SYN-DMAC: A Directional MAC Protocol for Ad Hoc Networks with Synchronization

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Abstract— **Directional antenna has received intensive research interests in recent years due to its potential to increase communication efficiency and resilience to interference and jamming. In this paper, we provide a novel directional MAC protocol termed SYN-DMAC for ad hoc networks with synchronization. We demonstrate our proposed SYN-DMAC can efficiently address the major open problems in the directional MAC design such as the deafness problem, the hidden terminal problem, the exposed terminal problem and the Head-of-Line(HOL) blocking problem. Preliminary simulation results show that our scheme significantly improves throughput in comparison with IEEE 802.11 MAC protocol.**

I. Introduction

There is an increasing need to provide high-rate, energy efficient, robust and scalable communications in military ad hoc networks as the battlespace is getting more information-centric. Directional antennas technology offers a variety of potential benefits for wireless communication systems. With directional antennas, spatial reuse ratio and antenna gain can be increased substantially; this leads to significant improvement on both throughput and energy efficiency. Moreover, using directional antennas can increase resistance to hostile interference and jamming, and enhance LPI and LPD, much needed in the military communication.

A lot of distributed MAC schemes [2]–[10] have been proposed in recent years. However, the well-known deafness problem [8], the hidden terminal problem and the exposed terminal problem still have not been well addressed. Some of these problems not only affect the local communication efficiency but lead to the ill operation of existing routing protocols (e.g., DSR and AODV) and transport protocols (e.g., TCP). For example, the deafness problem may cause frequent false link-breakage indication to the routing layer and destabilize the end-to-end congestion control.

This paper provides a novel directional MAC framework to address all these challenges. One assumption in our paper is that system-wide synchronization is available. Considering more and more mobile nodes in the heterogeneous ad hoc networks are equipped with GPS receivers, a mobile station can reach system-wide synchronization by receiving GPS signals from the satellites or by other synchronization schemes recently proposed for multi-hop wireless networks [13]–[16]. In this work, we will investigate the potential performance improvement with such synchronization.

The rest of the paper is organized as follows. In the next section, we describe the system model used in this paper. Then we present our scheme and discuss how our scheme addresses the major open directional MAC problems in Section III and Section IV, respectively. In Section V, we evaluate our scheme. Finally, we conclude the paper in Section VI.

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TABLE I
NOTATION

Θ_i	The set of achievable beamforming patterns by node i.
θ_i^j	The beam used by node i to transmit to or receive from node j, $\theta_i^j \in \Theta_i$.
i.mode	The operation mode of node i, which is either "sending" (to transmit DATA at a later phase) or "receiving" (to receive DATA at a later phase) or pending.
Q_i^j	Queue in node i where all packets wait to be delivered to neighbor j.
Q_i^j.length	Length of queue Q_i^j.
Q_i^j.state	State of queue Q_i^j, either "on" or "off" or "pending".
Q_i^j.weight	Weight of queue Q_i^j
$\mathbb{N}_i$	The set of neighbors to node i.
T_1^r	Residual T_1.
T_{cr}	Time for 3-way handshake, which equals RTS+SIFS+CTS+SIFS+CRTS.

II. System Model and Notation

Each node has only one transceiver that transmits/receives signal in the same carrier frequency band. Assume single-beam directional antenna, particularly the switched beam antenna, is equipped in each node, which can generate one high-gain main-lobe beam in a particular direction together with several low-gain side-lobe beams in other directions. As a widely used assumption, each node can run in two operational modes, i.e., omnidirectional mode and directional mode. In other words, each node can dynamically switch between omnidirectional transmission/reception and directional transmission/reception. When a node is in idle state, it runs in omnidirectional mode to receive signal. Some notations used in this paper are shown in Table I.

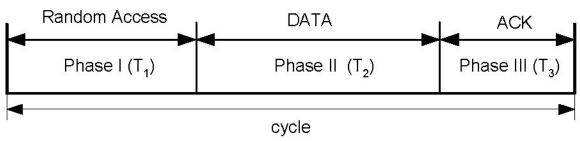

Fig. 1. Timing structure of the proposed SYN-DMAC.

III. Synchronized Directional MAC Protocol (SYN-DMAC)

In this section, we will present our MAC protocol.

A. Timing-structure of SYN-DMAC

The timing structure of SYN-DMAC is shown in Fig. 1. There are three phases in each cycle, random access phase (Phase I), DATA phase (Phase II) and ACK phase (Phase III). The random access phase serves as channel contention (for data transmission) and route discovery (including neighbor discovery). During the random access phase, multiple node-pair [1] may win out; the later winning node-pairs should not collide with previous winning node-pairs. Phase II is for parallel collision-free DATA transmissions; in this phase, each participating node-pair may use different data rate and/or transmission power according to the channel condition; multiple DATA packet transmissions are allowed for each node-pair within the time limit of Phase II. Phase III is for parallel contention-free ACKs; with the accumulated ACK, which acknowledges all the correctly received packets sent by a node-pair in Phase II, one ACK packet is enough for each node-pair.

We note similar MAC timing structure can be found in [12] to address the omni-directional ad hoc networks; the application of which to the ad hoc networks using directional antennas has not been investigated yet.

B. Random access

The high-level flow chart and corresponding protocol specification of SYN-DMAC at phase I are shown in Fig 2 and Fig. 3, respectively.

We mark a node in random access phase as one of three modes, sending mode, receiving mode and pending mode. A node is in pending mode if the node has not decided to transmit data or receive data in phase II; all nodes are marked as pending mode at the beginning of random access phase. A node is in sending mode if the node wins the channel to transmit data. A node is in receiving mode if the node confirms to receive data. Some collision-resolution algorithm like exponential backoff algorithm or p-persistent backoff algorithm is used for contention resolution.

A node which meets several requirements may contend for channel if channel is idle and NAV is zero. First, the node must be in pending mode and the residual time of phase I, denoted as T_1^r, is no less than the time required for exchanging control messages, denoted as T_{cr}; second, the queue state for the intended receiver is pending(the queue state will be marked as off if the intended sender knows that the intended receiver is already in sending mode or receiving mode); third, the intend-to-send beam, which is directed towards the intended receiver, has not been reserved by other nodes (we assume a node knows the intend-to-send beam for a neighbor by a neighbor discovery algorithm [11]). When all these requirements are satisfied, the intended sender will directionally send an RTS to the intended receiver. After receiving the RTS, the intended receiver will check whether it is in the pending mode and whether the intend-to-receive beam, which is directed towards the intended sender, has been already reserved by other nodes; if it is in the pending mode and the intend-to-receive beam is still available, the intended receiver will respond with a directional CTS; upon receiving the CTS, the intended sender will send a directional CRTS (confirmed RTS) to confirm the reservation. Now the intended sender and intended receiver go into the sending mode and the receiving mode, respectively.

[1] A node-pair consists of an intended data sender and an intended data receiver with certain data-transmission direction.

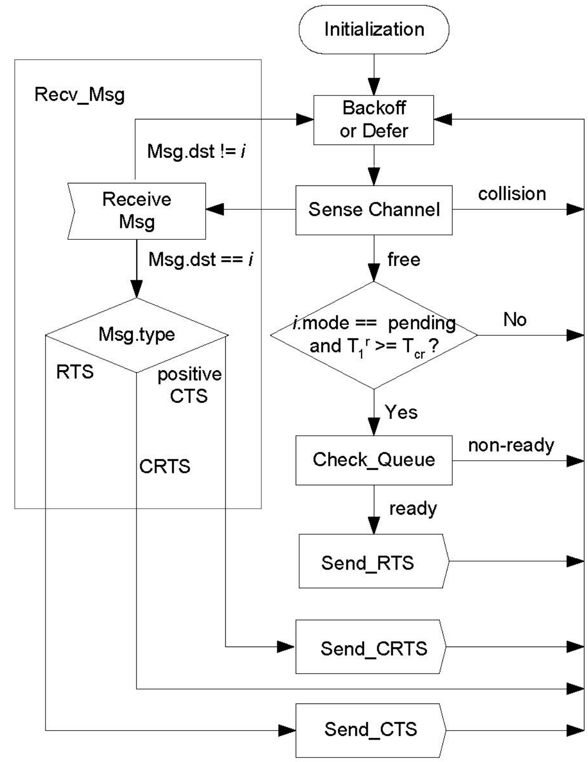

Fig. 2. High-level flow chart of SYN-DMAC at Phase I.

Any other node which hears directional CTS should block the beam directed towards the node sending CTS for intend-to-send; any other node which hears directional CRTS should block the beam directed towards the node sending CRTS for intend-to-receive.

If the intended receiver is not in the pending mode or the intend-to-receive-beam has already been reserved, the intended receiver will reply a negative CTS to indicate the reason. After receiving the negative CTS, the intended sender will either mark the queue for the intended receiver as off or mark the beam directed towards the intended receiver as unavailable.

More details on message processing can be found in Fig. 3.

```
Procedure Initialization
{
  Θ̂_i^a = Θ_i; /*available sending beam*/
  Θ̆_i^a = Θ_i; /*available receiving beam*/
  i.mode = pending;
  for(k ∈ ℕ_i)
     Q_i^k.state = pending;
}

Procedure Check_Queue
{
  ℝ_i = { };
  for( k ∈ ℕ_i)
     if( Q_i^k.length > 0 and θ_i^k ∈ Θ̂_i^a
         and Q_i^k.state == pending )
       ℝ_i = ℝ_i ∪ {k};
  if (ℝ_i != { })
     Return (ready);
  else
     Return (non-ready);
}

Procedure Send_RTS
{
  j = argmax_{k∈ℝ_i} {Q_i^k.weight};
  [Send RTS via beam θ_i^j];
  /*To recv CTS via beam θ_i^j, SIFS after sending RTS */
}

Procedure Recv_CTS
{
  if (CTS is positive)
  {  Q_i^j.state = on;
     i.mode = sending;
     [Send CRTS via beam θ_i^j to
      confirm channel reservation];
  }
  else if (CTS is negative)
  {  if (CTS.reason == receiver_na)
        Q_i^j.state = off;
     else if (CTS.reason == beam_na)
        Θ̂_i^a = Θ̂_i^a − {θ_i^j};
  }
}
```

(a)

```
Procedure Recv_Msg
{  /*j = Msg.src*/
 if (Msg.dst == i)
 {  switch (Msg.type):
    case RTS:
        Recv_RTS;
        break;
    case CTS:
        Recv_CTS;
        break;
 }
 else /*Msg.dst != i*/
 {
   switch (Msg.type):
   case RTS:
        NAV = max{NAV, current_time+CTS+CRTS+2SIFS};
        break;
   case CTS:
        if(CTS is positive or CTS. reason = beam_na)
        { NAV = max{NAV, current_time+CRTS+SIFS};
          Θ̂_i^a = Θ̂_i^a-{θ_i^j};
        }
        break;
   case CRTS:
        Θ̆_i^a = Θ̆_i^a-{θ_i^j};
        break;
 }
}

Procedure Recv_RTS
{  /*j = RTS.src*/
 if(i.mode == pending)
 {
   if(θ_i^j ∈ Θ̆_i^a)
   {  i.mode = receiving;
      [reply a positive CTS to node j via beam θ_i^j];
   }
   else
   { [reply a negative CTS to node j
      via beam θ_i^j with CTS.reason set as beam_na];
   }
 }
 else /*i.mode != pending*/
 { [reply a negative CTS to node j
    via beam θ_i^j with CTS.reason set as receiver_na;]
 }
}
```

(b)

Fig. 3. Protocol Specification of SYN-DMAC at Phase I

IV. Discussion

In this section, we discuss the major open problems in the directional MAC design. These problems include the deafness problem, the hidden terminal problem, the exposed terminal problem, and the HOL blocking problem. We will identify the origin of each problem, evaluate its impacts on the network performance and discuss how our suggested solution SYN-DMAC can help alleviate or eliminate these problems.

A. Address deafness problem

The deafness problem can be defined in various ways but it generally arises when an intended sender fails to communicate with an intended receiver because the intended receiver is beamformed in a direction away from the intended sender [6] [8]. For example, as shown in Fig. 4, node A senses channel is idle and tries to send RTS directionally to node B. However, node B is currently communicating with C by beamforming towards C. With the IEEE 802.11 based timing-structure (RTS/CTS/DATA/ACK) [1], on which almost all the existing schemes are based, node B may take long time to communicate with node C. Since node B cannot reply CTS to node A, node A may falsely think RTS is collided or think node B has moved to another position. If node A assumes RTS is collided, node A may keep transmitting RTS until it succeeds or the retransmission number reaches the maximal retry limit; if node A assumes node B has moved, node A may initiate the neighbor-discovery mechanism to locate node

B before sending RTS again to node B or may initiate re-routing procedure.

The deafness problem can be so severe that it may totally offset the advantages of using directional antennas if left unaddressed [8]. The deafness problem can be alleviated significantly if each node always transmit RTS/CTS omni-directionally and each of its neighbors hearing RTS/CTS is not allowed to contend for channel during other ongoing DATA/ACK transmissions. Unfortunately, the spatial reuse will be hurt significantly if we use omni RTS/CTS while still following the 802.11 timing-structure [3]. In other words, there exists a tradeoff between the deafness problem and the spatial reuse under the 802.11 MAC timing-structure. We note Choudhury and Vaidya proposed a mechanism named out-of-band tone to alleviate the problem. But the out-of-band tone solves only part of the deafness problem yet requires channel splitting and more complex transceiver, it will be more desirable if we can solve the problem using "in-band" solution and solve the problem more completely.

Our proposed SYN-DMAC is such an "in-band" solution that greatly alleviates the deafness problem while keeping high spatial reuse by introducing a novel timing-structure. With our scheme, the time that the deafness will last is compressed to the duration T_{cr}. The high spatial reuse is kept by allowing multiple RTS/CTSs to exchange before concurrent collision-free DATA/ACKs.

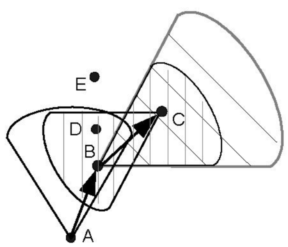

Fig. 4. An illustration of Deafness Problem.

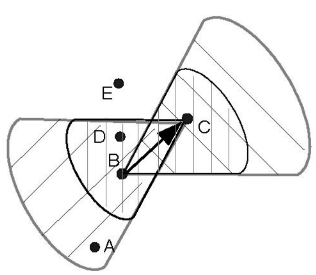

Fig. 5. An illustration of Hidden Terminal Problem.

B. Address the hidden terminal problem due to unheard RTS/CTS

A hidden terminal is a terminal which is not aware of another node-pair's ongoing data communication but whose intended transmission, which could be control messages or DATA/ACK, can make another node-pair's data communication unsuccessful.

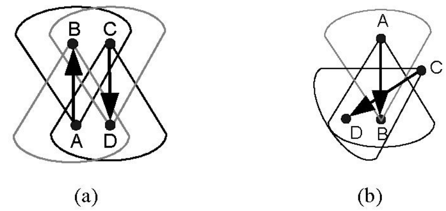

Fig. 6. (a) Exposed Terminal Problem; (b) Joint Exposed Terminal Problem and Receiver blocking problem.

A terminal in the RTS/CTS coverage of another ongoing node-pair could also be a hidden terminal. We call such a hidden terminal as the hidden terminal due to unheard RTS/CTS. A hidden terminal problem due to unheard RTS/CTS cannot be avoided if the directional transmission of RTS/CTS/DATA/ACK and the 802.11 based MAC timing structure are adopted. An RTS/CTS will not be heard by a node in the RTS/CTS coverage when the node was being beamformed away from the node-pair which exchanged the RTS/CTS. For example, in Fig. 5, node D was being beamformed towards node E when node B and node C exchanged RTS/CTS. After node D completes communication with node E, node D wants to communicate with node C even though node C is receiving data from node B, thus causing collision at node C.

SYN-DMAC groups all the control messages and all the data transmissions into two separate phases in each cycle, thus significantly reducing the collisions between control messages and data packets. In addition, the probability that RTS/CTS cannot be heard in SYN-DMAC scheme is much smaller than that under the scheme based on 802.11 MAC timing structure due to the following two reasons. First, all the nodes not exchanging control messages in the phase I of SYN-DMAC observe channel omni-directionally. Second, the time duration in which the RTS/CTS of another colliding node-pair cannot be heard is no longer than T_{cr}, much shorter than that under 802.11 based MAC timing structure (RTS+CTS+DATA+ACK).

C. Address exposed terminal problem

Exposed terminal problem is a problem in which two node-pairs are forbidden to transmit DATA simultaneously even though simultaneous data transmissions and simultaneous ACK transmissions of two node pairs will not collide with each other. For example, as shown in the Fig. 6(a), suppose node A intends to transmit DATA to B and exchanges RTS/CTS in the first place. At the same time, node C wants to transmit DATA to D. Obviously, node A and node C can simultaneously transmit DATA without collision with each other; after both node A and node C complete DATA transmission, node B and node D can simultaneously transmit ACK without collision with each other either. However, if we follow the 802.11 MAC timing-structure, node C should defer its transmission after it hears the RTS/CTS sent by node-pair AB; otherwise, the CTS to be sent by node D may collide with the DATA being received at B, and so on. The exposed terminal problem significantly reduces the spatial reuse.

Here we need to point out another type of exposed terminal problem; we name it as the joint exposed terminal problem and receiver blocking problem. As shown in Fig. 6(b), there is no collision if node-pair AB and node pair CD transmit data simultaneously and then transmit ACK simultaneously. However, if we use 802.11 MAC timing-structure together with directional RTS/CTS and assume each node in idle state runs in omni mode to receive signal, node D cannot reply CTS to node C if node A transmit RTS (then data after receiving CTS from node B) in the first place to node B. The joint exposed terminal problem and receiver blocking problem not only reduces spatial reuse but leads to the same negative effects as the deafness problem (explained in the previous section). Since node C is not aware of local communication activity, it will keep sending RTS to node D even though node D is blocked by the communication between node A and node B.

It is fair to say that those schemes based on the 802.11 MAC timing-structure leave the exposed terminal problem unaddressed. In contrast, our suggested SYN-DMAC protocol well address the exposed terminal problem by a novel MAC timing-structure.

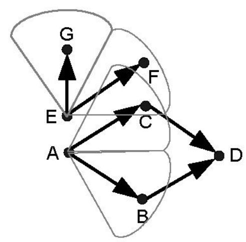

Fig. 7. An illustration of link diversity.

D. Address Head-of-Line(HOL) blocking problem and link-layer fairness

The Head-of-Line(HOL) blocking problem is a well-known problem in the network with the First-In-First-Out (FIFO) queuing service rule. The Head-of-Line(HOL) blocking problem becomes significant in wireless networks with directional antennas. For example, as shown in Fig. 7, when node A captures the channel in the first place for intended transmission to node C, node E can still contend for channel to transmit data to node G rather than node F. However, the channel will be underutilized if the FIFO queuing service rule is applied and the HOL packet of node E is destined to node F.

Our suggested SYN-DMAC protocol avoid the HOL blocking problem with the help of per-neighbor queue management, detailed in Fig. 3. Furthermore, the link-layer fairness could be solved by iteratively updating the weight of each queue and accessing channel based on the weight of each queue. We will investigate the specific queue management algorithm and the channel contention algorithm based on the formulation of fairness in the future.

TABLE II
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Basic rate	2 Mbits/s)	Packet Size	1000(bytes)
PHY header	192(μs)	T_1(4 elements)	3200(μs)
σ	20(μs)	T_1(8 elements)	5600(μs)
SIFS	10(μs)	T_2	4280 (μs)
DIFS	40(μs)	T_3	258 (μs)
RTS	160 (bits)	CTS	112 (bits)
CRTS	112 (bits)	ACK	112(bits)

V. PERFORMANCE EVALUATION

In this section, we demonstrate the effectiveness of our protocol through simulation. We consider a uniform scenario, under which node-pair i is contention-free with node-pair j if mod$(i, M) \neq$ mod(j, M), where M is the total number of beams, i.e., the number of antenna elements. The setting for simulation parameters is shown in Table II.

We compare the performance of our protocol with 802.11. As demonstrated in Fig. 8, the saturated throughput of our protocol with 4 antenna elements can be 2.67 times as much as that under 802.11. In case that the number of node-pairs is less than 4 (i.e., each node-pair is contention free with others), the throughput increases almost linearly with the number of node-pairs. The saturated throughput of our protocol with 8 antenna elements can be 4 times as much as that under 802.11. Similarly, in case that the number of node-pairs is less than 8 (each flow is free of contention with others), the throughput of our MAC increases almost linearly with the number of node-pairs. Note that the throughput of our MAC is less than that of 802.11 when only one node-pair is available; and the degradation is more pronounced when the number of antenna elements is larger. This is because no spatial reuse can be utilized but we fix the value of T_1. For example, in our simulations, we fix $T_1 = 3200\mu$s for 4 antenna elements and $T_1 = 5600\mu$s for 8 antenna elements. We believe the throughput can be increased if the value of T_1 can be adjusted according to traffic and node density in the system. We also notice that the saturated throughput increases with the number of antenna elements, but the slope becomes more gradual as the number of antenna elements increases. This is because the ratio of the duration used for the control messages to the length of data transmission increases with the number of antenna elements.

The non-saturated throughput is shown in Fig. 9. The throughput for each mode (4/8 elements) keeps increasing until it reaches the saturated throughput. We find the maximal throughput will be actually a little bit higher than the saturated throughput. The maximal throughput is reached when the traffic load is slightly less than the saturated traffic load.

VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed a novel directional MAC protocol termed SYN-DMAC for ad hoc networks with synchronization. We demonstrated our proposed SYN-DMAC can efficiently address the major open problems in the directional MAC design and achieve high spatial reuse. Preliminary

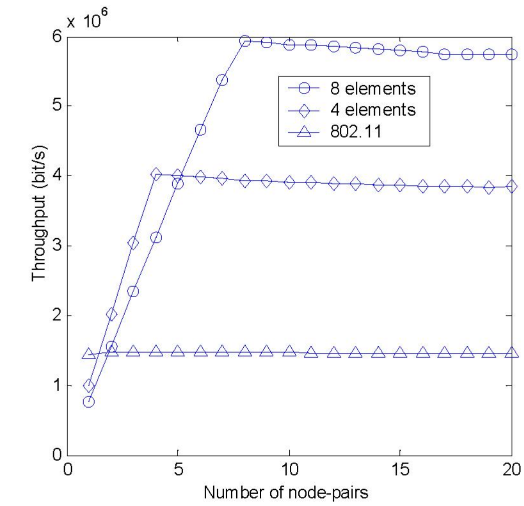

Fig. 8. Saturated throughput in uniformly-distributed topology.

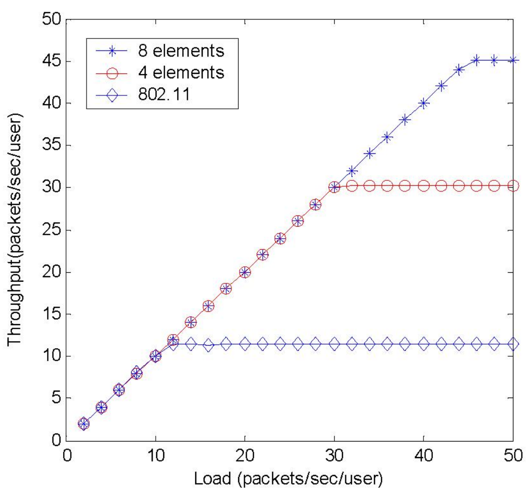

Fig. 9. Non-saturated throughput in uniformly-distributed topology.

simulation results show that our scheme significantly improves throughput in comparison with IEEE 802.11 MAC protocol. In the future, we will detail the link-layer fairness algorithm, enhance the scheme with power control and/or rate adaptation, and present a thorough study of the end-to-end performance of the SYN-DMAC protocol as a function of traffic, node density, mobility, and antenna gain.

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