# ON THE USE OF DIRECTIONAL ANTENNAS FOR SENSOR NETWORKS

Cesar Santivanez and Jason Redi
BBN Technologies, Cambridge, MA
*{csantiva|redi}@bbn.com*

## ABSTRACT

*Directional antennas have been shown to have the potential to provide dramatic increases in throughput and reduction in delay, while simultaneously requiring lower transmit power and increasing LPI/LPD and A/J qualities. Among military systems, sensor systems have a strong need for such characteristics due to their inability to move, length of deployment time, as well as a need for stealth operation. In this paper we describe and analyze significant issues for contention-based MACs for directional antennas which are of particular interest to sensor systems. We also provide a MAC design that overcomes these difficulties.*

## INTRODUCTION

Ad hoc networks provide great advantages to military missions because they require no existing infrastructure and can adapt to changes in topology due to mobility, node loss and node additions. Recent work on ad hoc networks has focused on the use and exploitation of advanced RF technologies. In particular, directional antennas have a number of advantages over omni-directional antennas in ad hoc networking because by focusing energy mainly in the intended direction, they can significantly increase the potential for spatial reuse and provide a longer range and/or more stable links due to increased signal strength and reduced multipath components. Increased spatial reuse and longer ranges translate into higher ad hoc network capacity, and longer ranges also provide richer connectivity. Further, since the spatial signature of the energy is reduced to a smaller area, chances of eavesdropping can be greatly reduced.

Among military systems, sensors typically have strong needs for low probability of detection, jam resistance, and low energy requirements due to their inability to move, yet expected operation over extended periods of time. Directional antenna solutions for sensors do not need to be expensive. Certainly phased arrays and other “smart” systems can have costs that are currently prohibitive for today's sensor systems. However, *switched beam* systems can be constructed using fairly inexpensive off-the-shelf components. Particularly at COTS frequencies such as 2.4 GHz or 5 GHz, switched beam directional systems can be inexpensive, moderately small, and can be provided by well understood hardware with known propagation characteristics.

The purpose of this paper is to consider a number of issues related to contention-based MACs for sensor networks that to our knowledge have not been fully considered in other works. We begin by considering ways that ad hoc networks which utilize directional antennas require a new view for analysis. We continue with a set of problems that limit the capacity of contention based directional antenna MACs, particularly those for sensor networks. We propose solutions to these issues as part of a total MAC algorithm.

## RELATED WORK

One of the first significant works on the use of directional antennas for ad hoc networks was [1]. Many subsequent works have focused on modifications of the existing 802.11 DCF protocol to be able to use directional antennas [2,3,4,5], though none have considered the power gain problems or head of line blocking issues that this paper is focused on.

## ISSUES WITH DIRECTIONAL POWER CONTROLLED MAC

Networks where the nodes use omnidirectional antennas without power control are typically represented by a graph *G(V,E)* , where *V* is the set of nodes and *E* is the set of undirected edges connecting some of the nodes. When transmit-power-based topology control is used, the set *E* needs to be modified to include directed edges, since unidirectional links are now possible. This model captures all the information needed for scheduling packets at the MAC level since all packets are transmitted at the same power and therefore all transmissions are the same.

However, if *per-packet* power control is used and each packet is transmitted at the minimum power required to close the link then the situation is quite different. We can no longer talk about a common channel between a node and all its neighbors. For example, if a transmission to a far away neighbor (high power) is not possible because it will interfere with an ongoing communication, it may be still possible to transmit (with low power) to a close by neighbor. Different channel usage (link-dependent) will result in a different interference pattern. The graph model *G(V,E)* needs to be augmented to capture this fact. An easy

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extension is to consider the network to be a graph *G(V,E,P)* where *V* and *E* are as before and *P* is a set containing the pathloss associated with each link in *E*.

Directional antennas present an even greater challenge to the model. Depending on the antenna pattern and neighbor position, a transmission to a neighbor may or may not cause destructive interference on another neighbor. Particularly without per-packet power control, the advantage of using directional antennas is greatly reduced [1]. Moreover, the amount of interference a node experiences depends on the direction this node is current pointing (i.e. the link it is using). Therefore, interference is determined in a link-pair basis. For example, a node *S* transmitting over its link $l_1$ may cause interference to a neighbor *I* when node *I* is receiving a packet over its link $e_1$, but not when node *I* is listening to its link $e_2$. Thus, the network needs to be represented by a directed graph *G(V,E,M)*, where *V* and *E* were defined before and *M* is an $|E| \times |E|$ interference matrix with an entry $M_{ij}$ set to 1 iff a transmission on the *i*-th link results in destructive interference over a transmission on the *j*-th link.

The fact that we need a different graph representation because the medium is no longer common and unique among neighbors means that contention based MAC functions like carrier sensing and backoff need to be reconsidered: To begin with, simultaneous transmissions in the same region are possible and desirable, and therefore most neighbors can be expected to be busy with transmissions in high traffic load situations. Physical carrier sensing no longer provides enough information to assess the state of a potential receiver, and since simultaneous communications are possible (causing nodes to miss RTS/CTS exchanges) virtual carrier sensing is often not effective either. Moreover, failure to be able to transmit a packet to one neighbor does no longer imply that a packet cannot be xmitted/received to/from another neighbor. Thus, a more appropriate decision upon a transmission failure isn't to retry transmitting the same packet but to briefly allow other nodes to transmit to you. Thus, an architecture where a node regularly transitions to a listening mode upon failed transmission attempts is strongly preferable.

To maximize throughput and minimize delay in a directional antenna system, it may not be efficient for a node *A* wait and retry a packet transmission to the same neighbor *B* if there is a packet to another neighbor *C* waiting in the queue just behind this packet for *B*. Traditional contention-based MACs, though, attempt to completely process (perhaps via retransmissions) a packet at the head of the transmit queue before trying another packet in the queue even if these other packets may be transmitted to other neighbors without causing interference. This situation is referred to as *Head of Line Blocking* (HoL Blocking), due to its similarity to a well-known problem with input-queued switches. Note that a directional radio system can be compared to a switch with multiple inputs and multiple outputs but only the capability to process one packet at a time. Note that this is quite different from the omnidirectional case where there is only one common channel.

For contention-less MACs, such as TDMA, transitioning from a *G(V,E)* to a *G(V,E,M)* model is less involved, since the effect of the matrix *M* is to modify the set of constrains, which used to be implicitly defined by *V* and *E* and now is explicitly defined by *M*. However, heuristics that were effective for *G(V,E)* type of networks, while still working for *G(V,E,M)* networks, may not be efficient. For example, link-scheduling heuristics based on node-degree ordering may not be a good idea for directional systems.

## ISSUES WITH CONTENTION BASED DIRECTIONAL MAC LAYERS

The previous section discussed directional systems from a general point of view. In this section we focus on the problems encountered when designing a contention-based MAC for a single-channel sensor network.

Several reasons motivate a choice for contention-based over contention-less MACs. Traditionally, one considers the fundamental trade-off between throughput and delay: TDMA-like MACs provide greater throughput than CSMA-like MACs, but they typically induce a higher delay under light loads. However, when a directional system is in place, the destructive effect of collisions can be mitigated (if the receiver is pointing in a different direction) and therefore the throughput difference between contention-based and contention-less systems under high load can be reduced. Moreover, addressing the HoL Blocking problem mentioned earlier allows for an even greater throughput under contention-based system, making these types of MACs more attractive. Finally, the bursty nature of data traffic, especially high data rate sessions tend to favor a solution that can deliver on-demand high throughput and low delay for particular sessions, and that can adapt to quick variations in the traffic patterns. So, even though a sensor network may be fairly static in terms of mobility (stable topology), it is likely to be highly dynamic in terms of its traffic requirements. Contention-less MACs, such as TDMA, will fail to satisfy the low delay requirements of such an environment.

We next discuss the main issues that need to be considered when designing a contention-based directional MAC.

### Head of Line Blocking

HoL Blocking is a well-known problem in input-queued switches, which also presents itself in traditional contention-based MACs when applied over radios with directional antennas. It occurs when the destination of the packet at the head of a transmitter queue may be unavailable, therefore causing the transmitter to backoff and retry this same transmission at a later time, meanwhile there are packets for other available nexthop destinations waiting unnecessarily (and wastefully) at the transmitter queue. An alternative is to attempt to transmit these packets before backing off and retrying the transmission for the unavailable destination. This solution is referred to as *HoL Unblocking*.

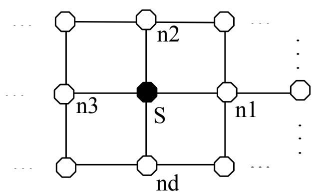



**Figure 1. A regular network of node degree d = 4.**

To assess the impact of the HoL Unblocking solution, consider the network shown in figure 1. This figure depicts a regular network where each node has *d* neighbors (d = 4 in figure 1), the same pathloss to each neighbor, and therefore each packets to each neighbor would be transmitted at the same power.

Furthermore, let's assume that the antenna patterns are narrow enough (and with small sidelobes) such that transmission over any one link does not interfere with any other communication. Also, let's assume that at any given time each nodes as at least one packet for each neighbor queued up for transmission.

Let's define the following events:

- $E^t_{i\to j}$ : At time *t*, node *i* is transmitting to node *j*.
- $B^t_{i|j}$ : At time *t*, node *i* is busy transmitting or receiving to any neighbor except node *j*.
- $CE^t_{i\to j}$ and $CB^t_{i|j}$ : Complements (negation) of events $E^t_{i\to j}$ and $B^t_{i|j}$ respectively.

The events $E^t_{i\to k}$ and $E^t_{j\to k}$ are mutually disjoint for different values of *i,j,k,* and so are the events $E^t_{k\to i}$ and $E^t_{k\to j}$. Furthermore, we will assume that the events $CE^t_{i\to j}$ and $CE^t_{x\to y}$ are independent for $i \neq j$ or $x \neq y$ to facilitate the analysis.[1]

Let nbr(i) denote the set of neighbors of node *i*, nbr(i|j) denote the set of neighbors of node *i* excluding node *j*, and HoL(i) denote the destination of the packet at the head of node *i*'s transmission queue.

This simple model, while is not able to capture the effect of collisions and non-unformity, allow us to assess the relative impact of the HoL unblocking solution by providing upper bounds on their performance. In the remaining of this section we will derive expressions and compare the achievable throughput of systems with and without a HoLunblocking mechanism.

**No HoL Unblocking**

When no HoL unblocking mechanism is present, node S's throughput ($Th^B$) can be computed as:

$$Th^B = \Pr\{E^t_{S\to HoL(S)}\} = \Pr\{E^t_{S\to n1}\}$$

Where we have assumed, without loss of generality, that HoL(S) = n1. Thus,

$$Th^B = \Pr\{ CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S} \cap CB^t_{S|n1}\}$$

Where the first *d* terms represent the condition that at time *t* node *S* is not receiving a packet from any neighbor (including destination n1), and the last term represent the condition that the destination (n1) must not be busy either transmitting or receiving from/to some other node (except *S*). Thus:

$$Th^B = \Pr\{ CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S} \} \times \Pr\{CB^t_{n1|S} \mid CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S} \} \ \ldots \quad (1)$$

Since $CB^t_{S|n1}$ is an intersection of events of the forms $CE^t_{y\to n1}$ and $CE^t_{n1\to y}$ where *y* is a neighbor of *n1* other than node S, recalling our independence assumption we get:

$$Th^B = \Pr\{CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S}\} \times \Pr\{CB^t_{n1|S} \mid CE^t_{n1\to S}\} \quad (2)$$

The first term in eq. (2) can be computed recalling that $\Pr\{CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S}\} = 1 - \Pr\{E^t_{n1\to S} \cup \ldots \cup E^t_{nd\to S}\} = 1 - \Sigma_{i\in nbr(S)} \Pr\{E^t_{i\to S}\}$, where the last equality holds since the events $E^t_{n1\to S}, \ldots, E^t_{nd\to S}$ are mutually disjoint. Also, $\Pr\{E^t_{i\to S}\}$ for any node *i* that is a neighbor of node S, is equal to the probability that the node *i* is transmitting ($Th^B$) times the probability that the current destination is node S (1/d, assuming equally likely destinations). Then, $\Pr\{E^t_{i\to S}\} = Th^B (1/d)$ and

$$\Pr\{CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S}\} = 1 - \Sigma_{i\in nbr(S)} Th^B (1/d) = 1 - Th^B. \quad (3)$$

[1] Strictly speaking, events $CE^t_{i\to j}$ and $CE^t_{x\to y}$ are related specially if any of the nodes *x* or *y* are neighbors of nodes *i* or *j*. In that case, the event $CE^t_{x\to y}$ implies that there is a slightly higher chance that nodes *x* or *y* are transmitting to nodes *i* or *j* which increases the likelihood of the event $CE^t_{i\to j}$. However, it can be seen that $\Pr[CE^t_{i\to j} \mid CE^t_{x\to y}] =$

$$\Pr[CE^t_{i\to j} \cap CE^t_{x\to y}] / \Pr[CE^t_{x\to y}] < \Pr[CE^t_{i\to j}] / \Pr[CE^t_{x\to y}] = \Pr[CE^t_{i\to j}] / (1 - \Pr[E^t_{x\to y}]) = \Pr[C^t_{i\to j}] / (1 - Th/d)$$

where *Th* and *d* are the average node throughput (less than *0.5* since the system is half duplex) and node degree respectively. For typical values of node degree (e.g. 6 to 12), the above expression show little correlation between $CE^t_{i\to j}$ and $CE^t_{x\to y}$ and we can approximate them to be independent.

The second term in eq. (2) can be computed as follows:

$$\Pr\{CB^t_{n1|S} \mid CE^t_{n1\to S}\} = 1 - \Pr\{B^t_{n1|S} \mid CE^t_{n1\to S}\} =$$
$$1 - \Sigma_{i\in nbr(n1|S)} \Pr\{E^t_{n1\to i} \mid CE^t_{n1\to S}\} + \Pr\{E^t_{n1\to i} \mid CE^t_{n1\to S}\}$$

Where the last equality holds since the events $E^t_{n1\to i}$ and $E^t_{i\to n1}$ are mutually disjoint. Now, since:

$$\Pr\{E^t_{i\to n1} \mid CE^t_{n1\to S}\} = \Pr\{E^t_{n1\to i} \mid CE^t_{n1\to S}\} =$$
$$= \Pr\{E^t_{n1\to i}\} \times \Pr\{CE^t_{n1\to S} \mid E^t_{n1\to i}\} \ / \ \Pr\{CE^t_{n1\to S}\}$$
$$= \Pr\{E^t_{n1\to i}\} / \Pr\{CE^t_{n1\to S}\} = \Pr\{E^t_{n1\to i}\} / (1 - \Pr\{E^t_{n1\to S}\})$$
$$= (Th^B/d) \times 1/(1 - Th^B/d) = Th^B/(d - Th^B)$$

(where we used the fact that the event $E^t_{n1\to i}$ implies the event $CE^t_{n1\to S}$ for all $i \neq S$). Then:

$$\Pr\{CB^t_{n1|S} \mid CE^t_{n1\to S}\} = 1 - 2(d-1)Th^B/(d - Th^B) \quad (4)$$

Replacing (3) and (4) in (1) we obtain the following expression for the throughput of a directional system suffering from HoL blocking:

$$Th^B = (1 - Th^B)\,[1 - 2\,(d-1)\,Th^B / (d - Th^B)\,] \quad (5)$$

The solution to the above equation for different values of *d* is shown in Figure 2. As *d* grows, eq. (5) approaches to the equation x = (1-x)(1-2x), whose valid solution (<1) is equal to $1-\sqrt{2}/2 = 0.2929$. Thus, the throughput achievable under the HoL blocking scenario can be at most around 30%.

**HoL Unblocking**

When the proposed HoL unblocking mechanism is present, node S's throughput ($Th^U$) can be computed as the probability that at time t node S is able to transmit to *any* of its neighbors. Since it is assumed that node S always has at least one packet to transmit to each of its *d* neighbors, node S will always be transmitting (one packet) at time *t* provided that none of its neighbors is transmitting to him and at least one of its neighbors is not engaged in a communication (transmitting or receiving) with another node (other than S). Thus:

$$Th^U = \Pr\{CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S} \cap (CB^t_{n1|S} \cup \ldots \cup CB^t_{nd|S})\}$$
$$= \Pr\{CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S}\} \times$$
$$\Pr\{CB^t_{n1|S} \cup \ldots \cup CB^t_{nd|S} \mid CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S}\}$$
$$= (1 - Th^U) \times (1 - \Pr\{B^t_{n1|S} \cap \ldots \cap B^t_{nd|S} \mid CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S}\})$$

Where the last equality was obtained by replacing $Th^B$ by $Th^U$ in eq. (3). Now, it should be noted that the events $B^t_{i|S}$ $B^t_{j|S}$ are, in general, correlated since nodes i and j may be neighbors or may share a common neighbor, and therefore node i's business may have an impact in node j's ability to transmit. However, for simplicity and due to the small impact of this correlation in the overall throughput computation we will assume the above events to be independents. Thus, we obtain:

$$Th^U = (1 - Th^U) \times$$
$$(1 - \Pi_{i\in nbr(S)} \Pr\{B^t_{i|S} \mid CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S}\}) \quad (6)$$

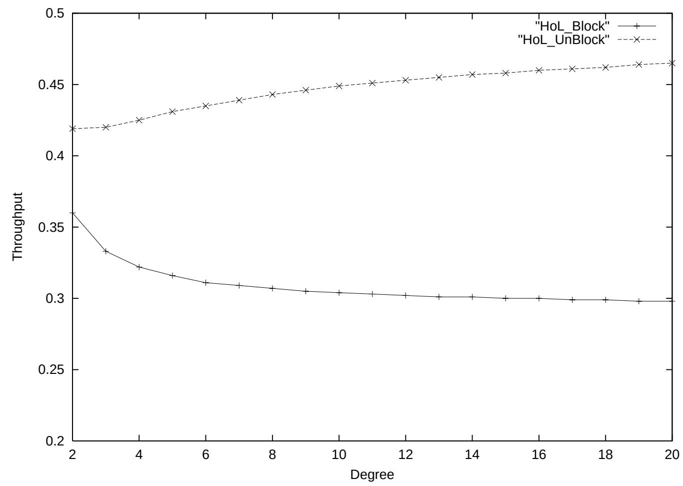



**Figure 2. Achievable throughput with and without HoL Unblocking mechanism in place.**

Now, since

$$\Pr\{B^t_{i|S} \mid CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S}\}) =$$
$$= 1 - \Pr\{CB^t_{i|S} \mid CE^t_{n1\to S} \cap \ldots \cap CE^t_{nd\to S}\})$$
$$= 1 - \Pr\{CB^t_{i|S} \mid CE^t_{i\to S}\} = 2(d-1)Th^B/(d - Th^B) \quad (7)$$

Where the second inequality holds due to the independence assumption, and the last equality results from replacing $Th^B$ by $Th^U$ in eq. (4). Finally, replacing eq. (7) in eq. (6) we obtain the equation for the throughput when the HoL Unblocking mechanism is in place:

$$Th^U = (1 - Th^U) \times \{1 - \Pi_{i\in nbr(S)}\, [2(d-1)Th^B/(d - Th^B)]\}$$
$$= (1 - Th^U) \times \{1 - [2(d-1)Th^B/(d - Th^B)]^d\,\} \quad (8)$$

Eq. (8) can be solved numerically. The results for different values of *d* are shown in Figure 2. As *d* grows, $Th^U$ approaches to 0.5. Comparing with the case where no HoL Unblocking is engaged, we can see that the HoL Unblocking mechanism increases the achievable throughput from around 0.3 to around 0.5, that is a 66% increase in achievable throughput.

It should be noted that a throughput of 0.5 is the maximum possible value for a single channel (half duplex) system. Traditionally, such throughput can only be achieved by contention-less (e.g. TDMA) schemes. Thus, the HoL Unblocking solution recovers some of the capacity lost due to contention-base access. However, RTS/DATA collisions still limit the capacity of a contention-based system. Attempts to avoid the likelihood of such collisions result in employing a higher average transmit power than what would be required in a TDMA system, as explained in the next subsection. Thus, the use of higher transmit power in a contention-based MAC may result in reduced spatial reuse and throughput with respect to a contention-less system. In the next subsection we address this issue.

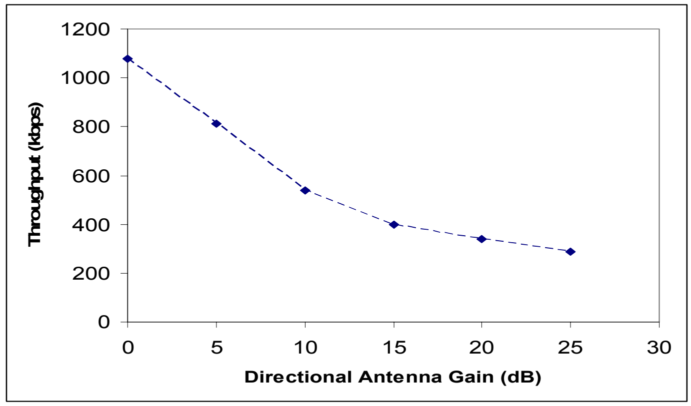
*Higher average transmit power due to need of a high-power bootstrapping packet (RTS)*

Contention based approaches are based on a sending node only being assigned time on the channel when a packet is ready for transmission. If one assumes that we typically cannot adequately predict packet flows, a receiver will therefore not know when a packet is about to be transmitted to it. In a system with directional antennas, all nodes which are not immediately attempting to transmit can therefore consider themselves to be potential receivers of a packet from any other neighbor. This forces each sensor node to use an omni-directional antenna pattern while *idle.* Even if we combine multiple directional antennas to create an omni-directional function, we will still wind up having less than directional gains in all directions due to combining losses of multiple out-of-phase signals and attenuation from the combining hardware.

When a transmitter *S* sends an unannounced packet to a receiver *R*, *S* must use greater transmit power than would be used if *R* was using a directional antenna for reception. The additional power needed is the difference between the omni-directional and directional antenna gains, plus some margin to take into account any off-boresight pointing of the directional antenna. This unannounced packet could either be an RTS (in the case of an RCDA exchange) or a Data packet (in the case of just a data/ack exchange), but it would be preferable from an energy conservation and LPI/LPD point of view to use an RTS since that would allow the presumably longer data packet have the gains of a directional antenna used at the receiver end as well.

Since this additional RTS margin may often be greater than the pathloss to another node, it is not unlikely that transmitter *S* will send an RTS packet that is received a nodes beyond *R* that *S* is not even a neighbor of. More importantly, this provides an opportunity for this RTS to collide with other packets.

As an example of this effect, we ran a simulation in OPNET of a 20 node sensor network, where each node was collinear on a line. The nodes were spaced apart with a distance based pathloss model such that they could discover their neighbors using their 0dB omni directional antennas, but not overhear any other nodes other than their 2 neighbors when using their omni-directional antennas. The networking protocol was a proactive link state style of protocol, but given that the network is static, the protocol overhead is an insignificant part of the over-the-air traffic. We provided the network with 30 seconds at the beginning of the simulation to insure convergence, and then sent traffic a rate that far exceeded the capacity of the network. Sources and destinations for the traffic were chosen from a uniform random distribution. Although the network was formed with omni directional antennas (using broadcast heartbeats), the unicast data was transmitted with an RTS/CTS/data/ACK exchange, where the RTS was transmitted directionally, but received omni while the other packets were transmitted and received with directional antennas. We varied the gain of the directional antenna over the x-axis from 0dB (same as omni) to 25dB, and all pointing was assumed to be perfectly correct. Power control was performed to keep the transmit power levels as just above the amount needed for reception.




The summary of this figure is that in particular topologies of ad hoc networks, increased directional antenna gain does *not* provide an increase in throughput, but in fact can create dramatic *reductions* in overall throughput. Of course, the particular topology we chose is one of the best for showing off this effect, but it should be noted that many sensor networks are deployed in exactly this topology, particularly when monitoring at a roadside.

Of course, it is possible to add a margin into the transmission of the data, CTS, and ACK packets in order to reduce the likelihood that noise or collisions from an overly-powerful RTS will become an issue. However, this will clearly further reduce the overall throughput since we are reducing the advantages that we gain from power control that have shown to be critical in [1].

## A CONTENTION-BASED DIRECTIONAL MAC FOR SENSOR NETWORKS

Our MAC is an extension to the Directional MAC (DMAC) designed and implemented on the UDAAN project [6] as part of DARPA's FCS Communications program. DMAC was demonstrated in January and September of 2002 at government defined 20-node field trials [6]. Our extensions to DMAC were driven to address the main issues discussed in this paper as well as a plethora of implementation issues related to the use of low-cost hardware for sensor networks (long switching times, sidelobes, low front-to-back ratio, etc.) that have not been discussed here due to size constraints.

DMAC is a CSMA-based MAC using a RTS/CTS/data/ACK exchange. The point of the RTS/CTS is not to provide a means for virtual carrier sensing as with omni networks, but to bootstrap the communication process instructing the receiver to point to the transmitter and to negotiate the required transmission power. Carrier sensing is performed directionally. All packets are transmitted and received directionally with the exception of the RTS packets which are received omnidirectionally. When DMAC has a packet to send, it points in the direction of the receiver and perform carrier sensing. If the carrier is free (indicating it will be able to receive an answer) it sends the RTS at the minimum power to close the link plus a margin and waits for a CTS. The minimum power is determined by previous exchanges. Upon reception of a CTS, the transmitter sends the DATA packet once again at the minimum power plus a margin. As mentioned in the previous section, the minimum required power for sending the CTS is smaller than in the RTS case since the receiver is now pointing to the transmitter.

A significant characteristic of this DMAC is the way it performs back-offs. After any transmission attempt (successful or unsuccessful) the MAC enters a so called forced-idle state, which it listens for incoming packets on an omni directional antenna. The introduction of this forced-idle state prevents deadlocks from occurring when most of the nodes are attempting to transmit so that none are listening for incoming packets. There are three reasons for a back-off, which each provide a different modification to the back-off time: When *carrier busy* occurs, the goal of the backoff is to give time to other nodes to transmit to the node backing off. For a *no CTS* failure the assumption is that the receiver is busy and therefore we should back-off for a time comparable with a packet's transmission time (quite different from the assumption of RTS collisions and the need for congestion control). A *no ACK* failure is assumed to be caused by RTS/data collisions resulting from the aggressiveness of DMAC under high load, and therefore the back-off timer is set to stabilize the traffic load by means of an exponentially increasing back-off window.

This sensor DMAC extends the original FCS DMAC to include the HoL Unblocking solution. Basically the NAV table is checked before a packet is picked for transmission attempt. Only those packets with non-busy destinations are considered. Moreover, before entering the force-idle state a node will try to transmit any packet in the queue destined to another non-busy neighbor. Only after all neighbors have been attempted will a node go into the forced-idle state.

Another important improvement over DMAC is the setting of *rendezvous* times to alleviate the problem of high-power bootstrapping packets (RTSs in our case). Basically, the MAC header was extended to include a *rendezvous time* field. The transmitter set the *rendezvous time* to the time it expects to transmit the next packet to the same destination. The destination then is able to point to the transmitter at the specified *rendezvous time*, thus avoiding the requirement of a higher power RTS. Note that setting the rendezvous time is not a guarantee of conflict-free transmissions. Also, more than one transmitter may sign up for the same rendezvous time. In these cases, the receiver chooses one of the neighbors to tune to, so that simultaneous transmissions do not result in collisions (no packet is received) but they results in one packet being received while the others are ignored.

The transmitter sets the rendezvous time by using a Kalman style of filter to estimate the time to the next packet transmission. This filter uses past history and the number of packets on the queue to make its estimation. Also, if the quality of the prediction is poor (as determined by the filter estimation error) or if the predicted time is too far into the future (that nodes may run into synchronization problems due to differences in their internal clocks) no rendezvous time is set.

## SUMMARY AND CONCLUSIONS

In this paper we first considered the ways that directional antenna systems change the theoretical model of MAC interactions between nodes. We overviewed two significant issues in the design of contention-based MACs, which are particularly significant for sensor systems. We then proposed a new MAC, based on a previously implemented MAC that overcomes these problems and theoretically can achieve TDMA levels of throughput efficiency for many topologies and traffic loadings.

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