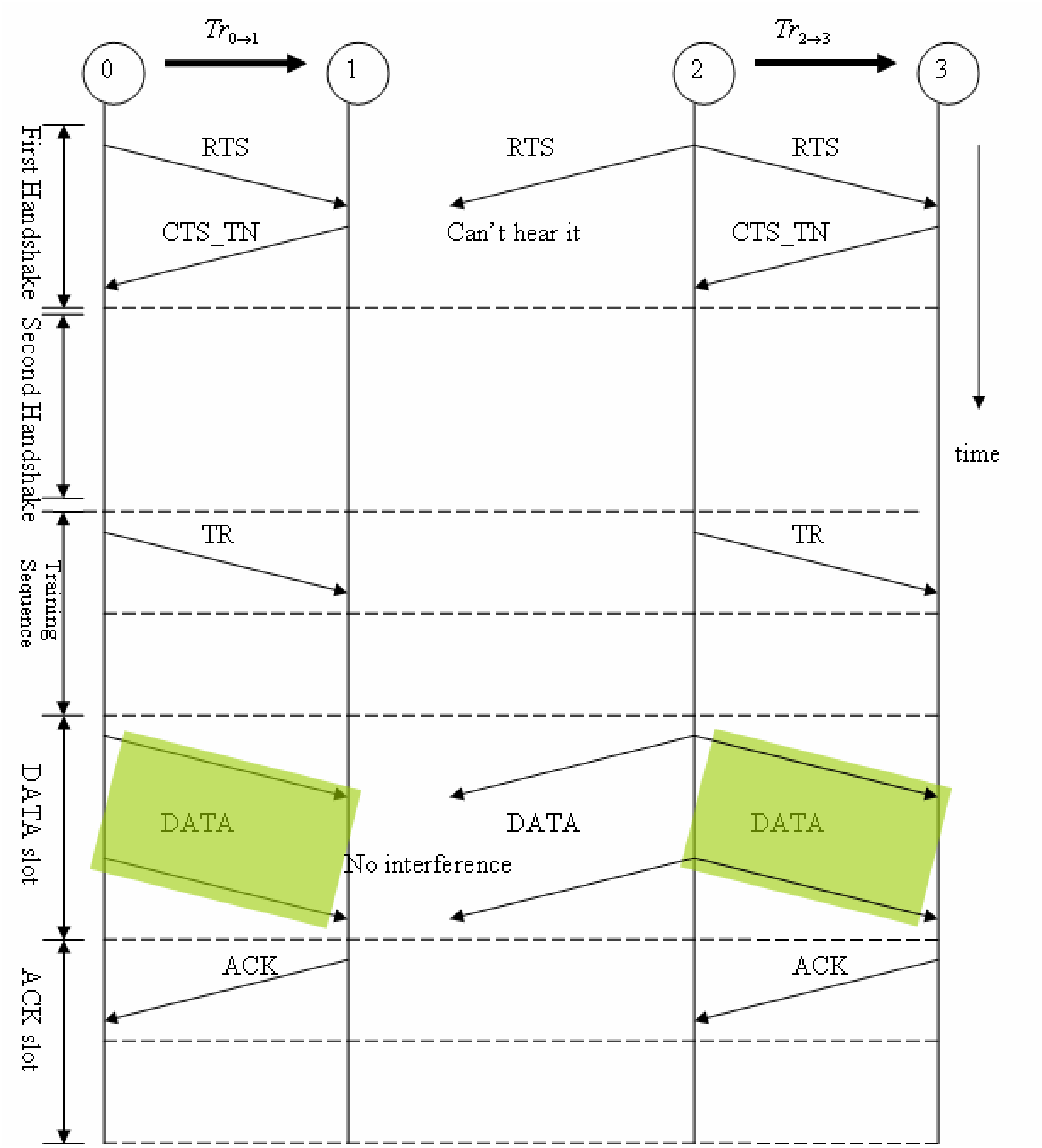


Figure 17. Operation of proposed AMTA-MAC protocol in special scenario

Consider the scenario in Figure 17 which is similar to scenario 2, because Node 1 and Node 2 are far apart, they will not interfere with each other. By using a MIMO channel, it is possible to use two transmit antennas in both $Tr_{0\to1}$ and $Tr_{2\to3}$. But the MIMA-MAC can't achieve this because the transmit antenna can't exceed one in MIMA-MAC. In contrast, consider the operation of proposed AMTA-MAC in this scenario. In first handshake slot, Node 1 will not have collision, because it can't hear the RTS from Node 2. Both Node 0 and Node 2 will get expected CTS_TN, and in second handshake slot nothing happen. Then both Node 0 and Node 2 will keep their transmit antennas number set to two. Then they will transmit their data packets by using two antennas and will not generate interference. Node 1 and Node 3 can differentiate the data packet successfully. With two antennas, the transmit rate is doubled. The throughput will also be doubled. In this case, the proposed AMTA-MAC obviously outperforms the MIMA-MAC in throughput, which can only use one antenna.

Note that an unexpected CTS_TN may collide with another unexpected CTS_TN in AMTA-MAC, if two or more neighbors grant transmission permit to other nodes at the same time as in Figure 18(d). But an unexpected CTS_TN can never collide with an expected CTS_TN. By the AMTA-MAC protocol, if a node is receiving an expected CTS_TN, all the neighbor nodes must received the RTS from this node in previous RTS slot. And those RTS messages prevent the neighbor nodes to receive RTS from other nodes. So it is impossible for one of the neighbors to send CTS_TN to other nodes as shown in Figures 18(a) and 18(b).

The solution of the collision of unexpected CTS_TN is simple, because the frame size is fixed and synchronized, and thus a node will discern the collision is in CTS_TN slot. It can simply treat this collision to be a receiving of unexpected CTS_TN, and decrease the transmit antenna number. That is, for the unexpected CTS_TN, we don't need to decode it. A node can decide this is an unexpected

CTS_TN message by sensing anything in the CTS_TN slot in which no CTS_TN expected. This situation was shown in Figure 18.

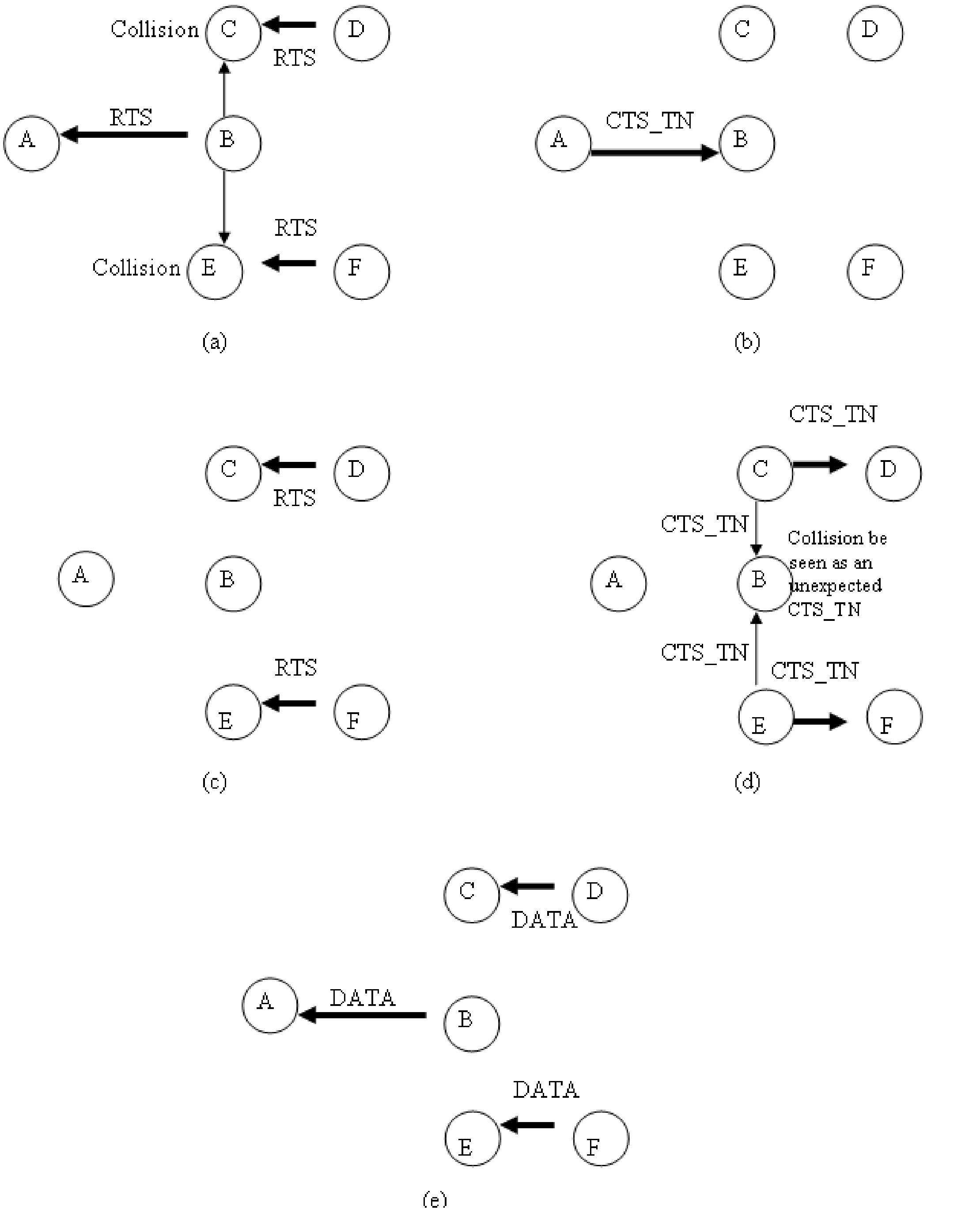


Figure 18. The collision of unexpected CTS_TN

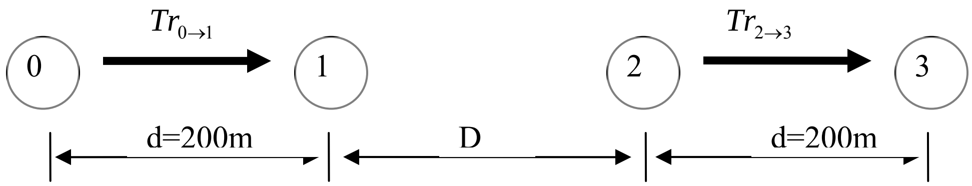
In Figures 18(a), Nodes B, D and F send RTS in the first handshake slot. But only Node B gets the expected CTS_TN (Figure 18(b)), because the RTS from Node D and F collide with the RTS from Node B. Then Nodes D and F send RTS in second handshake slot, and they get expected CTS_TN successfully. Although the CTS_TN from Node C and E collide at Node B in Figure 18(d), from above description Node B will simply tread this matter as receiving an unexpected CTS_TN. Because Node D and F did not get expected CTS_TN and Node B get an unexpected CTS_TN, they can transmit data using one antenna as shown in Figure 18(e).

Chapter 6. Simulation and Performance Analysis

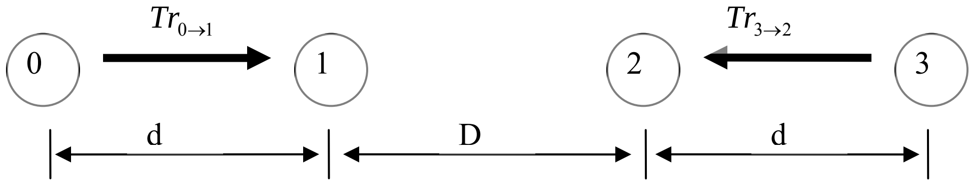
In this chapter, we simulate the operation of IEEE 802.11 MAC, MIMA-MAC, and the proposed AMTA-MAC protocol over MIMO links by using the program Network Simulator 2 (ns-2) [4]. Then we compare their results with respect to fairness and throughput.

6.1 Simulation Setup

6.1.1 Two Scenarios



(a) SDT scenario



(b)ODT scenario

Figure 19. Two scenarios for the simulation

We use the two scenarios shown in Figure 19 in the simulation: Same Direction Traffic (SDT) and Opposite Direction Traffic (ODT) [18]. When a source node starts to transmit data packets, the intermediate node will try to forward the data packets to the destination node in the same direction. This transmission along the route forms the same direction traffic shown in Figure 19(a). For the reliable data transmission protocol, such as TCP (transmission control protocol), there will be some ACK packets sent back from destination node. This transmission form the opposite direction traffic (ODT) shown in Figure 19(b).

As described in Chapter 3, the distance between node 1 and Node 2 is the key factor that can affect the transmission result. With different value of D in Figure 19, the interference from neighboring nodes may vary. So in our simulation, we evaluate the network performance based on different value of D. The distance between transmitter and receiver, d, is fixed to 200m.

6.1.2 Parameters

In our simulation, we use the ideal channel model, which only has path-loss effect and no packet loss due to fading. To show the impact of the MAC protocol on the performance of the network, we use constant bit rate (CBR) traffic model in the simulation. The packet interval and packet size are set to 10ms and 1000 bytes respectively, which is the same as the parameters of IEEE 802.11 in ns-2. Data rate of one antenna is 1Mbps. Transmission range is 250m and carrier sensing range is 550m. Since interference range cannot exceed carrier sensing range, it is approximately 550m. The parameters of AMTA-MAC protocol are listed in Table 1.

Handshake slot	1ms
TR slot	80us
Data slot	8.5ms
ACK slot	360us

Table 1 Parameters of AMTA-MAC protocol

6.1.3 Evaluation Metrics

In our simulation, we want to evaluate the network performance in terms of throughput and fairness. It is well know that the unit of throughput is bit/sec. Now we need to define a new metric, fairness-ratio (FR) [18], to measure the fairness of the network.

$$FR = 1 - \frac{|Th_A - Th_B|}{Th_A + Th_B} \qquad (5)$$

$$Th_A > Th_B \Rightarrow FR = \frac{2Th_B}{Th_A + Th_B} \to 0 \quad when\, Th_A >> Th_B \qquad (6)$$

$$Th_A < Th_B \Rightarrow FR = \frac{2Th_A}{Th_A + Th_B} \to 0 \quad when\; Th_B >> Th_A \qquad (7)$$

Here Th_A and Th_B represent the throughput of $Tr_{0\to1}$ and throughput of $Tr_{2\to3}$ for the SDT scenario (or $Tr_{3\to2}$ for the ODT scenario) respectively. If the throughput of $Tr_{0\to1}$ and $Tr_{2\to3}$ (or $Tr_{3\to2}$) are close, the FR is close to 1. We say the network is fair. On the other hand, if FR is close to 0, it represents that throughput of $Tr_{0\to1}$ and $Tr_{2\to3}$ (or $Tr_{3\to2}$) are extremely unfair. This happens whenever $Th_A >> Th_B$ or $Th_B >> Th_A$.

6.2 the SDT Scenario Simulation

To help us understand the simulation results, we first analysis the relation of neighboring nodes in the SDT and ODT scenarios in table 2.

D m	100	200	300	400	500	600
Nodes 0 and 2	Interference	Interference	Interference	N/A	N/A	N/A
Nodes 0 and 3	Interference	N/A	N/A	N/A	N/A	N/A
Nodes 1 and 2	Transmission	Transmission	Interference	Interference	Interference	N/A
Nodes 1 and 3	Interference	Interference	Interference	N/A	N/A	N/A

Table 2 Relation between the nodes in SDT and ODT

Interference in the table represents the two nodes are within the interference range and carrier sensing range of each other. Transmission represents the two nodes are within the transmission range of each other. N/A represents the two nodes are out of interference range and have no relation in data transmission.

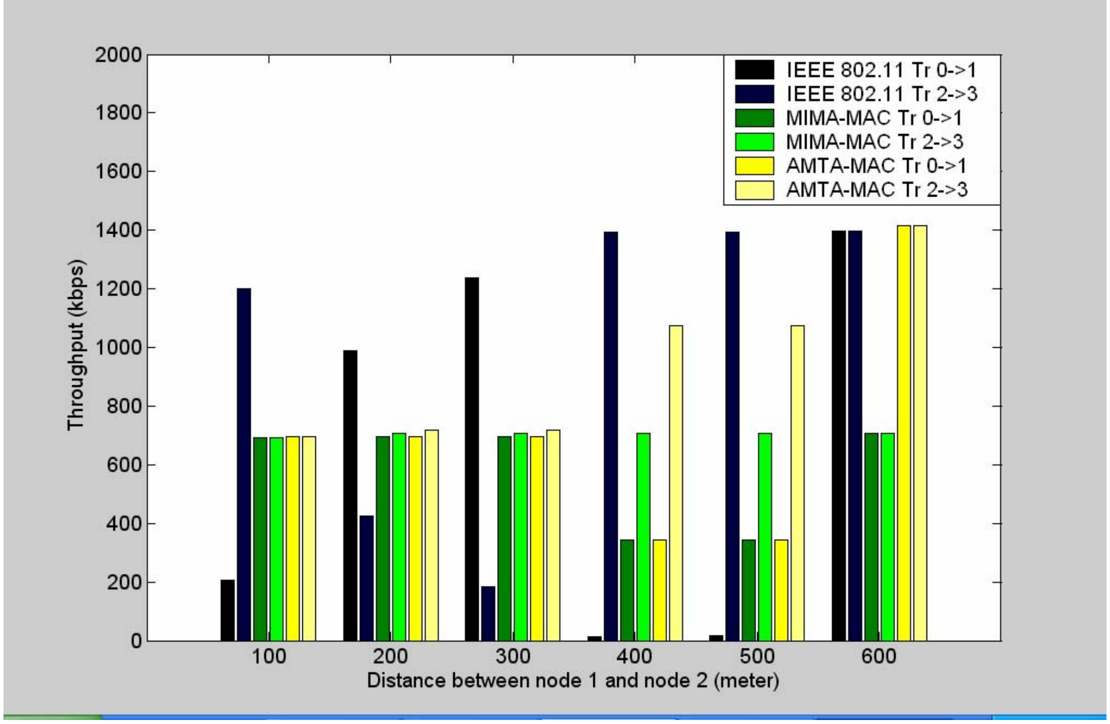


Figure 20. Throughput in SDT scenario

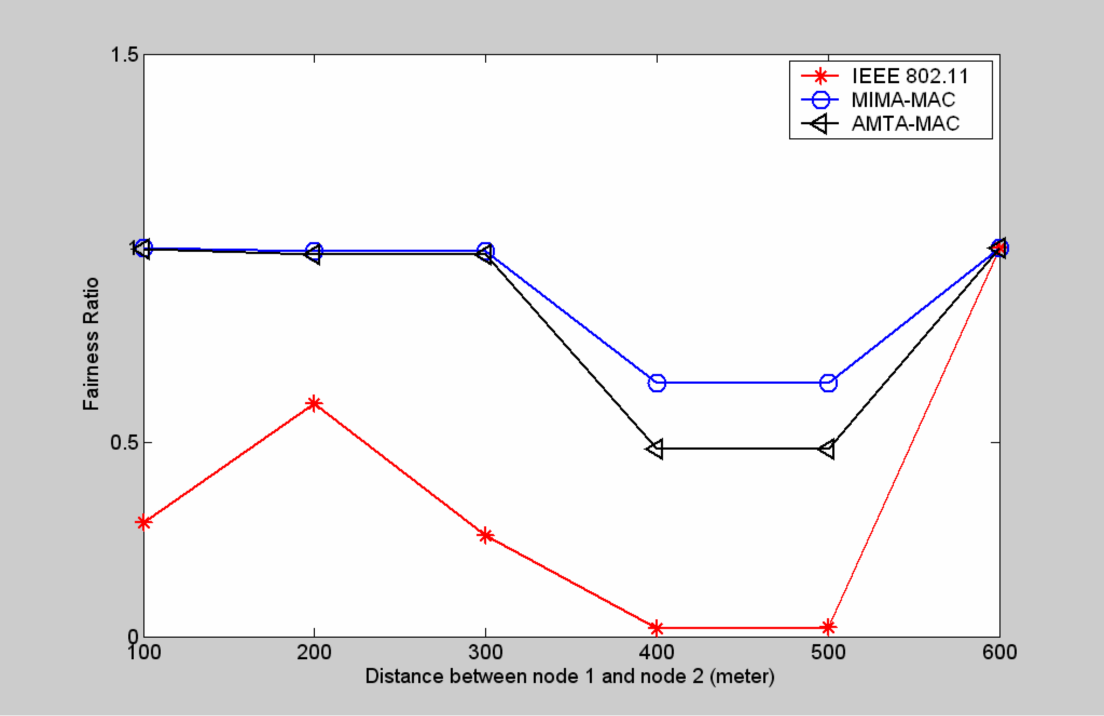


Figure 21. FR in SDT scenario

The simulation results of SDT scenario were shown in Figure 20 and Figure 21. Because the results depend on the details of the relation between of the nodes, we will discuss the results in each different distance.

- D = 100m: In this case, all the nodes can sense the transmission in the network. Consider the IEEE 802.11 MAC first. At beginning, the Node 0 and Node 2 have equal probability to transmit, both of them will delay a DIFS and some random backoff time before send RTS. If collisions happen, they will delay another DIFS and random backoff time until someone gets the channel. After the transmission $Tr_{0\to1}$, both Node 0 and Node 2 can decode the ACK from Node 1. So they know the transmission is finished, and begin to compete for next transmission with equal chance. But after the transmission $Tr_{2\to3}$, Node 0 can't decode the ACK from Node 3 (they are out of transmission range as shown in table 2). From IEEE 802.11 protocol, Node 0 will wait an EIFS period but Node 2 will wait a DIFS period. Because the EIFS is much longer than the DIFS, Node 2 has higher chance to access channel than Node 0. That leads to the unfairness as shown in Figure 21 and the throughput of $Tr_{2\to3}$ is much larger than $Tr_{0\to1}$.

  The behavior of MIMA-MAC and proposed AMTA-MAC is close to each other in this case. Node 0 and Node 2 will begin to send an RTS before some backoff slot. Because the backoff slot of Node 0 and Node 2 is different, one of them will send RTS first. The other node can sense this RTS and then stop to send its own RTS in the first handshake slot. Thus, the node that sends the RTS first will get CTS (or CTS_TN in AMTA-MAC). In the second handshake slot, the other node will send RTS and get CTS/CTS_TN successfully. So both transmission $Tr_{0\rightarrow1}$ and $Tr_{2\rightarrow3}$ can transmit with single antenna. There will be no unfairness problem.

- D = 200m: In IEEE 802.11, after transmission $Tr_{0\rightarrow1}$, both Node 0 and Node 2 can decode the ACK from Node 1. They have equal chance to access channel. But for the transmission $Tr_{2\rightarrow3}$, Node 0 can not sense the ACK from Node 3. It will send RTS only after Node 2 finish transmit data packet plus an EIFS period. And Node 2 will send RTS after receiving ACK from Node 3 and a DIFS period which is larger than EIFS in ns-2 [4]. So Node 0 has higher chance to access channel.

  For the MIMA-MAC and proposed AMTA-MAC, same with the scenario in Figure 12, Node 1 has a collision at first handshake slot, but not in the second handshake slot. So both transmission of $Tr_{0\rightarrow1}$ and $Tr_{2\rightarrow3}$ can take place with one antenna. They have the same throughput.
- D = 300m: In this case, Node 2 can't decode the ACK from Node 1. In IEEE 802.11 after $Tr_{0\rightarrow1}$, Node 2 waits an EIFS period but Node 0 has to wait a DIFS period. Since EIFS is much longer than DIFS, Node 0 has higher chance to access channel. For the transmission $Tr_{2\rightarrow3}$, as in the D=200m case, Node 0 will wait an EISF and Node 2 will send RTS after receiving ACK from Node 3 and a DIFS period. Thus, Node 0 has higher chance to access channel in both cases. The throughput of $Tr_{0\rightarrow1}$ is much larger than $Tr_{2\rightarrow3}$.

  MIMA-MAC and AMTA-MAC work same with the case D=200m.

- D = 400m and 500m: The extreme unfairness appears in IEEE 802.11. Both Node 0 and Node 2 can't sense other's transmission. But Node 2 can still interfere with the transmission of $Tr_{0\to1}$, same as the hidden node problem in Figure 6(a). While the transmission $Tr_{0\to1}$ is ongoing, Node 2 may start to transmit. That leads to the collision at Node 1 with the data from Node 0. The transmission $Tr_{2\to3}$ does not suffer any interference. So the transmission $Tr_{0\to1}$ has little chance to happen.

  In MIMA-MAC, because Node 0 and Node 2 can't sense each other's transmission, both will send RTS in first handshake slot. After the collision at Node 1, the transmission probability of Node 0 will decrease, and it is possible that Node 0 do not send RTS at second handshake slot. Thus, $Tr_{0\to1}$ has lower throughput than $Tr_{2\to3}$ as shown in Figure 20.

  AMTA-MAC works in a similar manner with the MIMA-MAC. But in AMTA-MAC, if Node 0 does not send RTS in the second handshake slot, Node 2 can transmit a data packet with two antennas. That is the reason AMTA-MAC have better throughput in $Tr_{2\to3}$ than MIMA-MAC.

- D = 600m: In this case, the transmissions $Tr_{0\to1}$ and $Tr_{2\to3}$ don't interfere with each other. They can transmit with all the IEEE 802.11, MIMA-MAC and AMTA-MAC protocols. Both of the IEEE 802.11 and AMTA-MAC can use two transmit antennas to achieve maximum throughput. But the MIMA-MAC can use only one transmit antenna. The throughput of MIMA-MAC is half of the IEEE 802.11 and AMTA-MAC.

From above analysis, in SDT scenario, the proposed AMTA-MAC can improve the throughput of MIMA-MAC and mitigate the unfairness in IEEE 802.11.

6.3 the ODT Scenario Simulation

The simulation results of ODT scenario were shown in Figure 22 and Figure 23. Same with SDT, we need to discuss the results in each different distance.

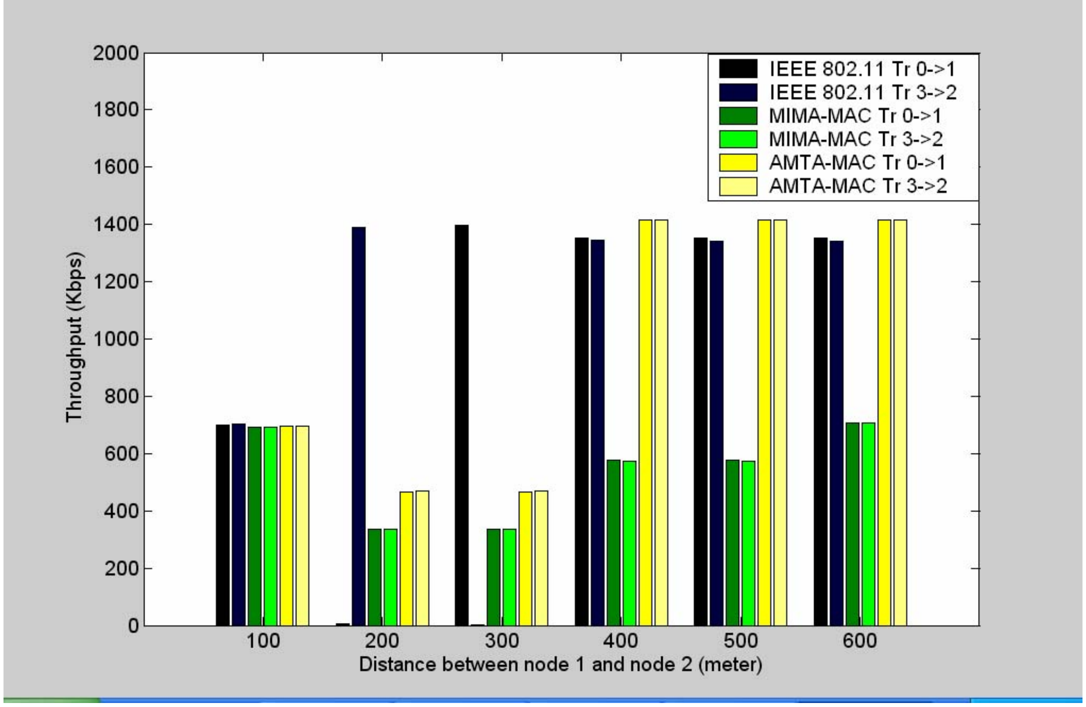


Figure 22. Throughput in ODT scenario

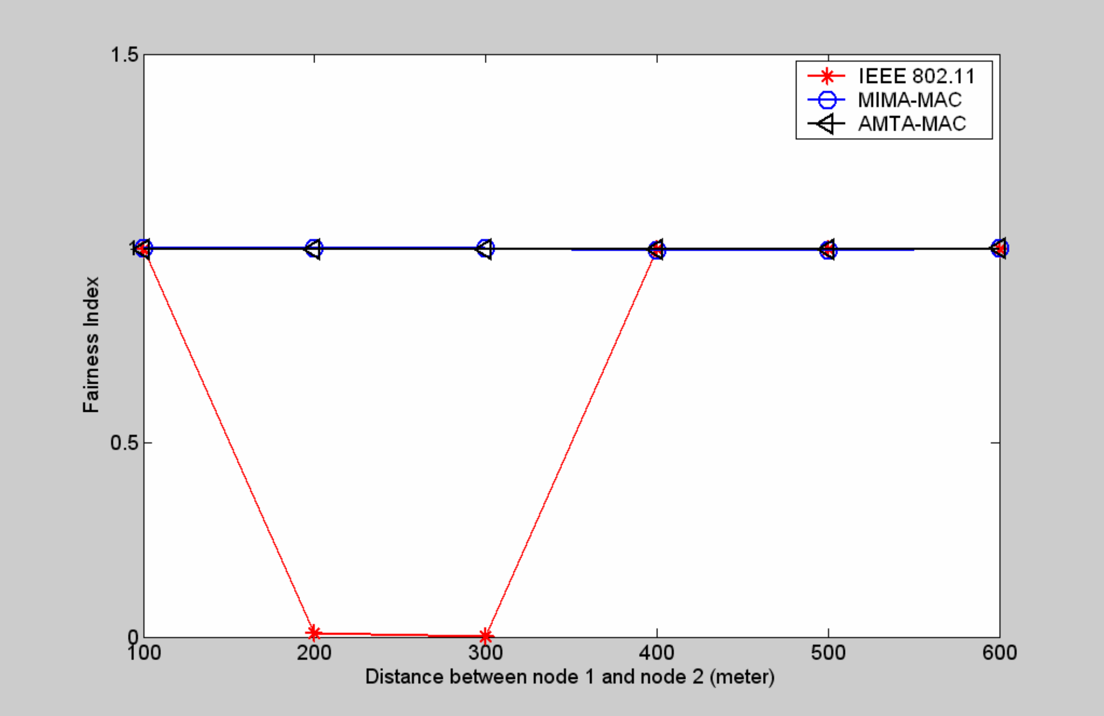


Figure 23. FR in ODT scenario

- D = 100m: In this case, both Node 0 and Node 3 can sense other's transmission. In IEEE 802.11, after the transmission $Tr_{0\to 1}$ finish, Node 0 will wait a DIFS period before send RTS. Since Node 3 can't decode the ACK from Node 1, it has to wait an EIFS period. On the other hand, after the transmission of $Tr_{3\to 2}$, Node 3 will defer a DIFS period, and Node 0 will defer an EIFS since it can't decode the ACK from Node 2. So the two transmissions are symmetric. They generate the same throughput in the long run. So there is no unfairness.

  The behavior of MIMA-MAC and AMTA-MAC is close to each other. Node 0 and Node 3 will begin to send RTS before some backoff slot. Because the backoff slot of Node 0 and Node 3 is different, one of them will send RTS first. And the other node can sense this RTS then stop to send its own RTS in the first handshake slot. Thus, the node that sends RTS first will get CTS (or CTS_TN in

AMTA-MAC). In the second handshake slot, the other node will send RTS and get CTS/CTS_TN successfully. So both transmissions $Tr_{0\rightarrow1}$ and $Tr_{3\rightarrow2}$ can transmit with single antenna. There will be no unfairness problem.

- D = 200m and 300m: The operation of IEEE 802.11 in this condition is complicated and uncertain. For the transmission $Tr_{0\rightarrow1}$, Node 3 can't sense the data transmission from Node 0 to Node 1. After sensing the CTS from Node 1, Node 3 will wait an EIFS period plus the backoff time. Because the packet size is small after fragmentation, after the long time waiting, the transmission $Tr_{0\rightarrow1}$ has finished already and Node 0 begin to transmit again. Node 3 have to wait again, at this time the backoff time was doubled due to the failure of transmission, that make Node 3 wait more time. With the repeat of this process, Node 3 can never access the channel. The same thing may happen with Node 1. As shown in Figure 22, in 200m case, Node 3 can always access the channel and the throughput of $Tr_{3\rightarrow2}$ is the same as the throughput in 400m case, which do not suffer from the interference problem. But Node 0 can never transmit data, its throughput is close to 0. The same thing happens in 300m case, here transmission $Tr_{3\rightarrow2}$ has no throughput but the throughput of $Tr_{0\rightarrow1}$ is close to maximum.

  Consider the operation in MIMA-MAC, when the Node 0 and Node 3 can't sense other's transmission. They will both send RTS in first handshake slot and generate a collision. The transmission probability will decrease after the collision. They may not send RTS in next handshake slot. Thus, the throughput of MIMA-MAC has some decrease compared to D=100m and D>300m cases.

The behavior of AMTA-MAC is similar to that of MIMIA-MAC. However, when there is only one transmission in the network, two antennas can be used to compensate throughput. Since the process is symmetric, there is no unfairness.

- D = 400m, 500m and 600m: In this case, the transmission $Tr_{0\rightarrow 1}$ and $Tr_{3\rightarrow 2}$ don't interfere with each other. They can transmit with all the IEEE 802.11, MIMA-MAC and AMTA-MAC protocols without worrying about collisions. Both the IEEE 802.11 and AMTA-MAC can use two transmit antennas to achieve maximum throughput. But the MIMA-MAC can use only one transmit antenna. The throughput of MIMA-MAC is half of the IEEE 802.11 and AMTA-MAC.

6.4 Random Scenario

To make our simulations close to reality, we use a random scenario in this section. At first, we generate 50 nodes in a 1000m x 500m area randomly, and each node defines its next node to which the node will send data packets. Then, we choose 5, 10, 15 or 20 nodes randomly to be active to transmit date packets. We compare the performance in term of the total throughput in the network.

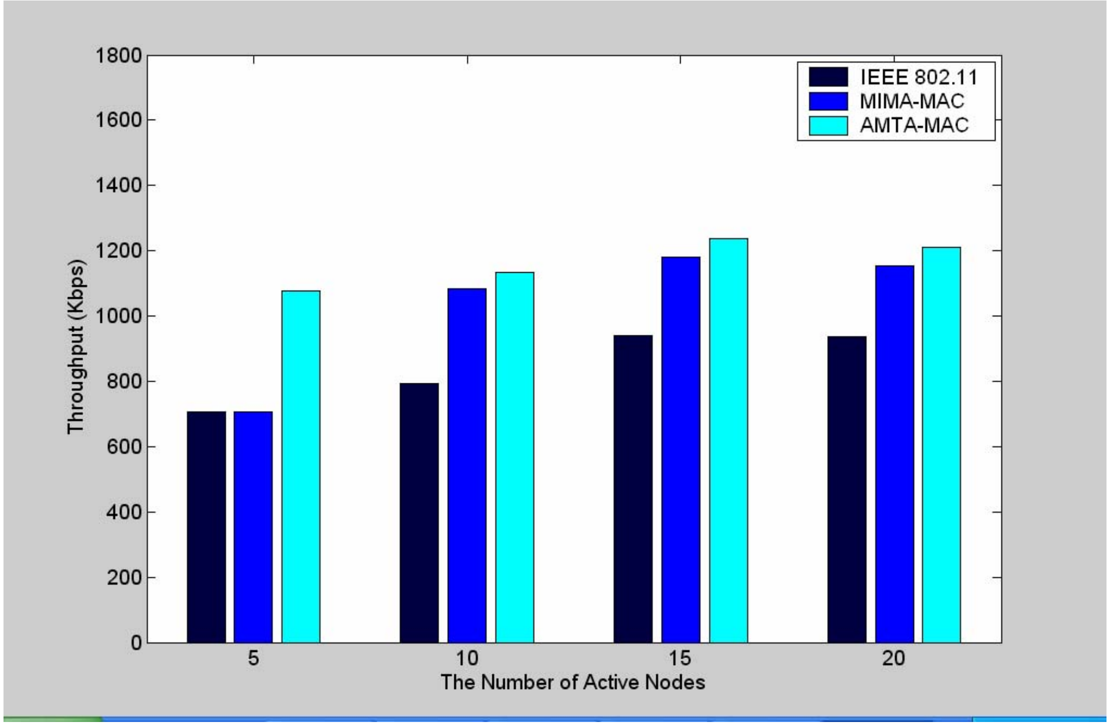


Figure 24. Random scenario

The simulation result of random scenario was shown in Figure 24. The result clearly shows that the proposed AMTA-MAC provides an improvement of around 35% and 15% when compared to IEEE 802.11 and MIMA-MAC respectively.

In practice, we need to consider the cost performance of using multiple antennas. From the simulation results, in case of heavy node density, the throughput improvement of the proposed AMTA-MAC is not remarkable. Using multiple antennas maybe is not a good choice.

Our simulation is based on a fixed data rate. If we change the data rate, our results can still hold, because the synchronized structure of AMTA-MAC can promise its operation is remain same with difference data rate. If we increase the number of antennas, more handshake steps are needed. This will lead to a large header of the frame structure. The performance may be worse. There is a tradeoff between the length of the header and the number of transmit data streams.

Chapter 7. Conclusion

In this thesis, we propose a new MAC protocol, AMTA-MAC, for wireless multi-hop networks with multiple antennas. The purpose of the new AMTA-MAC protocol is to achieve the maximum transmit antenna, and to solve the problems in IEEE 802.11 and MIMA-MAC.

The AMTA-MAC is simulated by network simulator ns-2. By comparing the throughput and fairness with IEEE 802.11 and MIMA-MAC, the simulation results show that the proposed AMTA-MAC protocol outperforms the throughput of MIMA-MAC and mitigates the unfairness in IEEE 802.11.

Bibliography

1. L.L. Peterson, B.S. Davie, *Computer Network: a system approach (Second Edition)*. 2000: Morgan Kaufmann Publishers.
2. K. Xu, M.Gerla and S. a. Bae, *How Effective is the IEEE 802.11 RTS/CTS Handshake in Ad Hoc Networks.* Proc. IEEE Globecom, 2002: p. 17-21
3. S. Xu and T. Saadawi, *Does the IEEE 802.11 MAC Protocol Work Well in Multihop Wireless Ad Hoc Networks?* IEEE Commun. Mag., 2001. 39(6): p. 130-137.
4. *The Network Simulator NS-2*. http://www.isi.edu/nsnam/ns.
5. A. Paulraj and T. Kailath, *Increasing capacity in wireless broadcast systems using distributed transmission.* 1994.
6. Y. Guo, *Advanced MIMO-CDMA Receiver for Interference Suppression: Algorithms, System-on-Chip Architectures and Design Methodology*. Rice University, 2005
7. A. Paulraj, R. Nabar and D. Gore, *Introduction to Space-Time Wireless Communication*. Cambridge University Press, 2003
8. S. M. Alamouti, *A Simple Transmit Diversity Technique for Wireless Communications.* IEEE Journal on Selected Areas in Communications, 1998. 16(8): p. 1451-1458.
9. R. W. Heath, *MIMO Research at UT Austin*. http://www.ece.utexas.edu/~rheath/research/mimo/.

10. T. Yoo, E. Yoon and A. Goldsmith, *MIMO Capacity with Channel Uncertainty: Does Feedback Help?* Global Telecommunications Conference, 2004: p. 96 - 100

11. C.-K. Toh, *Ad Hoc Mobile Wireless Networks: Protocols and Systems*. Prentice Hall PTR. 2002

12. *Wireless LAC Medium Access Control (MAC) and Physical Layer (PHY) Specification.* IEEE Standard 802.11, 1997

13. P. Brenner, *A Technical Tutorial on the IEEE 802.11 Standard*. BreezeCOM, 1997

14. T. Rappaport, *Wireless Communications: Principles and Practice*, Second Edition. Prince Hall, 2002

15. P. Karn, *MACA - A New Channel Access Method for Packet Radio*. 9th Computer Networking Conference, 1990

16. F. Talucci, M. Gerla and L. Fratta, *MACA-BI (MACA By Invitation) A Receiver Oriented Access Protocol for Wireless Multihop Networks.* IEEE International Symposium 1997. 2(1-4): p. 435-439.

17. K. Sundaresan, R. Sivakumar, M. A. Ingram and T.-Y. Chang, *A Fair Medium Access Control Protocol for Ad-hoc Networks with MIMO Links.* IEEE INFOCOM, 2004.

18. M. Park, R.W. Heath and S.M. Nettles. *Improving Throughput and Fairness for MIMO Ad Hoc Networks Using Antenna Selection Diversity*. IEEE GLOCOM, 2004

19. I. E. Telatar, *Capacity of Multi-antenna Gaussian Channels.* European Transactions on Telecommunications, 1999. 10(6): p. 585-595.

20. M. F. Demirkol and M. A. Ingram, *Control using capacity constraints for interfering MIMO links.* Personal, Indoor and Mobile Radio Communications, 2002: p. 1032-1036.

21. A. Ahlen**,** E. Lindskog**,** M. Sternad**,** C. Tidestav and M. Wennstrom, *Research on Multi-antenna Reveivers and MIMO Systems in Digital Mobile Radio.* _ Signals and Systems, Uppsala University