

On the Channel Reservation Schemes for Ad-hoc Networks Utilizing Directional Antennas

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Abstract

In this paper, we introduce a novel CSMA/CA-based reservation scheme that improves the multiple access throughput of wireless ad-hoc networks using switched beam antennas. First, we show the performance limitations of the omni-directional and directional reservation paradigms investigated in the literature. This is done via emphasizing the trade-off between minimizing the number of control/data packet collisions and minimizing the number of neighbors that back-off unnecessarily. Next, we propose a novel concept that balances this trade-off via sending reservation messages, that carry information about the intended direction of transmission, on all unblocked beams. The innovation in this approach is to send directional information to as many neighbors as possible in order to better assist them in deciding whether to transmit or refrain from transmission on a specific beam. Finally, the algorithm is examined via simulations and compared to the omni-directional and directional reservation approaches.

Keywords

Wireless ad-hoc networks, directional antennas, channel reservation, CSMA/CA, IEEE 802.11.

INTRODUCTION

One of the major contributors to capacity limitations in cellular and wireless ad-hoc networks is the broadcast nature of omni-directional antennas. The distribution of energy in directions other than the intended direction causes considerable levels of multi-user interference at neighboring receivers. This, in turn, constitutes a major hurdle towards efficient utilization of the scarce wireless bandwidth. Coordinating the transmissions of contending users may be done in the time domain (TDMA), frequency domain (FDMA) or spatially via the use of directional antennas. Recently, there has been overwhelming evidence that directional antennas enhance the capacity of cellular [1-3] as well as wireless ad-hoc networks [4-10]. This is mainly due to the following features unique to directional antennas: i) Interference reduction and ii) Transmission range extension.

Several MAC protocols for ad-hoc networks using directional antennas have been proposed in the literature [4-10]. The work in [4] introduces a performance analysis study that shows the impact of directional antennas on the

performance of slotted aloha. In [5], the authors introduce a multiple access protocol that minimizes interference by using a group of tones to identify active neighbors. The reservation schemes in [6-9] modify the RTS/CTS handshake mechanism to exploit the interference reduction feature of directional antennas. The common aspect among these studies is that they all use combinations of omni-directional and directional reservation messages. However, they fail to balance the trade-off pointed out in this paper. The studies in [6-8] consider *switched beam antennas* that consist of several fixed, predefined, beams formed usually with antenna arrays [11]. In [9,10] both switched beam as well as steerable antennas are considered. In [10], very narrow beam-widths are assumed. However, this assumption may not be practical, due to frequency band and data rate constraints. The RTS/CTS handshake mechanism is employed primarily for neighbor discovery.

Our main contribution in this paper is to answer the following question: How to develop a channel reservation scheme that optimizes the trade-off between minimizing the number of neighbors unnecessarily blocked from transmission and minimizing the number of collisions due to neighbors unaware of an on-going transmission? Unlike previous work, we believe that the focus should be shifted from sending reservation messages to a subset of neighbors (due to their geographical location) to sending reservation packets carrying directional information to as many neighbors as possible. We propose a novel reservation scheme that sends reservation messages, carrying information about the beams used during reservation and DATA/ACK transfer phases, to as many neighbors as possible in order to better assist them in knowing their locations relative to the transmitter-receiver pair and hence decide whether to transmit on a specific beam or not.

The paper is organized as follows: in the next section we introduce the underlying assumptions. Next, we show the trade-off that motivates this work. This is followed by a description of the proposed reservation scheme. Afterwards, performance results and discussion are provided. Finally, the conclusions are drawn.

ASSUMPTIONS AND DEFINITIONS

We consider an ad-hoc network consisting of n nodes that can communicate only via the wireless medium. We assume that each node is supported by a fixed number (B) of switched beams, each of width $2\pi/B$ radians. In addition, we assume that nodes receive omni-directionally, *i.e.* signals received by all beams are combined, via diversity

combining techniques [11], in order to combat multi-path fading and scattering effects. Furthermore, unlike previous work, we assume that a node lying in the direction of a neighbor's DATA/ACK transmission, would be blocked from transmission on all its beams. Otherwise, this node, which would act later as a receiver for data or ACK, would suffer considerable interference levels while combining signals from all beams due to multi-path fading. In an open environment where multi-path is not a challenge, this conservative assumption may be relaxed (*i.e.* you may unblock all beams except the one pointing towards the transmitter). We limit our attention to the case of nodes supported with fixed switched beam antennas in order to focus on the trade-off. Introducing reservation schemes for more complex and expensive steerable antennas that support mobile tracking and direction of arrival estimation is out of the scope of this paper and is a subject of future research. Finally, we assume that each node, i , has the following information about its neighbors (provided by neighbor location discovery (NLD) schemes): i) The identities of all neighbors of node i , stored in the vector $N(i)$ and ii) The identities of neighbors that lie within the coverage of beam j onboard node i , stored in the vector $DN_i(j)$. Each node is expected to keep an updated version of these data structures along with the status of each beam (blocked/unblocked). Hence, by the end of the NLD phase, each node is supposed to know *which beam to use in order to reach a specific neighbor*. Introducing specific NLD algorithms that efficiently utilize the range extension feature of directional antennas is out of the scope of this paper and is a subject of future research.

OMNI-DIRECTIONAL VS. DIRECTIONAL RESERVATION

In this section, we show that the RTS/CTS channel reservation packets should not be transmitted in the direction of the intended neighbor only, they should be transmitted in all unblocked directions. This is motivated by the need to notify the maximum number of neighbors of the expected transmission (in order to minimize collisions) while at the same time inform them of the intended DATA/ACK directions of transmission (in order to minimize the number of nodes unnecessarily blocked from transmission in non-conflicting directions).

The following examples illustrate the trade-off. We denote the set of nodes within the geographical area covered by the transmission radiation patterns of all beams at node x as $N(x)$. This set can be partitioned into two subsets, namely *unblocked neighbors* and *blocked neighbors*, depending on their awareness of the ongoing reservation process carried out by node x . A neighbor is said to be blocked if and only if at least one of its beams is blocked from transmission due to overhearing a reservation message. On the other hand, a neighbor is said to be unblocked if it does not hear any reservation message, and hence, is completely unaware of the ongoing reservation attempt. Unblocked neighbors could initiate a reservation request independently and hence cause interference

(collisions) to the ongoing transmission. We denote the sets of blocked and unblocked neighbors as $BN(x)$ and $UBN(x)$ respectively. The objective is to optimally partition the set of neighbors, $N(x)$, into blocked and unblocked groups depending on their location with respect to the transmitter, their required direction of transmission and the direction the transmitter intends to use for sending data or ACKs.

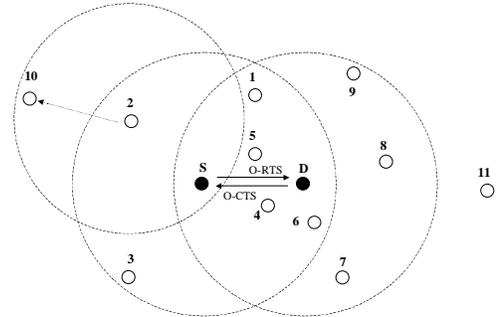


Figure 1. Omni-directional Reservation

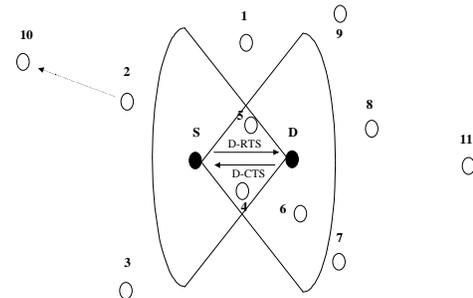


Figure 2. Directional Reservation

In the communication scenario shown in Figure 1, we consider the conventional CSMA/CA protocol where the reservation messages are exchanged omni-directionally between S and D. We refer to this case as “*omni-directional blocking*”. It is straightforward to notice that the neighbor sets of nodes S and D are given by $N(S) = \{1, 2, 3, 4, 5, 6, D\}$ and $N(D) = \{1, 4, 5, 6, 7, 8, 9, S\}$ respectively. Furthermore, $BN(S) = N(S)$, $UBN(S) = \Phi$, $BN(D) = N(D)$ and $UBN(D) = \Phi$. This is due to the fact that the reservation packets are sent in all directions and hence all neighbors become aware of the ongoing transmission and refrain from transmission. This degrades the multiple access throughput due to the possibility of blocking neighbors unnecessarily.

On the other hand, we examine the other reservation extreme where reservation messages are exchanged between S and D in a directional manner (D-RTS/D-CTS) [8] as illustrated in Figure 2. We refer to this approach as “*Directional blocking*”. In this case, we do not consider the range extension feature of directional antennas, *i.e.* the set of neighbors reached omni-directionally is assumed to be equal to the union of the sets of neighbors reached by each

beam individually. This is mainly due to the fact that omnidirectional transmissions are achieved by transmitting on all beams simultaneously. In this case, it is straightforward to notice that $BN(S) = \{4,5,6,D\}$, $UBN(S) = \{1,2,3\}$, $BN(D) = \{4,5,S\}$, $UBN(D) = \{1,6,7,8,9\}$. Clearly, there is a trade-off, between the possibility of collisions caused by unblocked neighbors and the number of unnecessarily blocked neighbors, associated with the directional reservation approach. Thus, a neighbor knowing about an ongoing transmission may degrade performance (e.g. node 2 sending to node 10, or node 8 sending to 11), while another neighbor not knowing about an ongoing transmission could degrade performance as well, because of the possibility of collisions (e.g. node 2 sending to node S, or node 6 sending to D). This trade-off can not be solved by these two extremes or the approaches proposed in [6-8], which use combinations of omnidirectional and directional reservations. The work in [9] has previously pointed out this trade-off, however, no specific solutions were proposed. Therefore, we introduce a new concept that is motivated by the following unique observations: i) All neighbors of the source and the destination should be aware of the intended transmission, if possible and ii) Antenna blockings should be based on the information included in the RTS/CTS packets, not on the mere event of receiving or not receiving a reservation packet.

PROPOSED RESERVATION SCHEME

According to the previous discussion, we propose to include information about the “*current*” and “*intended*” directions of transmission in the reservation packets. Therefore, we add two fields that carry the index of the directional beam currently being used during the channel reservation phase and the index of the directional beam intended to be used during DATA/ACK transmission. These two fields would generally have different values, however, their values become equal if and only if the neighboring node lies within the transmitter’s intended direction of transmission (e.g. node 4 in Figure 2). This information is crucial for each neighbor to know its relative location with respect to the source and destination and hence take appropriate antenna blocking decisions accordingly. In addition, any node that receives a reservation packet should store the index of the beam pointing towards the transmitter in order to update its antenna blocking information. The prime motivation for adding the previous information is to decouple the event of receiving a reservation packet from blocking a beam from transmission. The decision to transmit on a specific beam depends solely on the required direction and the information included in the reservation packets.

According to the proposed scheme, node S sends an RTS packet on all unblocked beams to inform neighbors that it wishes to initiate a transmission with node D. Thus, neighboring node 5 would know that it lies within the intended direction of data transmission from S to D and therefore should block all beams in order to avoid interference caused by S as indicated earlier. On the other

hand, node 2 would figure out that it is out of the intended direction of data transmission from S to D, and hence it blocks only the beam pointing towards node S. Moreover, node 2 would know that it can initiate a transmission with node 10 since it would use a different beam from the one pointing towards S, and thus it will not cause any interference at node S and will not suffer any interference from S. Hence, the proposed approach would be able to decide that node 2 belongs to the set $UBN(S)$. Otherwise, if node 2 wishes to transmit towards node S, it should belong to the set $BN(S)$.

The following challenge remains unsolved by the proposed reservation scheme: a neighbor may miss reservation messages due to lying in the coverage of a blocked beam. This neighbor, who may be active or inactive, would be left unaware of the attempted reservation and may cause collisions later. One way to circumvent this problem is to have *auxiliary channel(s)* that can be used to transmit special reservation packets on blocked beams. Under such proposition, blocked beams transmit special RTS/CTS packets, on a different frequency, whereas regular RTS/CTS packets are still transmitted on the unblocked beams at the same time. This scheme eliminates the aforementioned type of collisions caused by inactive neighbors lying in the coverage of the blocked beam. This is gained at the expense of using more than one channel, adding more complexity to the radio transceivers, and the possibility of having collisions among the special reservation packets on the auxiliary channel. However, the threat of suffering collisions from active users, after completing their ongoing transmission, still exists. Clearly, this problem involves a trade-off between protocol complexity and control overhead in one hand and throughput on the other hand. In this paper, we limit our attention to eliminating collisions caused by inactive users via the above mentioned technique. Handling the above mentioned type of collisions caused by active users is out of the scope of this paper. We briefly discuss two candidate approaches that are under investigation. The first is based on sending “*pending*” RTS/CTS packets once the blocked beam becomes unblocked. The transmission from source to destination could be temporarily halted, such that the source can transmit the pending packet on the beam recently unblocked. Once the packet is sent, the source node can resume its transmission on the beam pointing towards the destination. This approach is only feasible due to the short time needed to send a control packet, which can be tolerated by the longer data packet transmission. However, it involves synchronization complexity due to the possibility of having multiple pending reservation packets. Another variation of this approach exploits the underlying radio’s ability to transmit different packets on different beams at the same time. Therefore, the pending packet can be sent on the recently unblocked beam while at the same time continue sending data on the beam pointing towards the destination. The second approach involves adapting the

aggressiveness of the proposed reservation scheme depending on the number of blocked beams per node.

PERFORMANCE RESULTS AND DISCUSSION

In this section, we present performance results obtained using the *ns-2* simulator. The results show the performance gain of the proposed scheme over the omnidirectional and directional reservation extremes under a wide variety of network loads.

Simulation Environment

We limit our attention to small networks consisting of $n = 50$ nodes since it sufficiently captures the trade-offs addressed in this paper. We consider a rectangular area of dimensions 500 meters x 500 meters where the n nodes are *uniformly* distributed in the area. Routing is not considered in this study. We focus on single-hop (next neighbor) transmissions since the performance of MAC algorithms depends solely on the single-hop transmission requirements. Therefore, data packets of fixed length (500 bytes) are generated by each node, with constant rate, and destined to one of the neighbors according to a uniform distribution. In this study, we will not consider nodes' mobility since the arguments made in this paper are independent of mobility. We believe that the addressed trade-off remains valid under mobility conditions. We assume that each node has a buffer for temporarily storing generated packets awaiting transmission. The size of each buffer is assumed to be *arbitrarily large* since our main focus in this paper is throughput rather than queuing delays. Throughout the simulations, omnidirectional transmissions are achieved via using all directional beams. Therefore, the range of omnidirectional transmissions (250 meters) is assumed to be equal to the range of directional transmissions. We assume $B = 6$ switched beams per node, each of 60° width. In order to simplify simulations, we abstract any aspect of ad-hoc networks that is irrelevant to the main focus of the study. Thus, we will not introduce specific NLD algorithms, *i.e.* we adopt an abstract model that simulates its output based on the geographical location of neighbors. Each simulation run is carried out for the duration of 900 sec.

Simulation Results

The performance metric used to evaluate the proposed algorithm is the *multiple access throughput* which is defined as the long run average number of bits that reach their respective neighbors successfully per second. This ratio is to be computed at the end of each simulation run. First, we compare the long run average number of data packets sent per second under the three schemes. The importance of this experiment stems from the fact that this parameter reflects the “aggressiveness” of the reservation scheme. It can be easily noticed from Figure 3 that classical CSMA/CA is the most conservative since it has least attempts of sending data packets. This is a direct consequence of unnecessarily blocking neighbors from transmission. On the contrary, the directional reservation scheme is the most aggressive since it transmits reservation

packets in the intended direction only. This leads to initiating an excessive number of data transmissions that are subject to frequent collisions with reservation packets transmitted by unaware neighbors. The proposed reservation scheme attempts to achieve a balance between these two extremes.

Next, we compare the long run average number of data collisions per second under the reservation schemes at hand as shown in Figure 4. This result reflects the price paid for the algorithm aggressiveness. It is intuitive that aggressive algorithms (directional reservation) suffer more collisions than conservative algorithms (CSMA/CA). The interaction between the two conflicting requirements, namely maintaining aggressiveness and minimizing data collisions, is what determines the MAC throughput. As shown in Figure 5, our algorithm provides superior performance since it guarantees favorable levels of data collisions (less than half the data collisions caused by the directional reservation scheme), while being relatively aggressive.

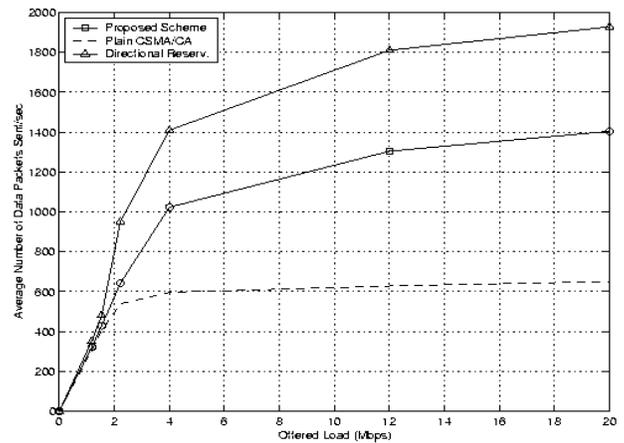


Figure 3. Average Number of Data Packets Sent/sec ($n = 50$, $B = 6$, Av. number of neighbors = 13.84)

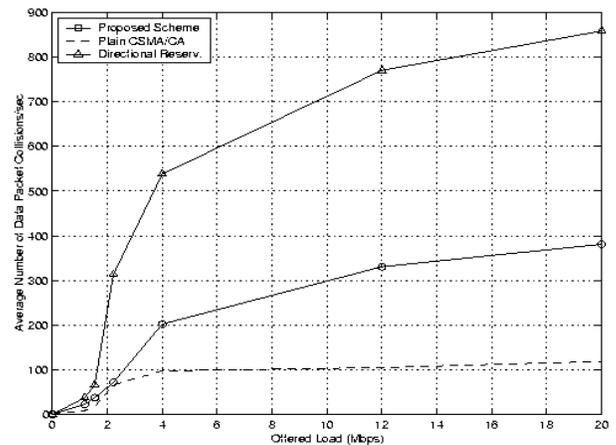


Figure 4. Average Number of Data Collisions/sec ($n = 50$, $B = 6$, Av. number of neighbors = 13.84)

We notice that as the offered load increases the MAC throughput increases for all reservation schemes. The proposed scheme outperforms CSMA/CA by a factor of approximately 80% at heavy loads and decreases to about 60% at moderate loads. Furthermore, it outperforms the directional reservation scheme by a factor of 45% at heavy loads and 35% at moderate loads. The performance gain reflects better handling of the aforementioned trade-offs by the proposed scheme. At light loads, all three schemes achieve almost the same performance. This is attributed to the low number of simultaneous transmissions, on the average, which rarely causes collisions.

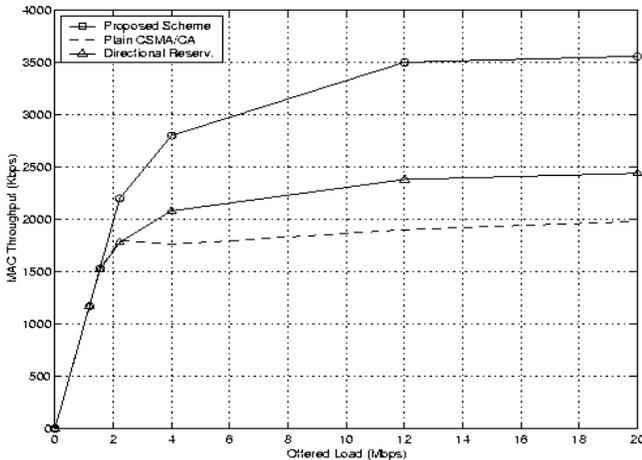


Figure 5. MAC Throughput
($n = 50$, $B = 6$, Av. number of neighbors = 13.84)

In this paper, we adopted the assumption of non-overlapping switched beams. However, real switched beam antennas experience some overlapping due to coverage constraints. This, in turn, may degrade the performance of the proposed algorithm since the proposed reservation scheme involves transmitting different packets over multiple beams at the same time. This problem can be solved using one (or more) of the following techniques: i) Careful antenna design that minimizes beam overlap subject to a constraint on the beam coverage, ii) Physical layer algorithms that “captures” the strongest signal from interference in the overlapped areas and iii) Carrying out reservations in a round-robin fashion over the course of K phases, where K may take values between 2 and B , since beam overlap decreases significantly between non-neighboring beams.

CONCLUSIONS

In this paper, we introduce a novel reservation scheme that increases the multiple access throughput of wireless ad-hoc networks using switched beam antennas. We show the drawbacks of omni-directional and directional reservation extremes proposed in the literature via emphasizing the trade-off between minimizing the number of neighbors that back-off unnecessarily and minimizing the number of

control/data packet collisions. Our main contribution is to send reservation messages, that carry information about the current and intended directions of transmission, in all unblocked directions. The rationale behind this approach is to notify the maximum number of neighbors of the ongoing reservation and, hence, assist them in taking the best decision of whether to proceed or refrain from transmission. Finally, we conducted a simulation study that shows considerable performance gains over the omni-directional and directional reservation schemes.

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