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Master's Degree Thesis

A Deafness-Free MAC Protocol in Ad Hoc Networks Using Directional Antennas

Graduate School of Chosun University

Department of Computer Engineering

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방향성 안테나 기반 애드혹 네트워크에서의

수신장애없는 MAC 프로토콜

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A Deafness-Free MAC Protocol in Ad Hoc Networks Using Directional Antennas

Advisor: Prof. Sangman Moh, Ph.D.

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ABSTRACT

A Deafness-Free MAC Protocol in Ad Hoc Networks Using Directional Antennas

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Directional antennas provide many benefits, such as higher gain and increased transmission range in both ad hoc networks and infrastructure networks. However, deafness problems occur only with directional antennas and can greatly decrease transmission efficiency. In the typical deafness problem, the source node fails to communicate with the intended destination node because the destination node is beam forming in another direction. This thesis proposes a deafness-free medium access control (DF-MAC) protocol with one channel based on a code division multiple access (CDMA) technique for ad hoc networks using directional antennas. In addition to transmission codes, in DF-MAC, two control codes are used for both handshakes and overcoming one type of deafness problem. Our proposed DF-MAC totally solves all types of deafness problem occurring in ad hoc networks using directional antennas. To the best of authors' knowledge, it is the first deafness-free MAC that solves all types of deafness problem. Furthermore, unlike other deafness-aware MAC protocols, DF-MAC supports mobility. Simulation results show that the proposed DF-MAC not only successfully solves all four types of

deafness problem but also out performs the existing deafness-aware MAC protocols in terms of network throughput and control overhead in both static and mobile environments. If deafness problems occur often, the effect of DF-MAC is dramatically maximized.

한글요약

방향성 안테나 기반 애드혹 네트워크에서의 수신장애 없는 MAC 프로토콜

수함

지도 교수: 모상만

컴퓨터공학과

조선대학교 대학원

방향성 안테나는 애드혹 네트워크 및 인프라 네트워크 모두에서 높은 이득과 전송범위 증가 등 많은 혜택을 제공한다. 그러나, 방향성 안테나에서 발생하는 수신장애(deafness) 문제가 전송 효율성을 현저히 감소시킨다. 전형적인 수신장애 문제에서, 수신노드가 다른방향을 지향함으로 인해 송신노드는 수신노드와의 통신에 실패한다. 본 논문은 방향성 안테나를 사용하는 애드혹 네트워크에서 코드 분할 다중 액세스(CDMA) 기법을 기반으로 단일 채널을 갖는 수신장애 없는 매체 접근제어(DF-MAC) 프로토콜을 제안한다. 또한, 핸드 쉐이킹은 물론 한 유형의 수신장애 문제를 극복하기 위하여 두개의 제어코드가 사용된다.

제안한 DF-MAC 은 방향성 안테나를 사용하는 애드혹 네트워크에서 발생할수 있는 모든 유형의 수신장애 문제를 모두 해결한다. 현재까지 알려진바에 의하면, DF-MAC 은 모든 유형의 수신장애 문제를 해결하는 첫번째 프로토콜이다. 더욱이 다른 수신장애인지 MAC 프로토콜과 달리 DF-MAC 은 노드 이동성을 지원한다. 시뮬레이션 결과에 따르면, 제안한 DF-MAC 은 모든 종류의 수신장애 문제를 성공적으로 해결할 뿐만아니라 고정 및 이동 환경 모두에서 기존의 수신장애인지 MAC 프로토콜에 비해 높은 유효 전송률과 낮은 제어 오베헤드를 갖는다. 수신장애 문제가 빈번하게 발생하는 경우, DF-MAC 의 효과는 극적으로 최대화된다.

I. INTRODUCTION

An ad hoc network is a type of decentralized wireless network which does not rely on preexisting infrastructure. Network nodes communicate directly with each other and share a single wireless channel. Many researchers assume that each node in an ad hoc network has an omnidirectional antenna that sends and receives information from all directions. A well-known MAC protocol for ad hoc networks is IEEE 802.11 DCF (Distributed Coordination Function). However, omnidirectional transmission limitations are obvious. Their low throughput can greatly waste space and degrade network capacity.

The rapid development of smart antenna systems can break through the limitations described above [1, 2]. These systems provide each node with several directional antennas. In certain situations, it is possible for some neighbor nodes to communicate with each other at the same time. In this circumstance, throughput can be enormously improved. With directional antennas, directional beams are transmitted within a specified angle and thus, spatial reuse is significantly improved [3, 4].

Furthermore, directional antennas can cover a larger area than omnidirectional antennas; this capability may also strengthen network capacity. Unfortunately, directional antennas are not ideal. There are several severe problems such as hidden terminals, exposed terminals, the deafness problem, and lack of mobility support, which decrease network performance. The definition of the deafness problem is that a node fails to communicate with its intended receiver because the intended receiver is beamforming in another direction or it cannot reply due to the risk of colliding with an ongoing transmission [5]. This problem occurs very often in ad hoc networks using directional antennas and results in multiple packet drops and an increase in back-off time. Prolonged deafness can mislead and affect fairness among transmitting nodes. Let us look at Figure 1. Assuming that node C intends to communicate to node A. However, node A is engaged in an ongoing transmission with node B, so node A cannot hear the RTS (Request To Send) packet which is sent by node C.

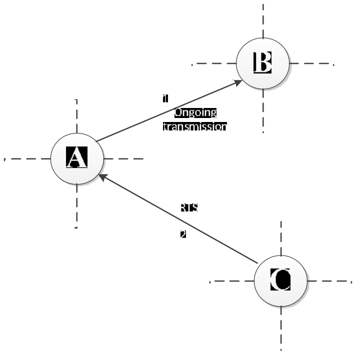


Figure 1. An example of the deafness problem.

Takata et al. [6] found via simulation that more than 60% of communication failures in directional MAC (DMAC) [5] are caused by deafness. Less than 40% of communication failures are caused by RTS collision, CTS collision, directional network allocation vector (DNAV) blocking, or the directional hidden terminal problem. As a matter of fact, many researchers have tried to solve the deafness problem. However, deafness-aware MAC protocols in ad hoc networks with directional antennas solve the deafness problem in part. In other words, no protocol can completely solve all four types of deafness problem.

Node mobility can affect the performance of MAC protocols. In the presence of mobility, nodes have to update their location information table from time to time. This could entail a significant burden of nodes and degrade network throughput. Meanwhile, some of the nodes move from one place to another, which change the network topology. Such network dynamics make communication protocols complicated.

Localization seems as the key to support mobile nodes' communication in ad hoc networks with directional antennas, because it is usually impossible for all nodes in ad hoc networks to be equipped with additional hardware such as global position system (GPS). In general, three types of nodes are defined in the localization [7]. The first type is anchor node, whose position is initially known to all. The second type is unknown nodes, whose positions are not known. The third type is settled nodes that were initially unknown but currently get their position through the localization algorithm. The localization algorithm aims to change all unknown nodes to settled nodes with the lowest position error rate and lowest control overhead.

In this thesis, MAC protocols addressing the deafness problem in ad hoc networks using directional antennas are surveyed in depth based on literature published between 1999 and 2012. We clearly define deafness in ad hoc networks using directional antennas, and then review the MAC protocols that address and partially solve the deafness problem. The MAC protocols are qualitatively compared in terms of characteristics and performance. Furthermore, challenges and opportunities are discussed and some suggestions are given. After that, we propose a deafness-free

MAC (DF-MAC) protocol based on code division multiple access (CDMA) that completely solves all four types of deafness problem. To the best of our knowledge, no deafness-free MAC that solves all four types of deafness problem in ad hoc networks with directional antennas has been reported in the literature. Furthermore, unlike other deafness-aware MAC protocols, DF-MAC supports mobility. In addition, the proposed DF-MAC can also mitigate some other issues, such as hidden and exposed terminal problems. DF-MAC uses omni-directional RTS/CTS to deal with a receiver beamforming in another direction. A special omni-directional RTS is introduced to handle unheard RTS/CTS packets. Finally, we apply the CDMA technique to overcome deafness due to deaf zone and collision avoidance. The performance study shows that our DF-MAC works better than existing CDMA-based MAC protocols in terms of throughput and control overhead. The higher the probability of deafness, the more improvement our protocol can achieve.

The rest of the thesis is organized as follows. In Section II, related works are overviewed and four types of deafness problems are presented in detail. Preliminaries, including antenna model and CDMA technique are described in the third section. Section IV presents the proposed DF-MAC protocol based on CDMA in detail. The formula that we use for simulation will be introduced in section V. The performance of DF-MAC is evaluated via extensive simulation and is comparatively discussed in Section VI. Finally, the thesis concludes in Section VII.

II. RELATED WORKS

In this part we will take a look at design issues for MAC supporting directional antennas and explain the deafness problem thoroughly. After that, we review the works that many researches have done on designing MAC protocols addressing deafness problem and have an exhaustive comparison among these protocols.

A. Design Issues for MAC Supporting Directional Antennas

1) Antenna Mo*del*

Unlike omnidirectional antennas, which radiate and receive in all directions, directional antennas radiate and receive in a single direction. As mentioned in [8], there are two kinds of directional antennas: traditional directional antennas and smart antenna systems. Apart from traditional directional antennas, smart antennas have an increased number of antennas of differing types and also feature a control unit to divide or combine networks [9].

Smart antennas can be classified into two types- switched beam antennas and adaptive array antennas. The switched beam antenna allows for the selection of signals from the desired direction, and it combines N antennas to N predetermined directions. This antenna system works along the lines of an omnidirectional antenna combined features of N directional antennas. In the adaptive array antenna, signals emanate from a combined network and added together to create a steerable radiation pattern. In addition to the ability to change an antenna pattern dynamically to adjust for noise, interference and multipath, the antenna also offers more comprehensive interference rejection. Smart antennas are superior to traditional directional antennas in many respects, including increased spatial reuse and enhanced throughput capability. In smart antenna systems, adaptive array antennas are preferred to switched beam antennas due to their good performance in resisting interference and hardware redundancy. However, adaptive array antenna systems cost more.

2) Radiation Pattern

An antenna pattern is the specification of the gain values going each direction in space. It typically has a main lobe and several side lobes that affect both transmitting and receiving. In general, the higher the gain, the smaller the bandwidth needed. Actually, there are two common models for radiation patterns- flat-top radiation pattern and cone plus sphere pattern. In the flat-top radiation pattern, there are no side lobes and the gain is constant in the bandwidth of the main lobe. The cone plus sphere pattern was proposed in [9]. The sphere accounts for the side lobes and the gain inside the cone is constant.

3) Carrier Sensing

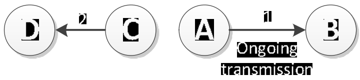
There are two ways of carrier sensing in directional antennas: omnidirectional and directional. In omnidirectional sensing, a node senses the existing transmission between two other nodes by using omnidirectional techniques. In directional sensing, a node senses the transmission between two other nodes using directional techniques. When it senses a transmission between nodes in different directions, it can begin its transmission simultaneously without any interference with other ongoing transmissions. Because of the simultaneous transmissions, it can improve network throughput.

Omnidirectional carrier sensing seems to be an imperfect solution for directional antenna systems. When a transmission is detected, the node will delay its own transmission even if the transmission is in another direction. Even though these two transmissions could happen at the same time, this will not occur if the nodes are utilizing omnidirectional carrier sensing.

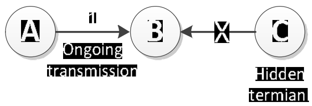
In addition to the above-mentioned physical carrier sensing, a new kind of mechanism is a possibility. It is called a DNAV (Directional Network Allocation Vector). Similar to NAV (Network Allocation Vector), which is used in IEEE 802.11, DNAV can help a node determine whether or not to start a new communication with another node. This kind of carrier sensing is called virtual carrier sensing.

4) Exposed Terminal and Hidden Terminal Problems

As we know, hidden terminal problems and exposed terminal problems are often seen in wireless ad hoc networks. These issues will greatly degrade MAC performance in ad hoc networks using directional antennas. The exposed terminal problem occurs when a node wants to communicate with another node, but it detects an ongoing transmission between other nodes. This ongoing transmission will not actually interfere with this future communication, but the node can be misled by the ongoing transmission and delay its own transmission. As an example in Figure 2(a), node C delays its transmission labeled 2. The hidden terminal problem occurs when all nodes are located in the receiver node's coverage area, but the sender node and the hidden node are distant from each other's coverage area. In Figure 2(b), node B is the receiver node for the transmission labeled 1 and node C is the hidden node.



(a) Exposed terminal



(b) Hidden terminal

Figure 2. Exposed and hidden terminal problems.

5) RTS/CTS Handshake

RTS/CTS (Request To Send / Clear To Send) packets are commonly used in IEEE 802.11 networks. With respect to the deafness problem associated with directional antennas, RTS/CTS packets can be transmitted either omni-directionally or directionally. Omnidirectional RTS/CTS was proposed by early directional MAC protocols which used directional antennas for DATA and ACK packets only. Compared with directional RTS/CTS, omnidirectional transmission suffers from obvious shortcomings, especially in transmission range. In addition, omnidirectional RTS/CTS packets may reduce the benefits of spatial reuse. Directional RTS/CTS has a long transmission range and makes simultaneous transmissions possible. It achieves high spatial reuse and may increase network throughput. However, it leads to the deafness problem which we will discuss in more detail later.

6) DATA and ACK Transmission

Node mobility can affect the performance of MAC protocols. In the presence of mobility, nodes have to update location information tables from time to time. This could entail a significant burden for nodes and degrade network throughput. Meanwhile, some of the nodes might move from one place to another. The situation is very complicated. The dynamics of the system will affect how the protocols work. It is a very difficult problem in a high mobility environment.

7) Mobility Support

Node mobility can affect the performance of MAC protocols. In the presence of mobility, nodes have to update location information tables from time to time. This could entail a significant burden for nodes and degrade network throughput. Meanwhile, some of the nodes might move from one place to another. The situation is very complicated. The dynamics of the system will affect how the protocols work. It is a very difficult problem in a high mobility environment.

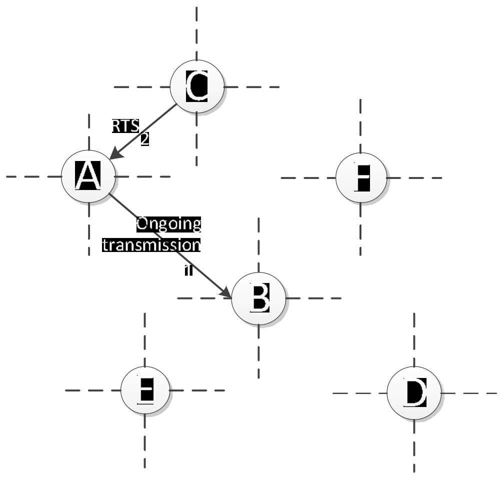
8) Deafness Problem

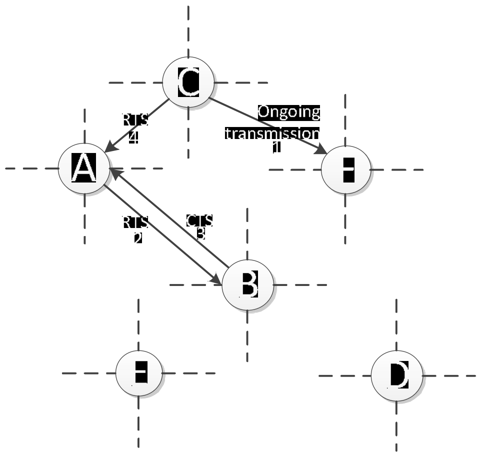
As introduced in Section I, the deafness problem occurs if a node has many packets for transmission. In this case, it will stay in a directional mode for quite a long time. If any other node wants to communicate with the transmitting node, it will not receive any message from its intended receiver (i.e., the transmitting node) because the intended receiver is busy transmitting other packets. The node intending to communicate with the transmitting node will not receive any message confirmations and will resend packets unnecessarily.

As mentioned by Chen and Jiang [10], Hrishikesh et al. [11], there are four varieties of the deafness problem in ad hoc networks: (i) receiver beamforming at other directions, (ii) unheard RTS/CTS, (iii) deaf zone, and (iv) due to collision avoidance. We will discuss these types in detail in the following section.

B. The Deafness Problem

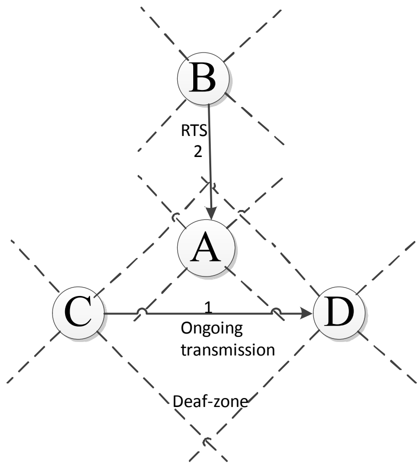
The deafness problem arises when the sender node fails to communicate with its intended receiver either because the receiver is beamforming in another direction or because it can hear the RTS packet but cannot reply because of potential collisions with an ongoing transmission. Four types of deafness problem have been defined [10, 11], and they are illustrated in Figure 3 and further described below.

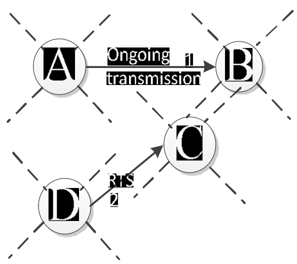




(a) Receiver beamforming in another direction

(b) Unheard RTS/CTS





(c) A deaf zone

(d) Due to collision avoidance

Figure 3. Four types of the deadness problem.

Type a: Receiver beamforming in another direction.

In this scenario, the intended receiver is engaged in an ongoing transmission. Thus, it cannot hear the RTS packet from the sender node. As shown in Figure 3, there is an ongoing transmission between node A and node B. Then, node C wants to communicate with node A. When node C sends its RTS packet to node A, node A will not receive it.

Type b: Unheard RTS/CTS

Deafness occur when the intended sender does not detect the transmission between the intended receiver (that will transmit its data to another node) and another node. As shown in Figure 3, node C and node F are communicating with each other. Meanwhile, node A sends its RST packet and receives a CTS packet from node B. When node C completes its transmission with node F, node C wants to send its data to node A. Then, node C sends its RTS packet to node A. But, node A cannot receive the RTS packet. This situation is always a possibility in some protocols, but it has not been addressed well yet.

Type c: Deaf zone

A deaf zone is a common phenomenon in ad hoc networks using directional antennas. The intended receiver lies in an area called a dead zone where a transmission is occurring. In Figure 3, the diamond area constitutes the deaf zone and there is an ongoing transmission between node C and node D. However, node A is located in the deaf zone covered by the ongoing transmission. At a given moment, if node B wants to communicate to node A and sends its RTS packet to node A, node A will be silent. The RTS packet will not be heard by node A.

Type d: Due to collision-avoidance

This fourth type of deafness scenario occurs when the intended receiver gets an RTS packet, but knows that there is a transmission in that direction and, thus, it cannot send a CTS packet back to the sender. As shown in Figure 3, node A is communicating with node B and node C receives an RTS packet from node D. However, node C cannot send a CTS packet back to node D because it is trying to avoid colliding with the ongoing transmission between node A and node B.

Of the four cases, the first three scenarios revolve around the intended receiver not being able to hear an RTS packet, while in the fourth scenario the intended receiver can hear the RTS packet but cannot reply with a CTS packet. Both the first and the third scenarios are commonly seen in ad hoc networks using directional antennas. However, the second scenario is more complex and occurs less often than the first and the third. Most MAC protocols that are designed to address the deafness problem solve only the first scenario. Although a lot of attention is paid to the first scenario, it turns out that the other three can also degrade the performance of a wireless network using directional antennas.

C. Deafness-Aware MAC Protocols

In this part, we discuss MAC protocols and how they deal with the deafness problem. MAC protocols are reviewed and compared with each other. There are two approaches to solving the deafness problem - proactive and reactive. In the proactive approach, the source node lets its neighbors know that it will begin a transmission. Thus, neighbors will not transmit to the source node for a certain time. In the reactive approach, when a node would like to communicate with a neighbor engaged in another transmission, it detects that the intended receiver (i.e., the neighbor) is running a transmission and, thus, it will not try to communicate. In both proactive and reactive approaches, the deafness-aware information can be released either prior to or after the RTS/CTS handshake.

1) Proactively Deafness-Aware MAC Protocols

Sending Deafness-Aware Information Prior to RTS/CTS Handshake

CDR-MAC (Circular Directional RTS MAC)

This MAC protocol was designed to fully exploit directional antennas [12, 13]. It uses switched beam antennas. The carrier sensing is directional. It also uses a DNAV. In this protocol, a location table is introduced. The data is transmitted directionally.

The sender node sends a circular DRTS packet. That means that every neighbor node receives the circular DRTS so that all its neighbors are aware of the imminent transmission and thus update their DNAV table. After all circular DRTS packets have been sent, the sender node will turn into an omnidirectional mode. The receiver node also receives the DRTS packet and then sends back a circular DCTS packet. A location table is used to record nodes and location information so as to increase the efficiency of transmission. Each node keeps a location table. The table consists of four columns with the following headers: my name, neighbor names, my beam, and neighbor beams.

In this protocol, the first deafness problem is solved. However, the other three situations turn out to be difficult to solve. For example, if a busy node might want to communicate with its next receiver after its first transmission, but does not know that its intended receiver is deaf. Also, when a node is located in a deaf zone, it will be silent. Furthermore, collision avoidance used in this MAC protocol cannot properly address the fourth deafness scenario.

CDMA-*based MAC*

The Code Division Multiple Access (CDMA)-based MAC protocol uses omnidirectional carrier sensing together with a DNAV table [14]. The directional model is used only in data transmission and ACK packets. It also keeps an information table and a code table.

The sender node checks the information table first to ensure that the receiver node is within its coverage. Then, the sender node sends an RTS packet omni-directionally. The receiver node that receives the RTS packet sends back an omnidirectional CTS packet. The neighbor nodes update their DNAVs. Then, the sender node sends DATA to the receiver node and the receiver node sends the ACK packet.

Since the protocol is based on CDMA, each transmission will be allocated a code number. The problem is how to assign a code number for each individual transmission. There are two kinds of code numbers. One is the control code number which is used for controlling RTS/CTS handshakes. The other is the transmission code number that is used for data transmission.

This protocol can solve all deafness problems with the exception of the second type. For the first scenario, it uses an omnidirectional RTS/CTS handshake. Similar to IEEE802.11, its neighbors can hear the control packet and update their own DNAV. For the third scenario, communication between two nodes will not be hindered because of the CDMA technique. In terms of the CDMA technique, the fourth scenario is not applicable. In this protocol, the second type of the deafness problem is a big problem. That is because the node is busy sending messages. It cannot hear any control packet from its neighbors during a given period of time.

LCAP MAC

This MAC protocol is proposed by Arora and Krunz [21]. We can regard this protocol as an extension of DMAC (Directional MAC). In DMAC only one channel is used, however, in this MAC protocol two channels are utilized for transmission. One channel is control channel and another channel is data transmission channel.

The sender sends DRTS in control channel, the receiver get the DRTS replies with DCTS also in control channel. After the RTS/CTS handshake, the sender sends data directionally. Upon finishing the data transmission the receiver sends ACK directionally. Because of using different channels, the author think this MAC protocol supposed to be deafness freedom. But the fact is it still cannot address the third and the fourth deafness problem.

Sending Deafness-Aware Information After RTS/CTS Handshake

AN-DMAC (Advanced Notice-DMAC)

This MAC protocol assumes a switched beam antenna system [15]. It uses directional carrier sensing. It introduces the AN (Advanced Notice) packet. It also keeps a location information table. The sender node uses DMAC to send a DRTS packet to the receiver node according to information in the local information table. When the ongoing transmission is near completion, the sender node will check if there is data for another node. If there is, the AN packet is sent to the intended receiver before it finishes the current transmission. The intended receiver node will detect this and beamforming that direction for the next transmission.

Every time a node sends RTS, it will transmit an AN packet to its next receiver. The next receiver will wait until it receives the RTS packet from the sender node. In this way, it can address two types of the deafness problem. For the first scenario, the intended receiver knows that there will be a transmission between itself and its neighbor. It will not start a transmission with another node. The second kind of deafness can also be totally solved. If the node recognizes that it will be the intended receiver in the next communication, it will not begin its transmission with other nodes. However, the third and fourth deafness scenarios remain unaddressed because new communications can interfere with the current transmission or collide with ongoing transmissions.

RDMAC/DM (Rotary DMAC with Deafness Mitigation)

This protocol [10] uses switched beam antennas. The carrier sensing in RDMAC/DM is directional physical carrier sensing. It also uses DNAV. An RTS packet is sent directionally and it also uses a directional CTS. After RTS/CTS handshake, the two nodes transmit DATA and ACK packets directionally.

This protocol assumes that the location information of all nodes is known. When a node wants to communicate with another, it first checks its DAV table. If the receiver node is not listed in the table, the sender will send a DRTS packet to the intended receiver. The receiver node receives an RTS packet and sends back a CTS packet. After receiving a CTS packet, the sender node sends a circular SOT (Start of Transmission) packet to inform its neighbors of the coming transmission. Then the neighbors that receive the SOT packet will put this node into the DAV table and update their DNAV. Meanwhile, the intended receiver sends out circular SOR (Start of Receiving) packets to its neighbors to inform them of the coming transmission. Also, the neighbors that receive the SOR packet will put this node into their DAV table and update their DNAV.

This protocol introduces the so-called FM (Forward Message) to mitigate the deafness problem type 2. If an unheard RTS/CTS situation occurs, a node would want to transmit data to the node engaged in another ongoing transmission. When a neighbor of the intended receiver node hears the DRTS, it will send an FM to the sender node with its own DNAV to inform the sender node that the intended receiver node is busy, thus helping the sender node to update its DNAV.

In this protocol, the sender node sends a rotary SOT packet to inform its neighbors. Thus, they will not try to send RTS packets to the sender node. It also uses an FM to mitigate the second deafness problem scenario. But, it cannot solve the third and fourth deafness scenarios. If a node is in a deaf zone, it will keep silent. This protocol avoids collision by delaying for some time in order to not interfere with ongoing transmissions.

FFT-DMAC* (*Flip-Flop Tone-based DMAC)

This protocol use adaptive array antennas [16]. The carrier sensing is directional. Both RTS and CTS packets are sent directionally. Also the data transmission between two nodes is directional. Finally, the ACK packet is transmitted omni-directionally. Each node keeps a DAV table.

A tone is a pure sine wave with a particular frequency. It is not a modulated signal and, thus, it cannot contain any information. A tone can only be detected (through energy estimation) on the corresponding narrow frequency band.

When a node would like to communicate with another node, it first checks if the intended receiver is in its own DAV table. The sender makes sure that there is no ongoing transmission in its desired direction. Then, it sends a DRTS packet to the receiver node. The receiver node receives the RTS packet and sends tone FFT_1^+omnidirectionallyto inform its neighbors of the imminent transmission. Then, it sends FFT_2^+ to the sender node. The sender node receives $FFT_2^+$and then sends out FFT_1^+ to inform its neighbors of the incoming transmission. The neighbors that get FFT_1^+ update their own DAV tables.

On completing the transmission, the receiver node sends FFT_2^- directionally, which functions similarly to an ACK packet. Furthermore, it sends out FFT_1^-omnidirectionally to cancel its deafness. On the other hand, when the sender node receives FFT_2^-, it also sends out FFT_1^- to its neighbors to notify them that deafness is no longer present.

This MAC protocol solves the first deafness scenario. However, it cannot solve the second scenario because the busy node is engaged in the current transmission. It does not know that its next intended receiver is deaf even though the intended receiver has sent FFT_1^+ before. The node in the deaf-zone keeps silent and, thus, it is not able to hear any RTS packets. Collision avoidance is utilized in this protocol and, thus, it cannot handle the fourth scenario.

DMAC/DA (Directional MAC with Deafness Avoidance)

This protocol [17] assumes each node is equipped with a switched beam antenna. The baseline of this protocol is DMAC. However, this protocol aims to address the deafness problem so that a new WTS (Wait To Send) frame is introduced.

When a source node tries to send packets to its destination node, it starts the DRT/DCTS handshake with the destination node and, then it sends the WTS frame to neighbors which may potentially send packets to the source node during the transmission time. After sending WTS, the source node transmits data to the destination node. This protocol also uses the Next Packet Notification (NPN) frame that is used to enhance performance and reduce deafness issues.

The main difference between this DMAC/DA and RDMAC/DM is that the WTS frame is sent randomly to its neighbors in DMAC/DA. However, RDMAC/DM sends SOT to all its neighbors.

2) Reactively Deafness-Aware MAC Protocols

Sending Deafness-Aware Information Before RTS/CTS Handshake

ATB-DMC (Auxiliary Tone-Based DMAC)

This MAC protocol [18] uses switched beam antennas and gets eight auxiliary tones: transmitter direction tone (TDT), receive direction tone (RDT), other direction busy tone (OBT), send direction busy tone (SBT), idle tone (IDT), desired directional tone (DDT), collision occurrence tone (COT), ad RTS collision occurrence tone (RCOT).

In this scheme, no prior information about neighbors is available. If a node wants to make a communication, it will first transmit the TDT tone over all directions continuously. If the idle receiver detects the TDT, it sends RDT. If the receiver is busy and cannot communicate with other nodes, it will reply OBT or SBT. After completion of the TDT transmission, the transmitter starts scanning in different directions. If the transmitter receives RDT and does not detect SBT, it starts to transmit the RTS frame. Nodes that receive RTS check the destination address. The node with the destination address is the intended receiver and must reply with the DDT tone to help the transmitter. If two or more RTS packets collide, the receiver transmits the RCOT tone in response. Upon receiving the DDT tone, the transmitter beamforms and responds to all other TDT tones with OBT or SBT tones to mitigate the exponential back-off. After completion of DDT tone transmission, the receiver sends the CTS packet toward the transmitter. Finally, the data transmission will be completed upon receiving ACK at the transmitter.

Sending Deafness-Aware Information After RTS/CTS Handshake

DSDMAC (busy tone-based Dual Sensing Directional MAC)

This MAC is a tone-based MAC protocol [19]. There are two kinds of busy tones, BT_1 and BT_2, which will be discussed later. The protocol assumes an adaptive array antenna system. Both omnidirectional and directional carrier sensing are used in association with DNAV. The RTS, CTS, DATA, and ACK packets are sent directionally.

If the specified sector is not blocked and the data channel is idle, the sender node sends DRTS and then turns on BT_1 in an omnidirectional manner. The receiver node receives DRTS and sends back the DCTS packet to the sender node. Then, the receiver node turns on its BT_2 to communicate that there is an ongoing transmission. BT_2 will last until the transmission is over. When the sender node receives the DCTS, it also changes its BT_1 to BT_2; the receiver node does the same.

This protocol solves the deafness problem by the use of busy tones. Neighbor nodes that want to begin transmission can detect the sine wave signal. Different sine waves correspond to different states. The first and second deafness scenarios are perfectly solved, but the third and fourth scenarios remain unaddressed.

Tone DMAC

This MAC protocol [5] uses switched beam antennas. All nodes are equipped with an additional tone transceiver which functions to generate out-of-band tone. This out-of-band tone is used to inform neighbors that packet transmission failure, occurs because the destination node is not deaf but is now idle. The neighbors can retransmit packets. DRTS-DCTS handshaking is used in this protocol. The DATA and ACK packets are also transmitted directionally.

Although this MAC protocol cannot completely prevent deafness, it can successfully mitigate deafness issues, improve throughput, and upgrade spatial reuse.

BT-MAC protocol

This MAC protocol [20] assumes that a node has two antenna interfaces: switched beam antenna and omnidirectional antenna. In this protocol, two busy tones of BTr and BTt are introduced. Both BTr and BTt have two sub-tones (an ID tone and a beam number tone).

If a node attempts to communicate with another node, it will search its NLT (Neighbor Location Table) in order to find the destination beam and check if the beam is available for transmitting in DNAVs. DRTS and DCTS handshaking, data transmission, and ACK are the next functions. During that period of data transmission time, the tones BTr and BTt are open omni-directionally to inform the neighbor of this current transmission.

D. Comparison of the Deafness-Aware MAC Protocols

We have summarized the protocols that address the deafness problem in ad hoc networks using directional antennas. As is shown in Table 1, many protocols assume that switched beams antenna systems are present. The switched beam antenna mechanism is easy to understand. However, as time goes by and costs decrease, an adaptive array antenna system will be more popular. What is more, negative effects of directional antennas such as side lobes should be considered. Among the MAC protocols, some are using directional carrier sensing while the others use omnidirectional carrier sensing. Directional carrier sensing has numerous advantages such as high spatial reuse and larger transmission area. However, the directional carrier sensing causes the deafness problem in ad hoc networks, which degrades network performance. Just as a coin has two sides, omnidirectional carrier sensing can avoid the deafness problem to some extent, but the other side is that it has disadvantages in transmission area, spatial reuse, and simultaneous transmission.

Table 1: Comparison of the deafness-aware MAC protocols in terms of features and characteristics.

MAC Protocol	**Antenna type**	**Radiation pattern**	**Carrier sensing and back off**	**RTS/CTS handshake**	**DATA& ACK transmission**	**Exposed / hidden terminal**	**Neighbor location**	**Mobility**
CDR-MAC [13]	Switched beam	Flat-top	DNAV Directional sensing	Circular DRTS /Circular DCTS	DDATA/ DACK	Solved	Location table	Not specified
CDMA-based MAC[14]	Not specified	Not specified	DNAV Omnidirectional	Omni-RTS/ Omni-CTS	DDATA/ DACK	Solved	Information table	Not specified
AN-DMAC [15]	Switched beam	Flat-top	Directional sensing	DRTS/ DCTS	DDATA/ DACK	Solved	Local information table	Not specified
RDMAC/DM [10]	Switched beam	Flat-top	DNAV Directional sensing	DRTS/DCTS	DDATA/DA CK	Solved	DAV(deafness allocation vector table)	Not specified
FFT-DMAC [16]	Adaptive array antenna	Not specified	Directional	DRTS/ directional CTS(FFT_2^+)	DDATA/ Omni-ACK(FFT_2^-)	Solved	Deafness node list transmission node list	Not specified
DMAC/DA [17]	Switched beam	Not specified	Directional sensing	DRTS/ DCTS	DDATA/ DACK	Solved	Neighbor table	Not specified
ATB-DMAC [18]	Switched beam	Not specified	Directional/ omnidirectional	DRTS/ DCTS	DDATA/ DACK	Solved	No	Support
DSDMAC [19]	Adaptive array antenna	Flat-top	DNAV Directional/Om nidirectional	DRTS/ DCTS	DDATA/ DACK	Solved	AoA caching information	Not specified
Tone DMAC [5]	Switched beam	Not specified	Directional sensing	DRTS/ DCTS	DDATA/ DACK	Solved	Not specified	Not specified
BT-MAC [20]	Switch beam and one omni-directional antenna	Not specified	DNAV Directional sensing	DRTS/ DCTS	DDATA/ DACK	Solved	Neighbor location table	Not specified
LCAP[21]	Solved	Solved	Not solved	Not solved	LCAP[15]	Solved	Solved	Not solved

Most protocols use DRTS and DCTS handshake and transmit DATA and ACK packets directionally. They fully exploit the benefits of directional antennas. By doing so, the coverage range is dramatically increased, which brings more benefits and improves performance. However, as the downside is the necessity of knowing neighbor location information and coordinating between senders and receivers. Table 1 also indicates that DSDMAC [19] uses an AoA caching scheme to store the location of neighbor nodes temporarily. The other protocols maintain a location information table and update it whenever a transmission begins. Supporting node mobility is another hard problem. Only one of the protocols, ATB-DMAC [18], explicitly considers node mobility in its initial design.

In Table 2, MAC protocols are compared in terms of deafness. None of the protocols can totally solve all the four types of the deafness problem. The first scenario of receiver beamforming in another direction is solved by almost all protocols by sending circular DRTS packets, omnidirectional RTS, rotary SOT, and AN many ways to make a sender's neighbors aware of the imminent transmission or by sending sine wave FFT or busy tone BT1/BT2 to prevent other nodes from communicating with a busy node.

Table 2: Comparison of the deafness-aware MAC protocols in terms of deafness and usability.

MAC Protocol	Deafness				Advantage	Disadvantage
	Receiver beamforming to the other direction	Unheard RTS/CTS	Deaf zone	Collision avoidance		
CDR-MAC [13]	Solved	Not solved	Not solved	Not solved	Better performance than 802.11[22]	Low spatial reuse and much overhead
CDMA-based MAC[14]	Solved	Not solved	Solved	Solved	Higher throughput than DMAC	Low spatial reuse (because of omnidirectional RTS/CTS)
AN-DMAC [15]	Partially solved	Partially solved	Not solved	Not solved	Higher throughput than DMAC and CDR-MAC	Difficult to take it into practical use
RDMAC/DM [10]	Solved	Mitigation	Not solved	Not solved	Lower delay and higher throughput than CDR-MAC	Low spatial reuse (because of rotary of SOT/SOR)
FFT-DMAC [16]	Solved	Not solved	Not solved	Not solved	Much higher throughput than 802.11	Extra hardware
DMAC/DA[17]	Solved	Partially solved	Not solved	Not solved	Enhancement of DMAC	High overhead
ATB-DMAC[18]	Solved	Solved	Not solved	Not solved	Better performance than 802.11	Additional hardware and very complicated for real applications
DSDMAC [16]	Solved	solved	Not solved	Not solved	Higher throughput than tone DMAC	Extra hardware, Low spatial reuse
Tone DMAC[5]	Partially solved	Partially solved	Not solved	Not solved	Higher throughput than 802.11	Additional hardware,
BT-MAC[20]	Solved	Solved	Not solved	Not solved	Performs better than DMAC	Additional hardware

The second scenario related to unheard RTS/CTS is totally solved by many tone based protocols, while two protocols of RDMAC/DM, DMAC/DA and AN-DMAC solve it partially. Of course, this scenario is unique because of the two simultaneous transmissions. The nodes engaged in earlier transmission are not able to hear any information from the nodes that are engaged in later transmissions. When the earlier transmission finishes, the node wants to communicate with the intended receiver which is busy transmitting, and that creates the problem. In tone-based DMAC, because the busy tone sine wave exists at all times, the node can detect the signal when it wants to communicate with the busy node. RDMAC/DM uses topology to mitigate this problem. If the busy node has neighbors that hear SOT from the sender node, the neighbors will reply with special information. Unfortunately, it cannot totally solve the problem. In AN-DMAC, the sender node sends AN packets to its neighbors. If it has multiple packets to send, the simultaneous transmission will not happen and, thus, the second scenario related to unheard RTS/CTS will not occur. However, if the sender node has just one packet (meaning that it does not have an AN packet to send to its neighbors), the unheard RTS/CTS problem still exists.

The third scenario of deaf zone is solved only by the CDMA based MAC protocol. When using CDMA, the node located in the deaf zone can still communicate with other nodes. In other protocols that use a TDMA technique, however, the node located in the deaf zone will keep silent in order to not interfere with the current transmission.

The fourth scenario, which is related to collision avoidance, is solved only by the CDMA based MAC protocol (as is the third scenario). But contrary to the third scenario, the presence of the deaf zone means the node is located in both the sender and receiver node's coverage. It can hear RTS packets but it is not able to reply so as to avoid collisions.

Solving both the second and third scenarios is difficult since both solutions cannot exist at the same time. In Table 2, the advantages and disadvantages are summarized. It is also should be noticed that all these MAC protocols work better than omnidirectional 802.11 DCF MAC in many respects.

E. Challenge and Opportunities

In this section, we will discuss challenges and opportunities for addressing the deafness problem in ad hoc networks using directional antennas. The fundamental problem is that the sender node does not know if the intended receiver is able to hear or reply to its RTS/CTS packets. If the sender node knows for sure that the intended receiver is deaf, it will not send RTS packets. Now we itemize challenges and opportunities to avoid the deafness problem.

- **Antenna model with one antenna:** Solving the deafness problem with this antenna model (either switched beam antenna system or adaptive array antenna system) is possible, but very difficult. The channel for transmitting information is fixed, and the working mechanism of the antenna is half-duplex, which cannot be changed. Although some degree of a busy tone is introduced to enhance performance, the result seems to be not as satisfactory as we expect. The only option is to change channel access methods among TDMA, CDMA, FDMA, and so on. All the protocols mentioned utilize the antenna model. As illustrated in Table 2, no protocol can totally solve all types of the deafness problem with respect to the antenna model.

- **Mobility support:** As shown in Table 1, mobility support is not mentioned in any of the MAC protocols. However, mobility affects the deafness problem due to the movement of nodes commonly seen in ad hoc networks. Mobile nodes have an important impact on the performance of MAC protocols. Furthermore, it takes time to update location information tables. A MAC protocol with mobility support and a solution for the deafness problem is a clearly needed in the future.

- **Antenna model consisting with two or more antennas:** It is possible that an antenna system with two or more antennas that can work individually or at the same time can deal with the deafness problem. A multiple-antenna deafness problem is easier to address than is a single-antenna model. We can use some antennas for transmission while some antennas are devoted to receiving. But the channel must be carefully divided and an optimal channel access method selected. However, if more antennas are used, implementation cost will increase.

- **Multichannel interface:** The node can use more than one channel to communicate with other nodes. It seems an excellent way to tackle the deafness problem. FFT-DMAC and DSDMAC protocols have many elements of this approach. The multichannel interface requires extra hardware to produce control signals for the purpose of protecting the ongoing transmission from interference. Significant improvements are still needed in order to definitively handle the deafness problem. Multichannel communication is complicated to design and extra hardware increases the cost.

III. PRELIMINARIES

A. Antenna Model

It is assumed that every node has six directional antennas and one omni-directional antenna. As shown in Figure 4, each antenna can work individually based on the CDMA technique. In this antenna model, a node can work in two modes: directional mode and omni-directional mode. In directional mode, only one of six directional antennas can work at a certain time, but in omni-directional mode, the omni-directional antenna works all the time. Unlike switched beam antenna systems, a node can stay in either directional mode or omni-directional mode. In our antenna model, every node with the CDMA technique will work in both modes at the same time.

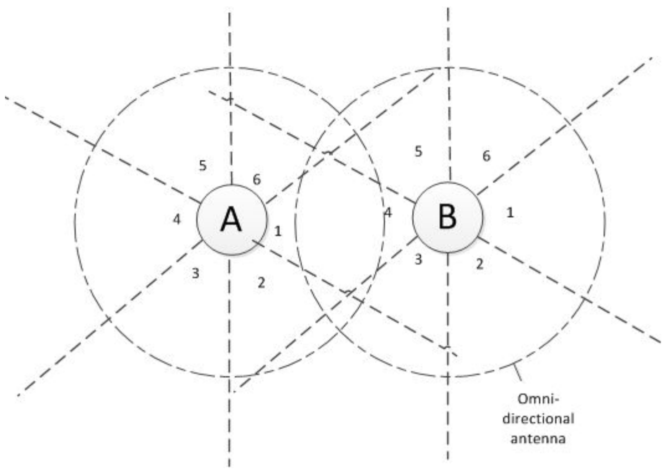


Figure 4. Each node has an omni-directional antenna and six directional antennas.

B. CDMA

CDMA is a channel access method used by various radio communication technologies. It allows several transmitters to send information simultaneously over a single communication channel. CDMA employs spread-spectrum technology and a special coding scheme (where each transmitter is assigned a code) to allow multiple users to be multiplexed over the same physical channel.

C. Localization

Localization systems can be divided into three distinct components of distance estimation, position computation and localization algorithm. The distance estimation is used to estimate the distance between nodes. The position computation is for calculating the actual position of a node. The localization algorithm determines show the available information will be manipulated in order to allow most or all of the nodes to estimate their positions. In this paper, the received signal strength indication (RSSI) is utilized in distance estimation and trilateration is used for position computation. In addition, the recursive position estimation (RPE) algorithm [22] is used as the localization algorithm.

IV. DEAFNESS-FREE MAC PROTOCOL

In this section, we present a deafness-free MAC (DF-MAC) protocol that solves all four types of deafness problem. The DF-MAC design is based on the IEEE 802.11 standard. The following three principals were used to design DF-MAC presented in this paper:

- A MAC protocol using directional antennas must use directional antennas for transmitting and receiving data.
- There must be a mechanism to instruct neighbors to defer their transmissions to avoid the hidden terminal problem.
- The proposed protocol should be deafness-free.

A. Location Information Table

In our protocol, each node keeps a location information table. The table is used to store information about the node's neighbors. Figure 5 describes an ad hoc network with seven nodes. Each node deploys with six directional antennas and one omni-directional antenna. Table 3 shows the location information of Node D in Figure 5.

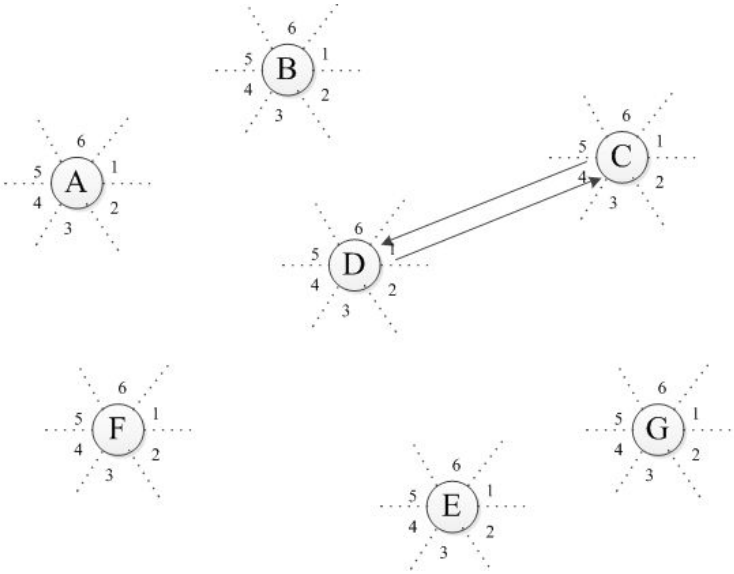


Figure 5. An ad hoc network with seven nodes.

Table 3: Location information table of node D in Figure.5.

Myself	**Neighbor**	**My beam number towards neighbor node**	**Neighbor node beam number towards me**
D	A	5	2
D	B	6	3
D	C	1	4
D	E	3	6
D	F	4	1
D	G	2	5

Table 4: CDMA code table.

Code number	Code type	Usage
0	Control code	Special RTS
1	Control code	RTS/CTS handshake
2	Transmission code	Data transmission
3	Transmission code	Data transmission
4	Transmission code	Data transmission
5	Transmission code	Data transmission
6	Transmission code	Data transmission
7	Transmission code	Data transmission
8	Transmission code	Data transmission
9	Transmission code	Data transmission

B. CDMA Code Table

Our protocol uses CDMA, and thus, a specific code should be assigned to a certain transmission. In addition to transmission codes, in DF-MAC, two control codes are used for RTS/CTS handshakes and for a special request to send to overcome one type of deafness problem, which will be explained later. As illustrated in Table 4, code 0 and code 1 are control codes. Code 0 is for the special RTS, and code 1 is used for RTS/CTS handshakes. Codes 2 to 9 are for data transmission.

C. Deafness Table

In our protocol, every node has a deafness table in order to recognize the nodes engaged in the current transmissions and, at the same time, to store the CDMA code numbers used. For example, in Figure 5, there is ongoing communication between node D and node C using CDMA code 2. Table 5 shows the deafness table of node B.

Table 5: Deafness table of node B in Figure.5.

Myself	Deaf node	My beam toward deaf node	Beam of deaf node towards me	CDMA code being used
B	C	2	5	2
B	D	3	6	2

D. Special RTS

In order to solve all types of deafness problem, a special RTS is introduced to inform the node suffering from deafness type 2 (unheard RTS/CTS). This special RTS is sent omni-directionally with CDMA code 0 to the deaf node.

E. DNAV

A DNAV mechanism is widely adopted in MAC protocols using directional antennas because it can effectively prevent the hidden terminal problem. DNAV functions under the philosophy of the NAV proposed by IEEE 802.11 and adapted in directional communication.

F. Mobility Support

In order to support mobile nodes, the localization system is introduced in Section III. In the system, RTS, CTS and special RTS packets contain the position information of the node transmitting the packet so that the node receiving the information updates its location information table.

G. Communication Procedure

At the initial state, the Sender checks the location information table and deafness table to see whether the intended receiver is in deafness. If the receiver is not in deafness, the sender sends omni-directional RTS in CDMA code 1 to all its neighbors. After that, the intended receiver will get the RTS and reply with omni-directional CTS. All neighbors that receive either RTS or CTS will update their location information table, deafness table and DNAV. When the sender receives the CTS from the receiver, it sends out special RTS omni-directionally to avoid deafness.

On finishing RTS/CTS handshake, the sender sends DATA to the receiver by using directional antenna in pre-determined direction and CDMA code. When the receiver gets the DATA successfully it replies with ACK directionally.

In the example shown in Figure 5, node D wants to communicate with node C. First, node D checks its location information table to make sure that node C is its neighbor. And it checks its deafness table to see whether node C is engaged in another transmission. When node D knows node C is free, node D sends an RTS omni-directionally in CDMA code 1. When node C receives the RTS, it sends CTS omni-directionally in CDMA code 1. The RTS contains the information for the source node, destination node, CDMA code number for transmission and duration time. The CTS also includes the information of the source node, destination node, CDMA code number for transmission and duration time. Then, the omni-directional antenna will listen to CDMA code 0 to see if there is a special RTS to inform it. When node D receives the CTS, it sends data directionally using its directional antenna. After finishing the data transmission, node C sends an acknowledgement (ACK) message using its directional antenna. Neighbor nodes that receive RTS or CTS will update their deafness table and DNAV.

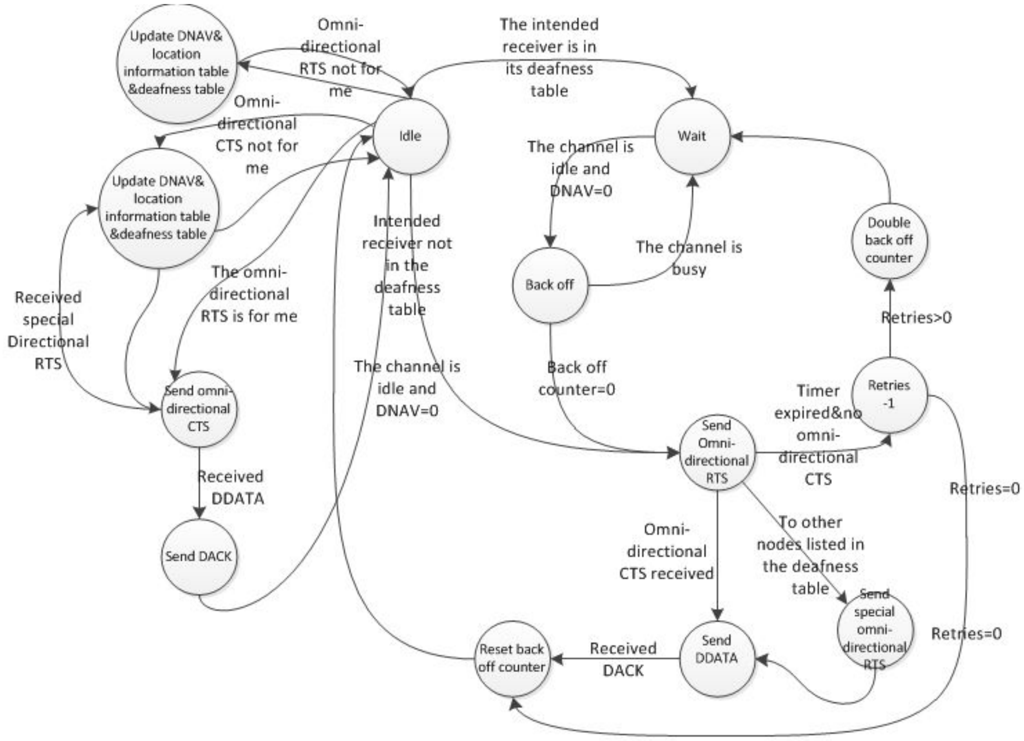


Figure 6. State transition diagram of DF-MAC at every node.

Now, there is an ongoing transmission between node C and node D. At this time, node E wants to communicate with node G. It checks its deafness table and determines that node G is free. It sends RTS in CDMA code 1. Node E knows neighbor nodes C and D are deaf, and it sends a special RTS with CDMA code 0 to node C and node D. This special RTS contains information about the source node, destination node, transmission CDMA code number and duration time. Then node E communicates with node G just like node C and node D. Nodes C and D, in ongoing transmission, receive the special RTS and update their DNAV and deafness table accordingly. Figure 6 shows the state transition diagram of DF-MAC at every node.

V. FORMULATION

In our formulation of DF-MAC, numerous parameters are defined, as shown in Table 6. We utilize mathematical formulations for evaluation. Table 6 shows the parameters that we need in the formulas.

Table 6: Notations for formulation.

Notation	Description	Notation	Description
n	Number of node (variable)	S	Channel utilization by successful transmission of payload bits
p_a	Probability of nodes engaged in transmission (variable)	T_{cycle}	Time between two parts of payload transmission
p	Probability of collision	T_{RTS}	Time to transmit RTS
T_{slot}	Slot time	T_{CTS}	Time to transmit CTS
w	Minimum window size	$T_{S\text{-}RTS}$	Time to transmit special RTS
m	m-*th* contention, the window size can be $2^m \times w$	$T_{physical}$	Time to transmit packet(including headers)
$W_{backoff}$	Backoff window size	$T_{payload}$	Time to transmit payload bits
T_{DIFS}	Time of DCF inter-frame space	$r_{success}$	Rate of successful transmission
T_{SIFS}	Time of short inter-frame space	α	Number of CDMA codes assigned for transmission
T_{ACK}	Time to transmit an acknowledgement (including header)	N_{total}	Number of total transmissions
p_d	Probability of deafness	T_{pd}	Time taken by a node that tries to communicate with a deaf node
T_{si}	Simulation time	$N_{success}$	Number of successful transmissions

First, we assume that $\lfloor p_a \times n \rfloor$ nodes are busy in the ongoing transmission. That means the rest of the nodes $\lceil (1-p_a) \times n \rceil$ do not have packets to send.

$$\begin{aligned} W_{backoff} &= (1-p)\times\frac{w}{2} + p\times(1-p)\times\frac{2\times w}{2} + \cdots + p^m \times (1-p)\times\frac{2^m\times w}{2} + p^{m+1}\times\frac{2^m\times w}{2} \\ &= \frac{1-p-p\times(2\times p)^m}{1-2\times p}\times\frac{w}{2} \end{aligned} \tag{1}$$

$$p = 1 - \left(1 - \frac{2 \times (1 - 2 \times p)}{1 - p - p \times (2 \times p)^m} \times \frac{1}{w}\right)^{n-1} \tag{2}$$

Formula (1) is used to calculate the average backoff window size, and Formula (2) is for calculating the probability of contention. The two formulas are also true in the IEEE 802.11 standard as explained by Tay and Chua [23].

In our proposed DF-MAC, simultaneous transmissions are available. Hence, the probability of contention between nodes changes from time to time. As shown in Figure 7, the number of nodes that contend for Transmission 1 is about $\lfloor p_a \times n \rfloor$ nodes, and then, contention for Transmission 2 is reduced to $\lfloor p_a \times (n-2) \rfloor$ nodes. Afterwards, contention for Transmission 3 is $\lfloor p_a \times (n-4) \rfloor$.

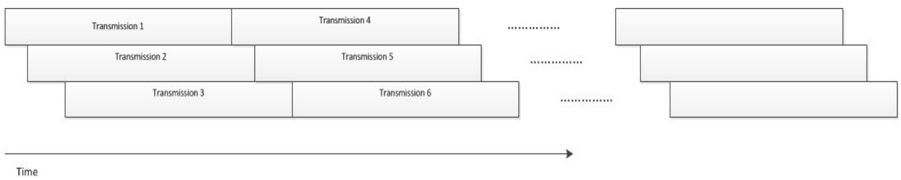


Figure 7. Simultaneous transmissions.

Formula (2) can be represented again by Formula (3). That is, the probability of contention in DF-MAC can be calculated as follows:

$$P = \begin{cases} (1-p) \times \dfrac{2}{\lceil (1-p_a) \times n \rceil + 2} \dfrac{\lfloor n \times p_a - 2 \rfloor}{n-1} & if(\lfloor p_a \times n \rfloor \geq 2 \times \alpha) \\ (1-p) \times \dfrac{2}{\lceil (1-p_a) \times n \rceil + 2} \dfrac{2 \times \alpha - 2}{n-1} & othersise \end{cases} \tag{3}$$

After we get the probability of contention, we can deduce the probability of deafness, p_d, for the existing CDMA-based MAC protocol. The proposed DF-MAC is based on CDMA and will be compared to the existing CDMA-based MAC protocol in order to show the effect of complete deafness freedom in DF-MAC.

$$Pd = \begin{cases} (1-p) \times \dfrac{2}{\lceil (1-p_a) \times n \rceil + 2} \times \dfrac{\lfloor n \times p_a - 2 \rfloor}{n-1} & if(\lfloor p_a \times n \rfloor \geq 2 \times \alpha) \\ (1-p) \times \dfrac{2}{\lceil (1-p_a) \times n \rceil + 2} \times \dfrac{2 \times \alpha - 2}{n-1} & othersise \end{cases} \quad (4)$$

The whole transmission consists of a contention window, RTS, SIFS (Short Inter-Frame Space), CTS, SIFS, special RTS, SIFS, DATA, SIFS, ACK and DIFS (DCF Inter-Frame Space) as described in Figure 8.

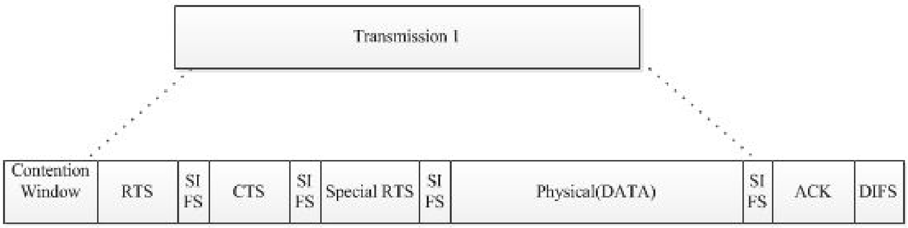


Figure 8. A complete transmission.

$$\begin{aligned} T_{cycle} &= T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{S\text{-}RTS} + T_{SIFS} + T_{physical} + T_{SIFS} + T_{ACK} + T_{DIFS} \\ &+ \frac{w}{\lceil (1-p_a) \times n \rceil} \times T_{slot} \quad (\lfloor p_a \times n \rfloor \leq 2 \times \alpha) \end{aligned} \quad (5)$$

$$\begin{aligned} T_{cycle} &= T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{S-RTS} + T_{SIFS} + T_{physical} + T_{SIFS} + T_{ACK} + T_{DIFS} \\ &+ \frac{w}{n + 2 - 2 \times \alpha} \times T_{slot} \quad (\lfloor p_a \times n \rfloor > 2 \times \alpha) \end{aligned} \quad (6)$$

The total simulation time equals the sum of times from successful transmissions and times from failed transmissions. Here, $r_{success}$ represents the percentage of successful transmissions in total transmissions.

$$T_{si} = T_{pd} \times pd \times N_{total} + (T_{RTS} + T_{SIFS}) \times p \times N_{total} + (1 - pd - p) \times N_{total} \times T_{cycle} \tag{7}$$

$$r_{success} = \frac{N_{success}}{N_{total}} \tag{8}$$

Finally, we get throughput: Formula (9).

$$S = \begin{cases} \left\lfloor \frac{p_a \times n}{2} \right\rfloor \times r_{success} \times T_{payload} & if (\lfloor p_a \times n \rfloor \leq 2 \times \alpha) \\ \alpha \times r_{success} \times T_{payload} & otherwise. \end{cases} \tag{9}$$

To estimate the communication efficiency, we now define the normalized control overhead (NCO) as the ratio of the total size of transmitted control packets over the total size of delivered data packets for a given period of time:

$$NCO = \frac{n_{RTS} \times s_{RTS} + n_{CTS} \times s_{CTS} + n_{S-RTS} \times s_{S-RTS} + n_{ACK} \times s_{ACK}}{n_{DATA} \times s_{DATA}} \tag{10}$$

where n_{RTS}, n_{CTS}, $n_{S\text{-}RTS}$, n_{ACK}, n_{DATA}, s_{RTS}, s_{CTS}, $s_{S\text{-}RTS}$, s_{ACK}, and s_{DATA} are the number of RTS packets, the number of CTS packets, the number of special RTS packets, the number of ACK packets, the number of data packets, the RTS packet size, the CTS packet size, the special RTS packet size, the ACK packet size, and the data packet size, respectively.

VI. PERFORMANCE EVALUATION

A. Simulation Environment

The performance of the proposed DF-MAC protocol is evaluated via MATLAB simulation. Table 7 summarizes the simulation parameters in a static ad hoc network used in our evaluation.

Table 8 summarizes the simulation parameters in a mobile ad hoc network used in our evaluation. Most of the parameters are the same as Table 7. The random waypoint model [24, 25] is used as the mobility model in our simulation. The model operates as follows:

- Each node picks a random destination uniformly within an underlying physical space and travel with a speed v, whose value is uniformly chosen in the interval $\{0, V_{max}\}$;
- On reaching the destination, the node pause for a time period Z; and
- The process repeats itself afterwards.

In the simulation, 100 nodes are assumed to be deployed randomly in a given area, where several anchor nodes have already been placed. These static anchor nodes broadcast their location information periodically.

Table 7: Simulation parameters in a static ad hoc network.

Parameter	Value	Parameter	Value
Network area	500 m × 500 m	Data rate	2Mbps
Transmission rate	4packets/sec	Packet size	512bytes
Transmission power for directional antennas	50mW	Transmission power for directional antennas	20mW
n	0–25 (number of nodes from 0 to 25)	p_a	0.8
w	16,32,64 (minimum window size can be 16,32,or 64)	m	3,5(m-*th* contention in order to calculate the max window size)
Packet payload length	1024 bytes	MAC header length	34 bytes
PHY header length	16 bytes	ACK length	30 bytes
RTS length	64 bytes	Special RTS length	64 bytes
CTS length	64 bytes	$T_{physical}$	8584us;
T_{RTS}	900us	T_{CTS}	900us
$T_{sprcialRTS}$	900us	T_{SIFS}	28us
T_{DIFS}	130us	T_{slot}	50us
T_{ACK}	640us	α	8 (numbers of CDMA codes for data transmission)
T_{si}	100s	T_{pd}	5×(900+28) s

Table 8: Simulation parameters in a mobile ad hoc network.

Parameter	Value	Parameter	Value
Network area	1000m ×1000 m	Data rate	2Mbps
Transmission rate	4packets/sec	Packet size	512bytes
Transmission power for directional antennas	50mW	Transmission power for directional antennas	20mW
Total number of simple nodes	100	Percentage of mobile nodes	10%-100%
Speed of node V_{max}	5 meters/sec	T_{si}	1200s
Packet payload length	1024bytes	MAC header length	34 bytes
PHY header length	16 bytes	ACK length	30 bytes
RTS lengthlength	64 bytes	Special RTS length	64 bytes
CTS length	64 bytes	$T_{physical}$	8584us;
T_{RTS}	900us	T_{CTS}	900us
$T_{sprcialRTS}$	900us	T_{SIFS}	28us
T_{DIFS}	130us	T_{slot}	50us
T_{ACK}	640us	Z	5 s

B. Simulation Results and Discussion

To demonstrate the superiority of DF-MAC, we compare our proposed DF-MAC with the existing CDMA-based MAC protocol [14] and CDR-MAC [13].

Figure 9 shows the contention probability for different numbers of nodes. Contention probability increases in proportion to the number of nodes. As window size increases, contention probability decreases as expected.

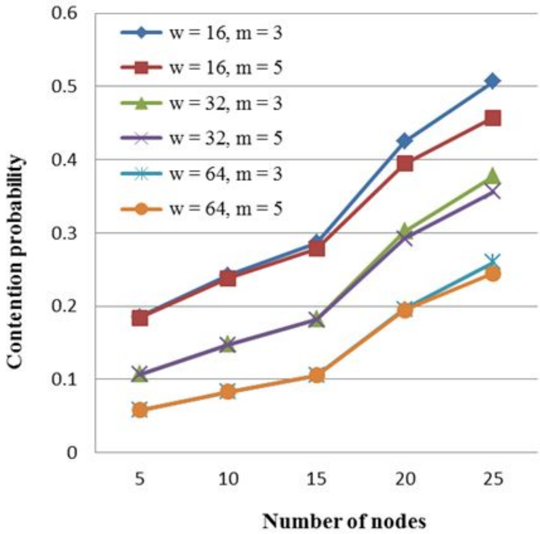


Figure 9. Contention probability.

Figure 10 shows a comparison of the three MAC protocols: the proposed DF-MAC, CDMA-based MAC [14] and CDR-MAC [13], in terms of throughput. As shown in Figure 10, DF-MAC outperforms the conventional MAC protocols. As the number of nodes increases, throughput also increases for DF-MAC and CDMA-based MAC [14].

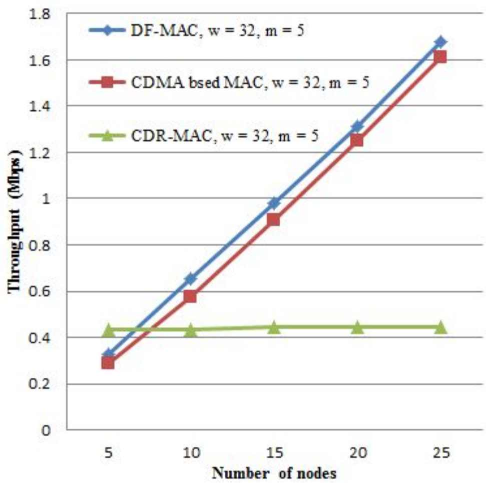


Figure 10. Throughput in a static ad hoc network.

Figure 11 compares the normalized control overhead of the three protocols. The proposed DF-MAC works a little better than CDMA based MAC, but it does much better than CDR-MAC by a factor of at least 6.7. That is because, in CDR-MAC, the sender has to send circular DRTS to all its neighbors, which dramatically increases control overhead. In DF-MAC, the sender sends special RTS to its neighbors, increasing control overhead. However, DF-MAC grantees that no deafness problem will happen in transmission resulting in improved throughput.

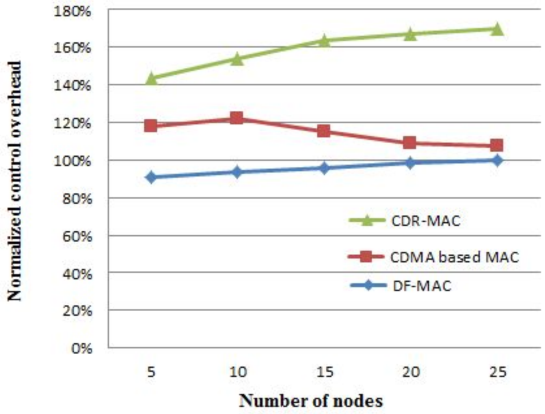


Figure 11. Normalized control overhead in a static ad hoc network.

Figure 12 shows the impact of the probability of deafness on throughput for the three different MAC protocols. When the probability of deafness is low, throughput of DF-MAC is slightly less than that of CDMA-based MAC [14] because of overhead. However, because the probability of deafness is more than 0.1, DF-MAC outperforms CDMA-based MAC [14] more and more. When the probability of deafness is 0.5, DF-MAC achieves almost 65% improvement over the conventional CDMA-based MAC protocol. CDR-MAC [13] does not use the CDMA technique, and thus, its throughput is the lowest among the three protocols. As shown earlier in Table 1, CDR-MAC solves only one type of deafness problem, and thus, its throughput drops inversely as the probability of deafness rises.

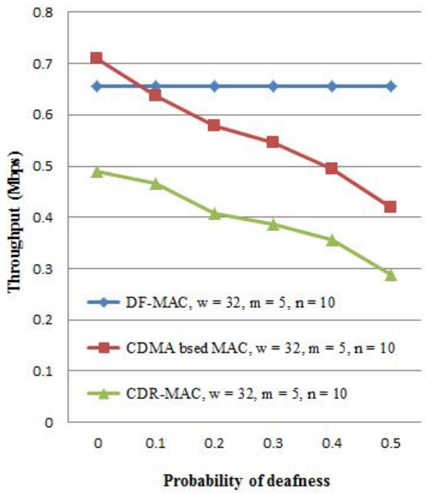


Figure 12. Impact of the probability of deafness on throughput.

To observe the impact of node mobility on network performance, the percentage of mobile nodes is varied from 10% to 100% and the three MAC protocols are compared in terms of throughput and control overhead as shown in Figures 13 and 14. In Figure 13, as the percentage of mobile nodes is increased, the throughput of all three MAC protocols drops. Both CDMA based MAC and DF-MAC significantly outperforms CDR-MAC, and DF-MAC can achieve 28% ~ 140% better throughput than CDMA based MAC. In DF-MAC, the throughput drops sharply when the percentage of mobile nodes is greater than 70%. It should be noted that, even when all nodes are mobile, DF-MAC can achieve 30% more throughput than CDMA based MAC.

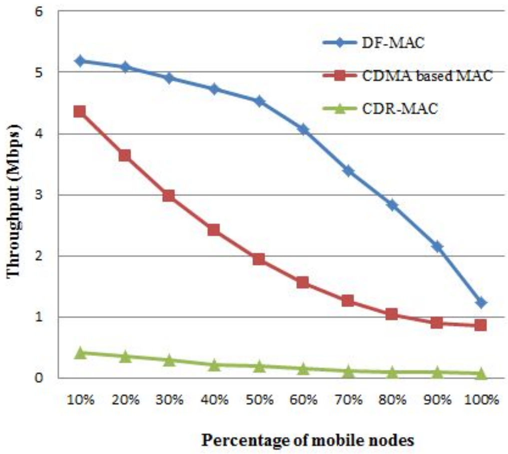


Figure 13. Throughput in a mobile ad hoc network.

Figure 14 represents the normalized control overhead of the three MAC protocols in a mobile ad hoc network. The control overhead of all the protocols inreasces with the increased percentage of mobile nodes. The proposed DF-MAC works best among three protocols. DF-MAC dramatically outpeforms CDR-MAC as clearly shown in the figure. On the average, DF-MAC achieves about 25% less overhead than CDMA based MAC protocol.

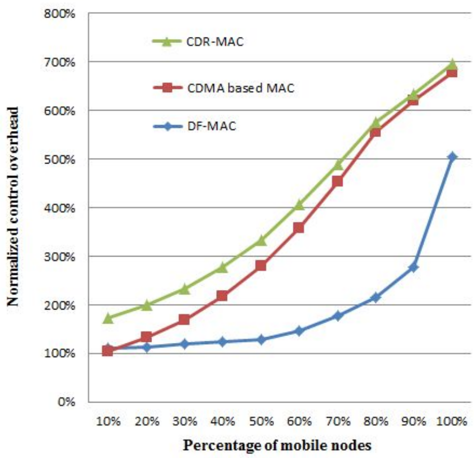


Figure 14. Normalized control overhead in a mobile ad hoc network.

VII. CONCLUSIONS

The utilization of directional antennas can improve network performance to a great extent. However, using directional antennas in ad hoc networks causes a number of problems such as the exposed terminal problem, hidden terminal problem, and deafness problem. All of these problems, if not appropriately handled, will impede network performance. The deafness problem that can degrade network performance often occurs in ad hoc networks using directional antennas. There is no survey that summarizes the way that the MAC protocols address the deafness problem. Therefore, the focus of our work has been to study the MAC protocols that solve the deafness problem and, to compare them with each other with respect to antenna model, radiation pattern, carrier sensing, and back off. Unfortunately, none of the protocols can totally solve all four types of deafness problem. Therefore, deafness remains a serious problem, and deserves future research.

In this thesis, we have proposed a deafness-free MAC protocol called DF-MAC for ad hoc networks using directional antennas. DF-MAC broadcasts RTS/CTS omni-directionally and sends data and ACK directionally. With a simple location information table, neighbors determine whether to transmit or wait to transmit. To the best of the authors' knowledge, the proposed DF-MAC is the first deafness-free MAC that solves all the four types of deafness problem and it supports the node mobility as well. According to our performance study, our proposed DF-MAC significantly outperforms the conventional protocols in terms of throughput and control overhead. For possible future work, we will try to apply DF-MAC to cognitive radio networks with directional antennas.

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