FFT-DMAC: A Tone Based MAC Protocol with Directional Antennas

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***Abstract*—This paper presents the FFT (flip-flop tone) DMAC protocol, a tone based MAC protocol using directional antennas to solve the deafness problem, hidden terminal and exposed terminal problems simultaneously. It uses two pairs of flip-flop tones. The first pair of tone is sent omni-directionally to reach every neighboring node to announce the start and the end of communication, and therefore to avoid the deafness problem. The second pair of tone is sent directionally towards the sender. It is used to solve the hidden terminal problem as well as the exposed terminal problem. Evaluation shows that FFT-DMAC can achieve better performance compared to the 802.11 and ToneDMAC protocol.**

Keywords-MAC;directional antenna; tone.

I. INTRODUCTION

Directional antennas can increase transmission range and reduce the interference by beamforming the radio towards a desired direction, which could significantly increase the MANET capacity. This has been demonstrated in theory [1] and real test bed [2] as well. However, the directional communication also brings some disadvantages and tradeoffs, for example, deafness and new hidden terminal problems such as unheard RTS/CTS [3]-[5]. These kinds of problems may significantly degrade the network performance.

Deafness is caused when a sender fails to communicate to its intended receiver because that receiver has been beamforming towards another direction. This would lead to the situation that the sender continually backs off. Furthermore, the sender's neighbors may defer their communication intention to the sender. The consequences of these phenomena could further propagate throughout the network and cause low performance, unfairness, and deadlock [6]. For the same reason, a node may not hear the RTS/CTS and becomes a hidden node.

Currently, many directional MAC protocols have been proposed to solve these problems, aiming at achieving better usage of wireless media and increase the throughput. As far as we know, these protocols do not solve the deafness problem completely. In this paper, a tone-based directional MAC protocol, called Flip-Flop tone DMAC (FFT-DMAC) is proposed. This protocol is designed to solve the hidden terminal problem, exposed terminal problem and the deafness at once.

The rest of this paper is organized as follows. Section 2 will introduce the related work in solving deafness and hidden terminal problem in the directional MAC protocols. In Section 3, we will outline the antenna model used in this protocol and introduce the characteristic of the tone. The basic idea of FFT-DMAC protocol and its schema are proposed in Section 4. We compare the performance of our proposed protocols with IEEE802.11 and other protocols in section 5. Finally, this paper is concluded in Section 6.

II. RELATED WORK

Generally speaking, directional MAC protocols in MANET can be divided into two categories: CSMA based and tone-based. Many CSMA based directional MAC protocols are similar to IEEE 802.11 [7], but using directional NAV (DNAV) or directional virtual carrier sensing (DVCS) [8] to reserve wireless channel, such as directional MAC (DMAC) [9], Circular-DMAC [10]. These protocols put focus on solving hidden terminal problem, and do not address the deafness problem.

The MMAC protocol [5] uses multi-hop RTSs to establish links between distant nodes and then transmits CTS, DATA, and ACK over a single hop directional link. MMAC puts focus on how to extend the transmission range using directional antenna. Reference [4] classifies the reason that caused deafness problem into four categories. The author proposes two approaches to handle some deafness scenarios by record the knowledge of an intended receiver's location information and ongoing transmissions in sender's neighborhood.

Tone based protocols are originally proposed to solve hidden terminal problem under the omni-directional assumption as in [11][12]. The Dual busy tone multiple access with directional antennas (DBTMA/DA) protocol [13] uses a directional busy tone to avoid collisions, along with the directional transmission of RTC/CTS and data packets. Smart-802.11 [14] uses two busy tone, sender-tone and receiver-tone. Using the busy tone in this protocol mainly focus on enabling a receiver to determine the Direction of Arrival (DOA) of transmission.

ToneDMAC [3] is proposed to alleviate deafness problem. A unique tone is assigned to every node, which is determined by a tone frequency and a duration using a simple static hash

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function. ToneDMAC is similar to DMAC. The difference is that after directional transmission, the sender notifies its neighbors by sending an out-of-band tone, indicating these nodes to choose a new, smaller backoff value to contend for the media. It can partially solve the deafness problem.

III. PRELIMINARIES

A. Directional antenna and antenna model.

A steerable beam antenna which can be directed in any giving direction is applied in this paper. This type of antenna can work in omni-directional and directional modes. If a receiver listens in directional mode, the maximum reception gain G_r will be reached. If a sender transmits in directional mode, the maximum transmission gain G_t will be reached. So the transmission range is different when two neighbored nodes work in different antenna modes.

Normally, directional antennas are used to increase the data communication range from omni-omni (*o-o*) to directional-omni (*d-o*). Although when the receiver and sender both work in the directional mode and beamform towards each other, the maximum transmission range directional-directional (*d-d)* is achieved, but how to inform neighbored nodes to beamform towards each other's direction is a challenge.

B. Transmission, interference, and carrier sensing ranges

The transmission range (R_t), interference range (R_i) and carrier sensing range (R_c) in MANET have been studied in [15]. The R_t and R_c are calculated using the physical parameter of the antenna which are fixed when nodes are stationary. But the interference range is a function of the distance between the sender and receiver and the power level of noise.

Most 802.11 based MAC protocols assume R_t, R_c and R_i are the same. With this assumption, CSMA based virtual carrier sensing (VCS) mechanism can solve hidden terminal problem. However, in real world, R_t, R_c and R_i are different, which results in more hidden nodes and exposed nodes when using RTS/CTS based protocols. This will greatly degrade the performance of MANET.

C. Tone

Tone is a pure sine wave with a particular frequency. It is not a modulated signal, thus cannot contain any information bit. Tone can only be detected (through energy estimation) on the corresponding narrow frequency band [3].

Because the detection of tone only depends on the energy estimation, so in most circumstance, tone can be transmitted at least to the carrier sensing range. Another benefit of using tones is it needs only a narrow bandwidth and does not need particular control packets to synchronization. According to [11], the bandwidth of a tone signal could be in the range of 0.1-10KHZ. The disadvantage of tone is that it needs additional hardware compared with the other approach.

IV. TONE BASED PROTOCOL

A. Basic concepts

When using RTS/CTS based protocols, there are three reasons for the hidden terminal problem with directional antennas. First, CTS sent by the receiver cannot successfully reach the nodes beyond the receiver's R_t. These nodes may become hidden nodes. Therefore, a tone approach is necessary to solve this problem as a tone can be successfully recognized within the carrier sensing range. In order to distinguish who sends the tone, the node id is coded in the tone's frequency, as proposed in [3] with assumption that that a higher layer is capable of assigning consecutive identifier to nodes. Second, a node within the receiver's R_t may still be able to initiate a new transmission as long as it does not interfere with the ongoing transmission but will be blocked by CTS. Third, a node cannot overhear the control message (such as RTS, CTS, Tone) if it is beamforming towards the other direction. Therefore, a node has to be able to overhear control messages even when it is transmitting or receiving data. As a result, it is presumed that every node is enhanced the capability to be able to omni-directionally detect tones even when it is working. The cost can easily be justified as it solves not only the hidden terminal problem but also the deafness problem.

Without being able to continually transmit or monitor control signals, it cannot guarantee the reception of announcement of a busy node. Therefore, other solutions, such as in [3], are proposed to reset the backoff timer by sending a busy tone after the node completes its work. In this way, the deafness problem is only partially solved but repeated transmission of RTS still consumes extra energy and interferes with other nodes. As a complete solution to the deafness problem, either *continually transmitting* control signal or *continually monitoring* control signal is inevitable, hence, calling for an additional device.

There are two possible approaches for a sender to announce its intention to send. The first is to send a directional RTS (DRTS) to reach the *d-o* communication range, with assumption that the sender had a prior knowledge about the receiver's direction and the receiver would listen in its omni-directional mode. The second uses an omni-directional tone without any presumption. The receiver needs a steerable antenna to determine the direction of the sender if needed. The second approach reaches the *o-o* tone range but requires beamforming capacity. Whether a *d-o* data range is longer than an *o-o* tone range or vice verse depends on the antennas used. In this paper, we adopt the first approach.

To solve the exposed terminal problem, a node that wants to notify others about its communication should ensure that it will not block unnecessary nodes. Thus, we control the transmission power of the tone according to the maximum noise that a receiver could tolerate. Hence only nodes that should be blocked will receive the notification.

B. Usage of the tone

This protocol uses two pairs of tones, to solve the deafness, hidden and exposed terminal problems all together.

The first pair of tone, FFT_1, is sent omni-directionally to reach every neighboring node within the carrier sensing range. FFT_1 is used to announce the start and the end of a communication, therefore overcomes the deafness problem.

The second pair of tone, FFT_2, is sent directionally towards the original sender by a receiver. It is used to solve the hidden terminal and the exposed terminal problem.

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The tones are transmitted by the main antenna and received by the capacity of continually tone detection.

C. The FFT-DMAC protocol

We propose a protocol called *Flip-Flop Tone* DMAC (FFT-DMAC) here. It follows a sequence of DRTS /FFT_1^+ /FFT_2^+/FFT_1^+ /DATA /FFT_2^- /FFT_1^- /FFT_1^-. Here, FFT_1^+ and FFT_1^- are a pair to flip flop its own deafness, whereas FFT_2^+ and FFT_2^- are another pair to flip flop its blockage of hidden terminal nodes. It also eliminates needs of duration length announcement for both hidden terminals and deafness. Note that such a duration length announcement involves not only its computation (even not accurate) but also its communication overheads. The detail protocol is shown in Table I.

When node n_A intends to initiate communication to node n_B, it will first check two conditions: i) n_B is not deaf; and ii) there is no ongoing transmission to be interrupted by this intended A2B transmission. If either condition is not satisfactory, n_A backs off, otherwise, it will transmit a directional RTS. On the other hand, if n_B is idle, DRTS will be most likely received at n_B. After that, n_B will send tone FFT_1^+ omni-directionally to inform its imminent deafness. Every neighboring node who receives FFT_1^+ will insert n_B into its deafness nodes list (described later). Node n_B then sends tone FFT_2^+ directionally towards n_A for dual purposes: i) to serve as CTS to n_A; and ii) to inform any potential hidden terminal node in this direction whose future transmission would go exceeding the maximum noise that n_B could tolerate. Tone FFT_2^+'s transmission power is governed by (7). Every node who receives FFT_2^+ will add that information into its ongoing transmission nodes list (described later). Once n_A receives FFT_2^+, it will also send tone FFT_1^+ omni-directionally to inform its imminent deafness. Transmission A2B can then start.

Upon complete of transmission A2B, n_B sends tone FFT_2^- directionally towards n_A for dual purposes: i) to serve as ACK to n_A; and ii) to cancel the previously blocked nodes. It then sends tone FFT_1^- omni-directionally to cancel its deafness. Similarly, once tone FFT_2^- arrives at n_A, tone FFT_1^- will be sent out omni-directionally to cancel n_A's deafness.

In this protocol, every node maintains two lists: *Deafness nodes list* (D-list) and *ongoing Transmission nodes list* (T-list). Generally speaking, D-list includes all deaf nodes that are currently booked with ongoing transmission. When a node intends to initiate a new transmission, it can, with information from its T-list, estimate whether the new transmission will interference with any ongoing transmission.

An element in a D-list contains 2-tuple, $<N_{ID}, T_{expire}>$. The N_{ID} indicates the sender of tone FFT_1^+. The T_{expire} is the current node's local time plus T_{max}, a default constant value by considering the maximum packet size plus overheads. The T_{expire} is used to cancel the deafness in case of tone FFT_1^- never received.

An element in a T-list is 2-tuple, $<T_{expire}$, direction of $FFT_2^+>$. The T_{expire} has the same meaning as in D-list. When a node overhears FFT_2^+, it will add the direction of that tone in its T-list, indicating that there is an ongoing transmission in this direction.

As we mentioned before, FFT_2^+ is sent by receiver n_B to inform only those nodes whose future transmission would interfere n_B's receiving in this direction. In order to do that,

Table I

Every node n_i maintains its local environment data
- D-list(n_i) , T-list(n_i) //deafness node & ongoing transmission list.
- idle(n_i) //initially set to T and set the mode to omni-directional
- intendToSend(n_i) = n_j // n_j= −1 implies no intention to send

As a sender:
upon request to send a packet to node n_j
Set its intendToSend(n_i) = n_j; reset CW_{max}
TRYtoSEND: if idle(n_i) and intendToSend(n_i) ≠ −1 // n_i → n_j
Let destination node n_j = intendToSend(n_i);
if $n_j \notin$ D-list(n_i) and notCollide(n_j, T-list(n_i)) // notCollide is given later
set back-off timer T_B as randomly chosen from (CW_{min},CW_{max})
when T_B expires
if $n_j \notin$ D-list(n_i) and notCollide(n_j, T-list(n_i)) //recheck its readiness
idle(n_i)=F; // busy with sending
beamform to n_j and send DRTS(n_i)
wait for FFT_2^+(n_j) unless timeout
if timeout
let idle(n_i)=T; CW_{max}*=2; goto TRYtoSEND;

As a receiver:
upon arrival of DRTS(n_k) // now n_k → n_i
idle(n_i)=F; // busy with receiving
send tone FFT_1^+(n_i) omni-directionally // inform n_i's deafness
send tone FFT_2^+(n_i) directionally to n_k with power of formula (7)
wait for incoming data packets from n_k unless timeout
if timeout idle(n_i)=T; // back to idle
upon completion of receiving data from n_k
send tone FFT_2^-(n_i) directionally towards n_k// end of n_i's transmission
send tone FFT_1^- (n_i) omni-directionally // inform end of ni's deafness
idle(n_i)=T; // back to idle

As any node, even during transmission or receiving:
upon detection of FFT_1^+(n_k) insert n_k into D-list(n_i)
upon detection of FFT_1^-(n_k) remove n_k from D-list(n_i);
if idle(n_i) and $n_k \equiv$ intendToSend(n_i) goto TRYtoSEND;
upon detection of FFT_2^+(n_k)
if $n_k \equiv$ intendToSend(n_i) // it is the sender
send tone FFT_1^+(n_i) omni-directionally // inform ni's deafness
start data transmission directionally towards n_k
when complete, wait for FFT_2^-(n_k) unless timeout
if timeout
let idle(n_i)=T; CW_{max}*=2; goto TRYtoSEND;
else insert n_k into T-list(n_i)
upon detection of FFT_2^-(n_k)
if $n_k \equiv$ intendToSend(n_i) // transmission to n_k finished
intendToSend(n_i) = −1; idle(n_i)=T; // back to idle
send tone FFT_1^- (n_i) omni-directionally // end of n_i's deafness
else
remove n_k from T-list(n_i);
if idle(n_i) and intendToSend(n_i) ≠ −1 goto TRYtoSEND;
for every T_{max} interval
while ∃ n_k, such that $n_k \in$ D-list(n_i) and T_{expire} is passed
remove n_k from D-list(n_i)
if idle(n_i) and $n_k \equiv$ intendToSend(n_i) goto TRYtoSEND;
while ∃ n_k, such that $n_k \in$ T-list(n_i) and T_{expire} is passed
remove n_k from T-list(n_i)
if any node has been removed from T-list(n_i)
if idle(n_i) and intendToSend(n_i) ≠ −1 goto TRYtoSEND;

procedure notCollide(n_j, T-list(n_i)) // for n_i → n_j
Let ε be beamwidth of antenna in the azimuth plane
Let θ be the direction of $n_i 2 n_j$ in the azimuth plane,
while ∃φ_i , such that $\varphi_i \in$ T-list(n_i) and within the expiration time
if $|\theta - \varphi_i| < \varepsilon$ return false // will interference the ongoing transmission
if any φ_i such that $\varphi_i \in$ T-list(n_i), $|\theta - \varphi_i| >= \varepsilon$ return true // not interfere

we use *the maximum noise that n_B can tolerate* to control the transmission power of FFT_2^+, whose calculation will be illustrated by the following example.

Let P_{t_max} denotes the maximum transmission power for every transmitter. Let $SNR_{threshold}$ denotes the minimum signal-to-noise ratio (SNR) threshold that the signal could be received. Let $CS_{threshold}$ denotes the minimum carrier sensing threshold. We also assume that all antennas have same physical parameters and the channel is symmetric.

Assuming n_A is trying to send data to n_B. The noise that n_B can tolerate (N_t) must satisfy

$$\frac{P_{ab}}{N_b + N_t} > SNR_{threshold} \quad (1) \quad \text{which is: } N_t < \frac{P_{ab}}{SNR_{threshold}} - N_b \quad (2)$$

where P_{ab} is the power level of the signal send from n_A, which is equal to the power level of DRTS received at n_B. N_b is the current noise level at n_B in the direction of n_A, which can be sensed through n_B's antenna.

The maximum noise that n_B can tolerate is given in Formula (3). We start from Two-Ray ground model for mobile radio environments [16] to calculate the power of FFT_2^+. According to this model, the received power at distance d is given by Formula (4).

$$N_r = \frac{P_{DRTS}}{SNR_{threshold}} - N_b \quad (3) \quad P_r(d) = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \quad (4)$$

where P_t is the transmitted power, equals to P_{t_max}. G_a and G_b are the antenna gains. h_a and h_b are the height of both antennas.

Node n_B will send out FFT_2^+ to inform every node within the radius r of n_B in the direction of A2B not start a new transmission. Obviously, when the transmission range of FFT_2^+ reaches r, the signal power should be equal to the $CS_{threshold}$ (6) for other nodes to sense it.

$$r = \sqrt[4]{\frac{P_c G_c G_b h_c^2 h_b^2}{\frac{P_{DRTS}}{SNR_{threshold}} - N_b}} \quad (5) \quad CS_{threshold} = P_b G_c G_b \frac{h_c^2 h_b^2}{r^4} \quad (6)$$

which demands n_B to send out the FFT_2^+ with the power of

$$P_b = \frac{P_c \, CS_{threshold}}{\frac{P_{DRTS}}{SNR_{threshold}} - N_b} = \frac{P_{t\_max} \, CS_{threshold}}{\frac{P_{DRTS}}{SNR_{threshold}} - N_b} \quad (7)$$

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the FFT-DMAC protocol. We consider several scenarios and analyze the factors that impact this protocol. We do not consider mobility here. The packet size in this protocol is 1500B. The data rate is 11 Mbps. CS and RX threshold are 2.5604 e-10 W and 1.2392 e-9 W, respectively.

The directional antenna gain can be represented as ($2\pi/\theta$), where θ is beamwidth [17]. Assuming $r_{directional}$ and r_{ommi} are the transmission ranges in directional and omni-directional modes, respectively, their relation can be expressed in (8).

$$r_{directional} = \sqrt[\alpha]{\frac{2\pi}{\theta}} * r_{omni} \quad (8)$$

The relation of area where the energy can be sensed when using different antenna mode and omni-directional antenna mode can be roughly calculated in (9).

$$S_{directional} = \left(\frac{2\pi}{\theta}\right)^{\frac{2}{\alpha}-1} * S_{omni} \quad (9)$$

Assuming α is 4 when using Two-Ray ground model and θ is 20 degrees. The transmission range in directional model will be 2.06 times as in omni-directional mode and the area where the energy can be sensed in directional model will be 24% of that in omni-directional mode. When the beamwidth decreases，the transmission range will be extended and the carrier sensing area will decrease. To our best knowledge, the minimum beamwidth can be 5° [18].

Figs.1, 2 and 3 show the relationship of the beamwidth of the steerable antenna and the performance of FFT-DMAC protocol. The scenario is 500meters*500meters with 30 nodes randomly distributed in it. With the increase of the θ, more packets drop and the network throughput decreases. When the traffic is heavy, the performance drops faster than that in lighter traffic.

They also indicate that even in FFT-DMAC, MAC collision is inevitable. There are two kinds of the collision, one is the collision of DRTS and the other is the collision of DATA. The former happens more often than the later especially when traffic is heavy where the chance of two nodes get the information of media idle at the same time is high. Accordingly, the chance of starting transmission simultaneously increases.

Whether the tone can be successfully received also plays an important role in the performance of FFT-DMAC. The tones act as CTSs and ACKs and are used to avoid interference and deafness and unnecessary data retransmission in this protocol. Fig. 4 shows the packets received and dropped when tones success rate varies. The beamwidth is set to 20 degrees. The packets received will decrease as the success rate decreases. It is interesting that the number of dropped packets also reduces, which is contrary to the intuition since we use tones to protect the communications. The reason for this lies in two points. The first one is that we use tone as CTS. If this tone is not heard by a sender, the sender will not send the data packet at all. Thus the sender may not be a potential noise source to other nodes. The second reason is that we use tone to notify deafness. When such tone is missed, deafness may occur. But as we know, deafness will cause the prolonged waiting time, not the interference. This again causes the decrease of received packets and then the decrease of dropped packets.

We have implemented ToneDMAC and IEEE 802.11 MAC protocols for comparison. Fixed routing is used.

We compare the aggregate throughput of FFT-DMAC with ToneDMAC and IEEE802.11. We generate twenty different distributions of nodes randomly, and use the average throughput of those distributions and traffic flows to evaluate the performance. The results are shown in Figs. 5 and 6. The performance of FFT-DMAC is much better than 802.11 and ToneDMAC because it can avoid the deafness effectively. ToneDMAC are not efficient because it uses a tone to indicate that the former backoffs are caused by deafness, not the media contention. It prevents more loss to happen after loss has been caused. FFT-DMAC prevents deafness itself. Meanwhile, it can reduce the collision which is caused by the hidden terminal problem and improve the spatial reuse by solving the exposed terminal problem.

VI. CONCLUSION

This paper proposes a tone based DMAC protocol FFT-

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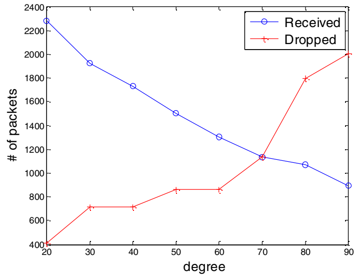

Fig. 1. The impact of θ (3000 pkt/sec)

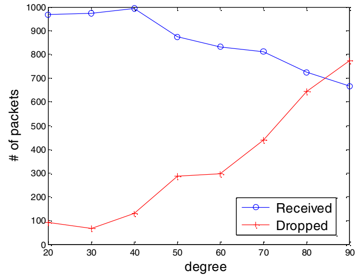

Fig. 2. The impact of θ (1200 pkt/sec)

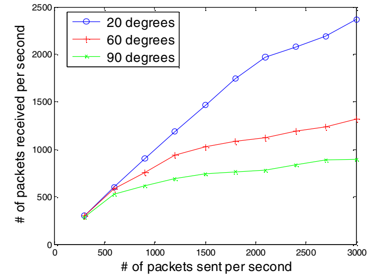

Fig. 3. Aggregate throughput with different beamwidth

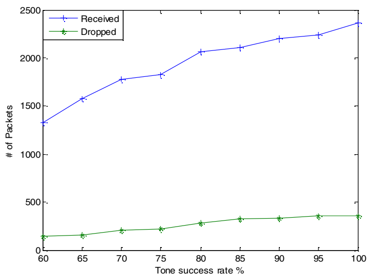

Fig. 4. The impact of different tone success rate

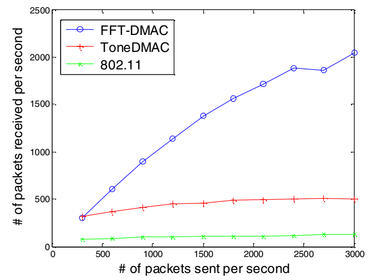

Fig. 5. Aggregate throughput (θ=30 degrees).

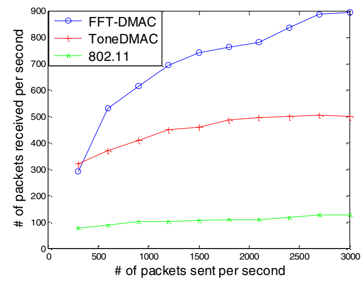

Fig. 6. Aggregate throughput (θ=90 degrees).

DMAC to solve deafness, hidden terminal and exposed terminal problems at once. A separate antenna is demanded to continually monitor control signal. However, it provides a good solution for the deafness problem and can also be used for other purposes, such as the spatial reuse problem. The simulation results show FFT-DMAC can solve those problems effectively.

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