A Novel MAC Layer Protocol for Space Division Multiple Access in Wireless Ad Hoc Networks*

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Abstract

Use of directional antennas in cellular wireless networks offers many advantages such as range extension, reduced interference for signal detection and improved throughput. Recently, MAC protocols using directional antennas for wireless ad hoc networks that are based on and similar to IEEE 802.11 type WLANs have been proposed. These protocols, however, are unable to attain substantial performance improvements because they do not enable the nodes to perform multiple simultaneous transmissions/receptions. In this paper, we propose a MAC layer protocol that exploits Space Division Multiple Access, thus using the property of directional reception to receive more than one packet from spatially separated transmitter nodes (under the assumption that the nodes are equipped with smart antenna systems). Our simulation results show that drastic throughput improvements may be achieved through this scheme.

1. Introduction

A mobile wireless ad hoc network (MANET) comprises of a set of nodes equipped with wireless transmit-receive capability, such that the nodes can communicate with each other without any fixed infrastructure relay. In order to ensure connectivity between between all nodes of the set, the nodes not only send packets to adjacent nodes and receive the packets intended for them, but also forward packets that are meant for other nodes that can be reached through them. Typically, ad hoc networks use omnidirectional antennas at nodes. This limits the system performance because the entire space around the node up to its radio range is seen as a single logical channel in which only one node may transmit to a neighboring node or receive from a neighboring node. Limited research has been documented on the use of directional antennas in packet radio networks [21, 22] and multihop ad hoc networks [7, 13]. Some basic ideas on the application of directional beamforming antennas to ad hoc networks have been discussed in [17].

The potential use of directional antennas in *base stations of cellular networks* has been attracting the attention of researchers for some time now [12, 20]. Radio frequency (RF) mobile units in handheld devices, however, currently do not use directional antennas because of size limitations, but may be deployed in vehicle mounted systems. Various techniques for using spatially selective transmission and reception of RF energy have been considered by researchers [14]. Perhaps, the most advanced of these is Space Division Multiple Access (SDMA) [3]. This allows simultaneous multiple reception (or transmission) of data at the base station using *smart antennas* equipped with spatial multiplexers and demultiplexers. The application of SDMA entities at the base station as well as low mobility wireless terminals has been investigated in the Integrated Broadband Mobile Systems (IBMS) project [2]. Furthermore within this project, it has been shown that for Infra-red based physical layers, the size of the antenna system is small.

Typically, ad hoc networks use multihop routing mechanisms for message transfer [15, 6]. In such a scenario, some nodes may lie on many active routes, i.e., routes on which data is currently being sent. These nodes need more bandwidth than other nodes that lie on fewer active packet forwarding paths. Since current networks with omnidirectional antennas allow

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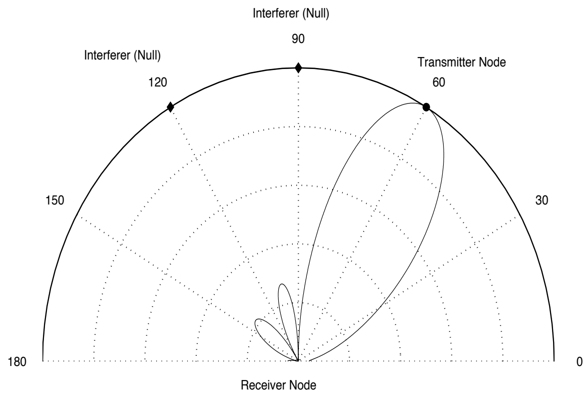

Figure 1. Beamforming to obtain maximas and minimas in desired directions

processing of a single message by a node at a time, the heavier bandwidth demand cannot be supported. These nodes then become bottleneck nodes for each of the routes on which they lie, since the slowest step in the multihop forwarding process limits the rate of information transfer. Interactions of the 802.11 MAC and ad hoc forwarding, and the effect on capacity for several simple configurations and traffic patterns have been examined in [9]. The authors conclude that although 802.11 does a reasonable job of scheduling packet transmissions in ad hoc networks, the network capacity is surprisingly low due to the requirements that nodes forward each others' packets (poor spatial reuse is a critical factor). This prompts us to believe that the current mechanism would have to be supplemented with improved spatial reuse to extract better capacity results. In this paper, we propose a MAC layer protocol that employs SDMA at each node by synchronizing the packet receptions from other nodes, thereby improving the throughput at bottleneck nodes.

2. Smart Antennas

Simultaneous transmission (or simultaneous reception) by a node requires smart antennas equipped with spatial multiplexing and demultiplexing capability. Smart antennas can be classified into two groups, both systems using an array of (omnidirectional) antenna elements: switched beam and adaptive beamforming antenna systems. A switched beam system consists of a set of predefined beams, of which the one that best receives the signal from a particular desired user is selected. The beams have a narrow main lobe and small sidelobes so signals arriving from directions other than that of the desired main lobe direction are significantly attenuated. Adaptive antenna arrays, on the other hand, rely on beamforming algorithms to steer the main lobe of the beam in the direction of the desired user and simultaneously place nulls in the direction of the interfering users' signals. Popular beamforming algorithms like the Recursive Least Squares (RLS) algorithm use a training sequence to obtain the desired beam pattern, while blind beamforming methods such as the Constant Modulus Algorithm (CMA) do not impose such a requirement [10].

Smart antennas are implemented as an array of omnidirectional antenna elements, each of which is fed with the signal, with an appropriate change in it's gain and phase. This array of complex quantities, constitutes a steering vector, and allows the resultant beam to form the main lobe and nulls in certain directions. With an L-element array, it is possible to specify (L-1) maximas and minimas (nulls) in desired directions, by using constrained optimization techniques when determining the beamforming weights. This flexibility of an L-element array to be able to fix the pattern at (L-1) places is known as the *degree of freedom* of the array [5].

Figure 1 depicts a scenario where beamforming is done using the RLS algorithm to obtain the weights that place a main lobe in the direction of the desired user's signal (arriving at an angle of 60 degrees with respect to linear array) and simultaneously place nulls in the interferers' directions (90 and 120 degrees). All nodes of an ad hoc network use the same spreading sequence (same logical channel) to modulate their information bits. This implies that multiple users' signals will superimpose at a reciever node and a collision will result, if an omnidirectional antenna is used for reception. To exploit their spatial location for simultaneous reception, we require the use of an antenna array and a beamforming algorithm at the receiver node, along with unique training sequence bits for each of the transmitting nodes. The training sequence of a transmitting node enables the beamforming algorithm weights at the receiver to converge and form a main lobe in the desired look-direction. Thus, the receiver can spatially separate the different nodes and receive their transmitted packets.

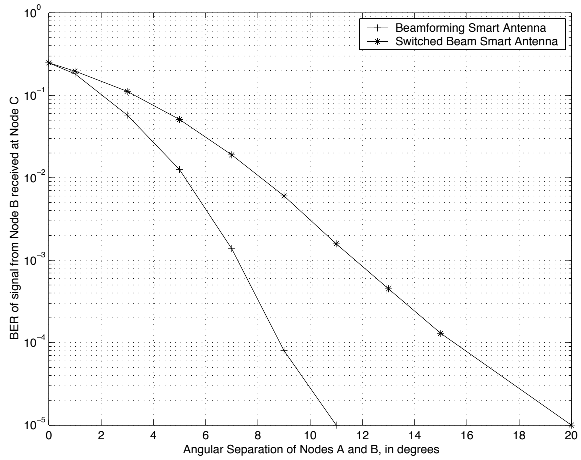

Figure 2. Bit Error Rate at a receiver node for different angular separations of two simultaneously transmitting nodes.

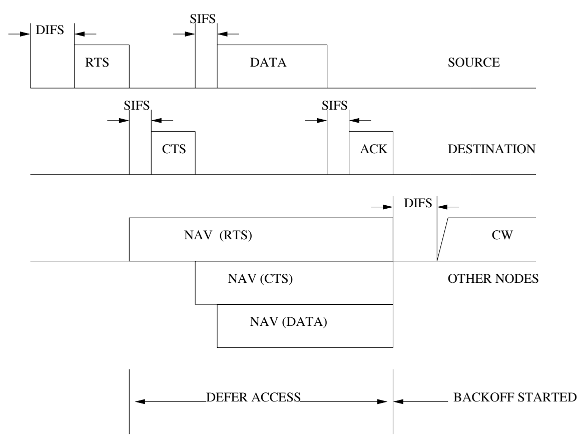

Figure 3. IEEE 802.11 MAC timing diagram using RTS/CTS

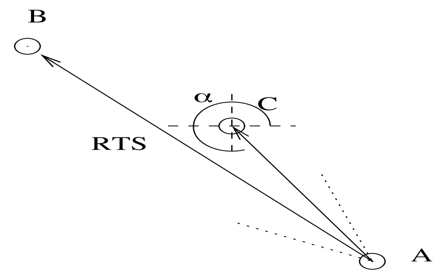

Figure 4. Reception of DRTS from A at B, overheard by C

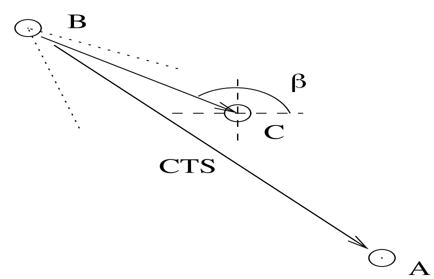

Figure 5. Reception of DCTS from B at A, overheard by C

A collision does not occur in reception provided the angular separation between the transmitting nodes is large enough to allow the receiver to simultaneously form separate beams in their directions. Simultaneous beams in separate directions are formed by applying different steering vectors, one for each beam, to the signals at the antenna elements, using programmable DSPs. Figure 2 plots the Bit Error Rate (BER) for node B's transmission versus the angular separation of two transmitting nodes A and B, received using the two smart antenna techniques (switched beam and adaptive beamforming) at node C. The simulation was performed in Matlab, with a four element antenna array and a 128 bit Walsh Hadamard Training sequence for beamforming. We see that the beamforming scheme (RLS method) outperforms the switched beam technique, and reports high BER values only for angular separation values of the nodes being less than 10 degrees. A comparison between the suitability of switched beam systems and adaptive beamforming systems for ad hoc networks, is detailed in [16].

3. The Proposed Scheme

The IEEE 802.11 standard for wireless LANs [1, 4] uses carrier sense multiple access with collision avoidance (CSMA/CA) at the MAC layer. In addition, it offers a handshake mechanism based on exchange of an omnidirectional Request-to-Send (RTS) packet from sender and an omnidirectional Clear-to-Send (CTS) packet from intended receiver that allows reservation of the channel prior to transmission of actual data. The timing diagram of IEEE 802.11 is shown in Figure 3. The omnidirectional RTS and CTS packets ensure that the hidden terminal problem does not occur when the receiver is receiving the DATA frame (or when the sender is receiving the ACK).

The magnitude of throughput enhancement that may be achieved by using directional RTS (DRTS) and directional CTS (DCTS) messages over spatial subchannels (instead of omnidirectional RTS/CTS) in wireless ad hoc networks has been explored in [8]. The use of DRTS and DCTS is illustrated in Figures 4 and 5. In Figure 4, node C overhears a DRTS that is sent from node A to node B. Consequently, it blocks direction α (practically, a narrow angular sector centered around

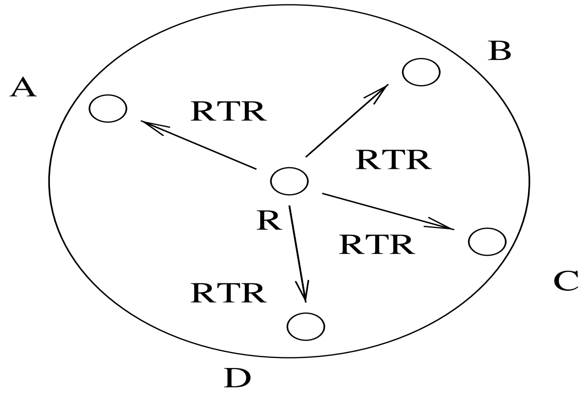

Figure 6. Omnidirectional Transmission of RTR packet by R

α) for the time duration of the data transfer, as notified by the appropriate field in the RTS packet. When it overhears the CTS message, as shown in Figure 5, it blocks direction β for a time duration mentioned in the CTS packet. In this manner, specific directions (or a range of angles) may be blocked by the smart antenna system of a node if it detects ongoing data transfer. An assumption in [8] is that separate antenna entities are available to a node for transmission and reception, and that mutually exclusive directions are used for transmission and reception at any given time instant. A disadvantage in this assumption is that appropriate nulls (or very low sidelobe levels) need to be placed so that electromagnetic power from ongoing transmissions does not interfere with receptions at the same node. Although this is theoretically possible, it is practically difficult to achieve[1].

Our scheme employs time division duplex (TDD) between transmission and reception, thus it does not require two separate antenna systems. At the same time, it harnesses parallelism in the reception process, improving the throughput at a node. To enable simultaneous reception in parallel, a node needs to synchronize its receptions from other nodes. This means that prospective transmitters need to be synchronized to a receiver. Therefore, transmitting nodes cannot synchronize their own transmissions to others (since each of their transmissions is dictated by a potential receiver). Receiver-initiated handshakes at the MAC layer have been presented in earlier literature, such as the MACA-BI scheme [19]. We use the receiver-initiated approach to achieve the time synchronization for receptions, as mentioned above. The following treatment enlists the salient features of our proposed method.

3.1 Modified Handshake Mechanism

The basic functioning of our scheme is illustrated in Figures 6, 7, 8, 9 and 10. A node that wants to initiate reception sends out an omnidirectional Ready-to-Receive (RTR) packet to poll all neighboring nodes simultaneously for data (Figure 6). The RTR packet contains the unique training sequence assigned to the receiver node R and transmitter nodes (A, B, C) use this training sequence to form directional beams in the direction of the receiver (the directional reception beams of nodes A, B, C are not shown in Figure 6) . The receiver node also advertises the maximum size of the data packet (a network parameter) that it shall accept, in the RTR packet. We shall modify the requirement that RTRs be *omnidirectional* at a later stage. The potential transmitter nodes that have packets for node R, reply to the RTR message, each with their RTS request, after forming directional beams in the direction of R. Each of these nodes also transmits its training sequence, allowing node R to simultaneously form beams towards them (Figure 7). They also inform the receiver of the size of the data packet that they intend to transmit, a parameter not greater than the size advertised by the receiver. After this, the receiver informs each of the potential transmitters of the negotiated packet size, which is the maximum of all the packet sizes requested by the transmitters. This is done in a CTS packet, which is transmitted directionally towards the intended transmitters (Figure 8).

All transmitters pad their DATA packet size up to the negotiated value, after marking the logical ‘End of Packet’. The DATA packets are transmitted directionally towards the receiver (Figure 9). A possible optimization to save transmission power is that transmitters need not perform bit-stuffing if they actually calculate the expected time of ACK arrival based on

[1]Theoretically, a linear antenna array with a binomial weighting applied to the antenna elements, yields zero sidelobe levels. However, this needs a large variation in the current that is fed to the different elements of the array.

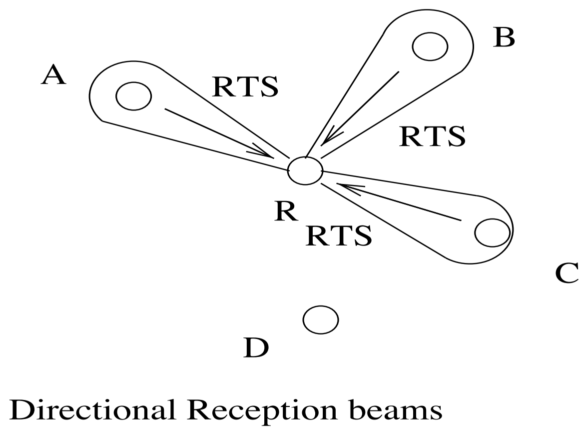

Figure 7. Directional Reception of RTS packets by R

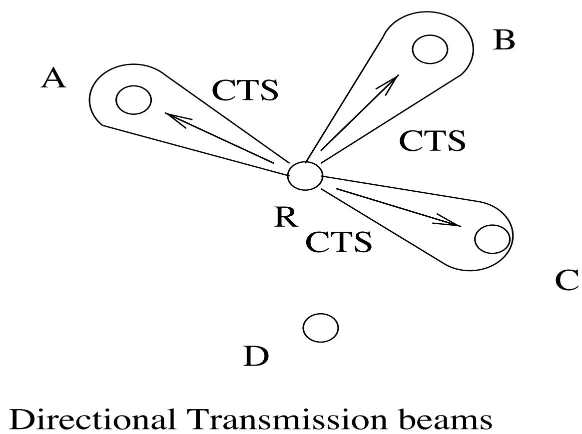

Figure 8. Directional Transmission of CTS packets by R

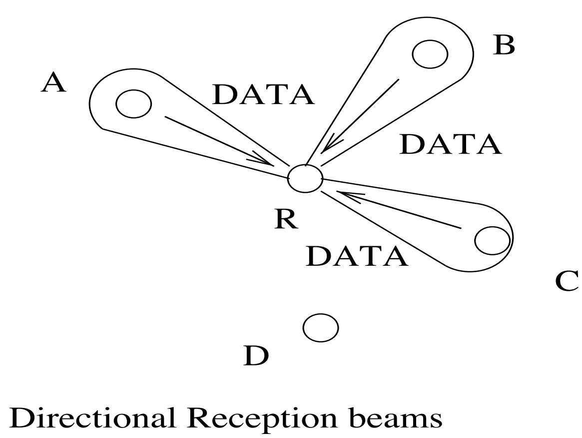

Figure 9. Directional Reception of DATA packets by R

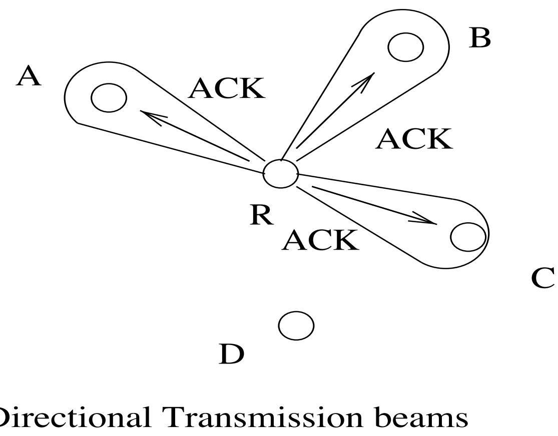

Figure 10. Directional Transmission of ACK packets by R

the negotiated packet size, which is obtained from the CTS packet. After receiving the DATA frames simultaneously, the receiver replies with simultaneous directional ACKs to each of the transmitters (Figure 10). In this manner, synchronization is achieved for all receptions to a node. An assumption in the above mechanism is that the nodes have low mobility, so that beams can be formed on the basis of training sequences in the RTR and RTS packets, and the same directional beams can be used for transmission or reception (which are reciprocal processes) for the entire duration of the DATA and ACK exchange. Also, nodes that are not attempting to receive data from others are listening for any RTRs that they may receive.

An interesting observation is that the RTR and RTS packets in our scheme are larger than the typical size of a control packet in the 802.11 standard, whenever a non-blind beamforming method is employed. This is because each node must have a unique training sequence that is reasonably orthogonal to all other sequences, in order that beams are formed satisfactorily. For example, the use of a 128-bit Walsh Hadamard Code [18] as a training sequence adds 16 octets to an RTS packets, nearly doubling its size. However, the increase in size of the control packets does not increase the probability of collisions because nodes can be separated in the spatial dimension.

3.2 Spatial Null Angle Vector

Each node records the control information that it overhears from other ongoing transmissions, and uses this information to modify its radiation pattern by placing nulls in appropriate directions. This state information is maintained in a spatial null angle table (which is analogous to the Network Allocation Vector of 802.11), that lists the transmitting node, its radial direction relative to the node maintaining the angle table, the time this entry was made, and the time after which the entry must be purged. For example, a node X that hears an RTR message from another node Y, and later hears a directional CTS (DCTS) from the same direction (node Y), but has nothing to send to Y, adds this information to its spatial null table. It reads the value of the time for which it must keep this entry current, from the time duration field in the DCTS. It knows that Y shall be busy for this time, and will have formed beams to receive from other nodes (one of which is in the same direction as X) during this time. Thus X places a null in the direction of Y while this entry remains current in its spatial null table, for all of its transmission or receptions.

A node X that receives an RTR from Y, but does not receive a DCTS, knows that there is a likelihood of Y being busy, but Y has not formed a beam in its direction. However, it does not know the exact negotiated packet size, hence it fills the spatial null table with the direction of Y, and uses the average packet size (a network parameter) to calculate the time field for the duration that this entry has to be kept current. This means that X does not transmit in the direction of Y for a time duration needed to transfer an average size data packet (including the ACK time). Note that even if X transmits in the direction of Y, it shall not affect Y because it has formed beams in directions different from X (as indicated by the fact that X did not receive any CTS). The null placement is done because transmission in the direction of Y can have no useful purpose (Y is busy receiving packets from other nodes).

Similarly, a node X receiving a DRTS from a node Y blocks that direction for the time duration of transfer of a packet of maximum possible size (including the ACK time). This is done because it does not wish to interfere with the reception of an ACK at Y after it has finished transmission of DATA, but it does not know the exact negotiated packet size (in the CTS). Note that this direction is shifted from the direction in which this node receives RTR and CTS packets of the same data exchange by approximately π radians when the transmitting entities use narrow-beam antennas (see Figures 4 and 5). At this point, it is appropriate to modify our previous assertion that an RTR is omnidirectional. An RTR is actually sent out in all directions *other than those that are current in the spatial null angle table*.

The time duration (in terms of the time needed for transfer of a packet given its size, including the returning ACK) for which a node marks a null in a particular direction, based on receipt of RTR, RTS or CTS packets, is summarized in the table shown below.

RTR	RTS	CTS	Null Time duration
yes	no	no	(Avg. Packet Size + ACK) time
yes	no	yes	Duration Field in CTS
no	yes	no	(Max. Packet Size + ACK) time

3.3 RTS collisions

Collisions of DRTS packets at a node transmitting an RTR packet may occur whenever two or more nodes do not satisfy a certain minimum angular separation (as seen from the frame of reference of the node sending the RTR) [16], i.e., when the receiver node cannot form separate beams in the direction of the transmitters satisfactorily. In this case, the competing nodes must wait for the next round of contention, i.e., the subsequent RTR. The contending nodes then reduce their probability of transmission of an RTS in response to the RTR accordingly. After the contending nodes are unsuccessful in transmitting their RTS packets (indicated by the absence of a CTS in response), in the next round they make the assumption that there is one more competitor for the medium in the same angular space. Each node, therefore transmits with a probability of 1/2. After another unsuccessful round of contention, the nodes assume that there are two other competing nodes, hence they transmit with a 1/3 probability subsequently. For each unsuccessful round of contention, this probability is reduced further. This method of backoff is gentler than an exponential backoff; however, since the probability that more than two nodes are in a limited angular space is very low, the method is adequate.

3.4 Periodicity of RTRs

All nodes should transmit RTRs periodically and poll neighboring nodes for packets. Choosing a constant time interval between transmission of two successive RTR messages is not advisable since more than one RTR may be received repeatedly at a node that is polled by two other nodes at the same time. Whenever a node receives more than one RTR packet, it must choose to respond to one of them, because it can adjust its TDD schedule for transmission and reception acording to one receiver only. Hence, this situation is unnecessary and should be avoided. We choose a uniform distribution to determine the time gap between two RTR dispatches. The mean of the distribution determines the average time period between two RTRs. A receiver may also decrease or increase the (mean of the) time period of RTRs based on information from the transmitters about their buffers. This may be conveyed to them by the transmitters in their RTS packets. A node that receives an RTR packet, and chooses to respond to the RTR with its RTS packet (because it has data for that node that sent the RTR), freezes its own RTR timer (reschedules its next RTR transmission) during the entire duration of data transfer (including the ACK).

4. Performance Evaluation

Our MAC layer simulation investigates the ability of a bottleneck node to receive packets sent to it and forward them to other nodes. The simulation is written in PARSEC [11], a C-language based discrete event simulator developed at UCLA. In the PARSEC approach, we define different node entities and use time-stamped message exchange constructs for communication between them over logical channel entities (thus simplifying the directional transmission/reception model). The timing parameters for IEEE 802.11 Direct Sequence Spread Spectrum (DSSS) have been coded into the simulation framework. The simulation topology is visualized as a set of N nodes surrounding a certain central node (and within its radio range) that is the bottleneck. The MAC layer of each of the surrounding nodes receives a data packet based on a Poisson arrival process. This means that the inter-arrival time between the packets at a node is exponential. The mean of the exponential distribution is a parameter in the simulation denoted by T. The size of the data packets is uniformly distributed between 1 KB and 2 KB. The raw data rate of the wireless channel is 1 Mbps. The nodes surrounding the bottleneck send the packets received at their MAC layer to the bottleneck for forwarding to any of the other surrounding nodes, selected at random. The omnidirectional

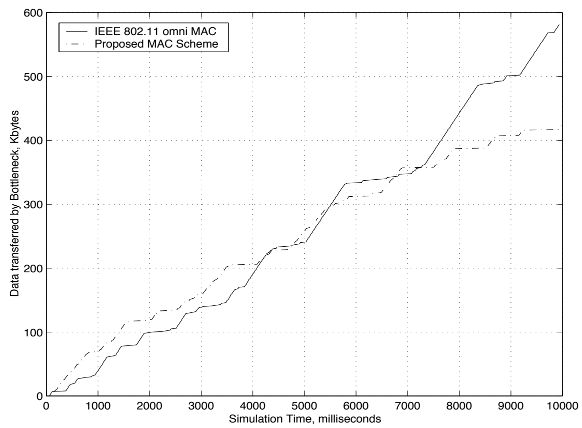

Figure 11. Data forwarded by Bottleneck: N = 5, T = 125 ms

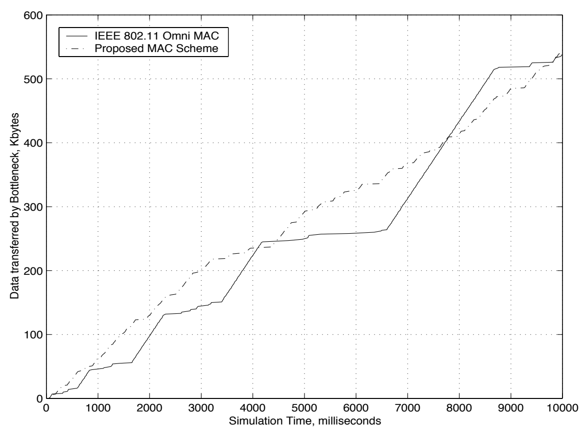

Figure 12. Data forwarded by Bottleneck: N = 5, T = 100 ms

and directional (smart antenna) transmission cases have been compared using the same timing parameters. The size of the RTR and RTS packets for our scheme, however, is taken as 40 octets due to the extra overhead of training sequences. RTS packets in IEEE 802.11 are only 20 octets long. For convenience of simulation, we assume that in the case of directional antennas, each of the N nodes have sufficient angular separation between them so that the central/bottleneck node can form separate beams towards each of them.

Figures 11, 12, 13 and 14 show the total amount of data transferred (forwarded) by the bottleneck node to all other nodes with time (10 seconds of simulation time), when it surrounded by 5 nodes (N=5). The means of the packet inter-arrival time (T) at the MAC of the neighboring nodes are 125 ms, 100 ms, 75 ms and 50 ms respectively. The packet inter-arrival time indicates the pressure on the wireless channel, since it is the periodicity with which the surrounding nodes try to access the channel to send packets to the central node. We observe that at low load (T=125 ms), IEEE 802.11 with omnidirectional antennas performs better than our proposed scheme. This is because of the extra overhead of RTR packets and the larger size RTS packets in the scheme. Also, 802.11 nodes do not exhibit much collision at lower loads. At T=100 ms, omnidirectional 802.11 and the proposed MAC have similar performance. RTS packet collision in 802.11, and hence channel capture by a single node, are more pronounced here, as seen from Figure 12. For T=75 ms and T=50 ms, we see that drastic improvements are achieved through our scheme (Figures 13 and 14). Omnidirectional 802.11 shows heavy collision and channel hogging (all other nodes undergo large backoff, while one node that has captured the channel keeps acquiring it repeatedly) at such loads. On the other hand, we see that for our scheme, the nature of the simulation plots is linear. This is because of the ability of the bottleneck node to form separate beams in different directions, and hence avoid collisions. For each of the above cases, the nodes transmit their RTR packets at random times. A uniform random distribution between 0 and 5 ms is used to schedule the next RTR transmission by a node.

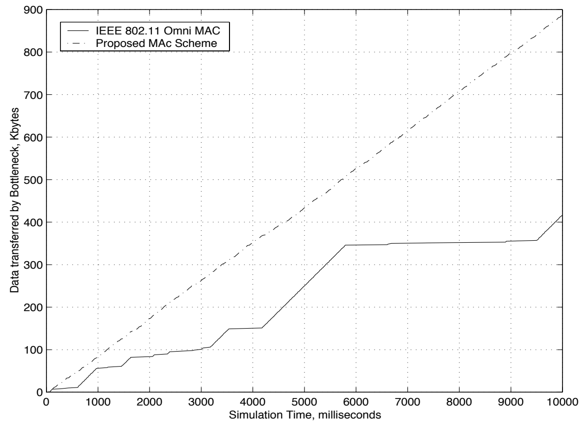

Figure 13. Data forwarded by Bottleneck: N = 5, T = 75 ms

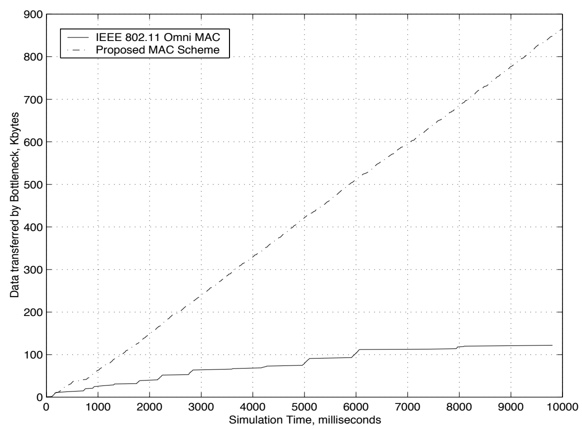

Figure 14. Data forwarded by Bottleneck: N = 5, T = 50 ms

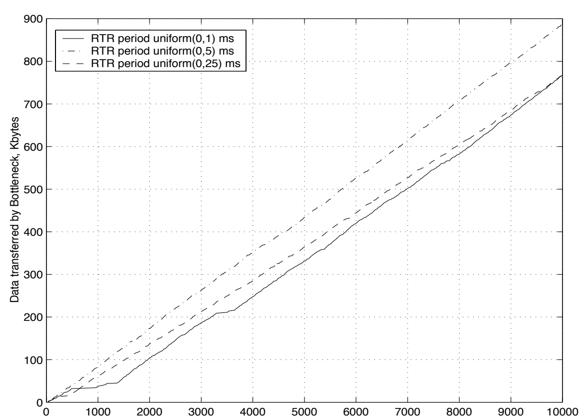

Figure 15. Data forwarded by Bottleneck for different values of RTR time period: N = 5, T = 75 ms

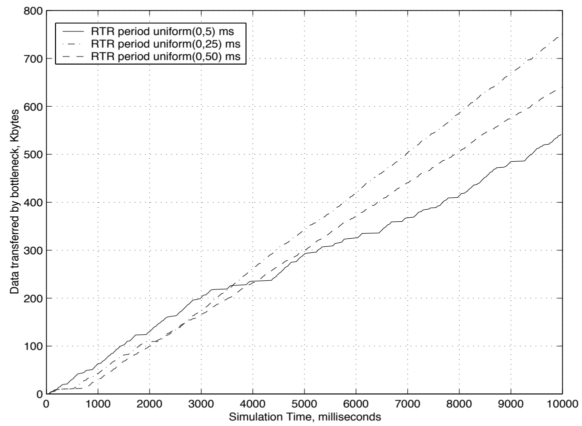

Figure 16. Data forwarded by Bottleneck for different values of RTR time period: N = 5, T = 100 ms

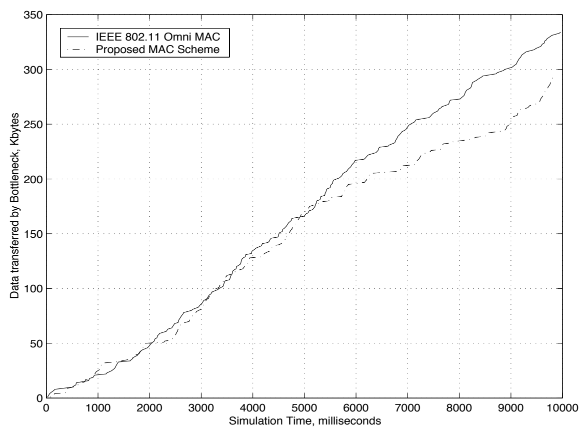

Figure 17. Data forwarded by Bottleneck: N = 2, T = 100 ms

Figures 15 and 16 show the effect that RTR periodicity has on the throughput. For T=100 ms, we see that the bottleneck transfers more data when its next RTR (each of the surrounding nodes also transmits RTRs at the same rate) is scheduled uniformly between 0 and 25 ms. For T=75 ms, the maximum performance is achieved when RTR period is distributed between 0 and 5 ms. The optimum RTR transmit frequency is a function of the number of surrounding nodes and the frequency with which they attempt to acquire the channel. A larger transmit frequency may be wasteful and may actually be degrading to the performance since a node that is transmitting an RTR cannot be polled successfully for data by another node. A lower transmit frequency means that a node is not requesting all the data that is meant for it.

Figures 17, 18, 19, 20 and 21 show the effect of loading the channel by varying the number of neighboring nodes, on the performance of the bottleneck. Keeping T constant at 100 ms, we vary N as 2, 4, 6, 8 and 10 and observe that the directional scheme outperforms omnidirectional 802.11 substantially when the channel is heavily loaded. Our simulation results show that there is a large performance gain when the pressure on the wireless channel is heavy, even though parallelism is exploited only in the reception process in our scheme. Another significant observation is that the performance of the omnidirectional method actually falls as the pressure on the channel is increased. This is because of the growing difficulty in acquiring the channel, as the number of neighboring nodes increase.

5. Conclusions and Future Work

We have proposed a MAC layer protocol that exploits the creation of spatial channels to enhance the throuphput at a node of an ad hoc network. We observe that our method, used with smart antennas, gives drastic improvements over IEEE 802.11 with omnidirectional antennas at heavy channel load. Our scheme takes advantage of the parallelism in the reception

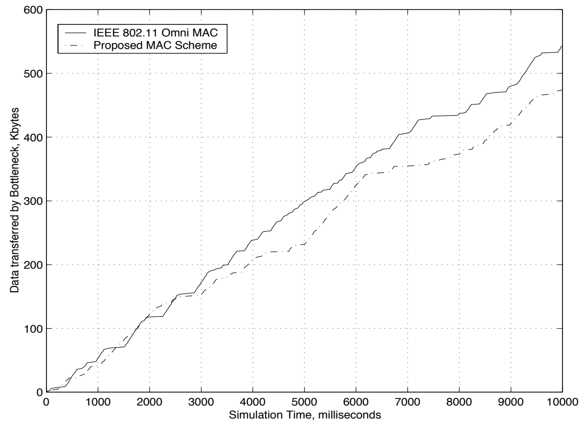

Figure 18. Data forwarded by Bottleneck: N = 4, T = 100 ms

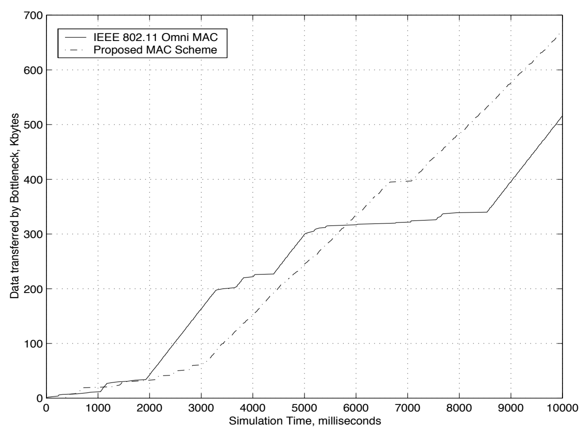

Figure 19. Data forwarded by Bottleneck: N = 6, T = 100 ms

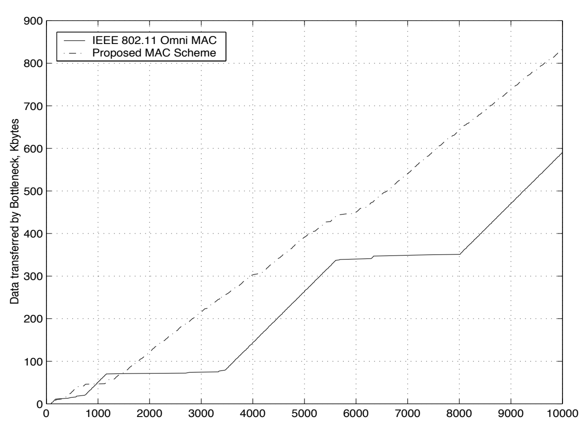

Figure 20. Data forwarded by Bottleneck: N = 8, T = 100 ms

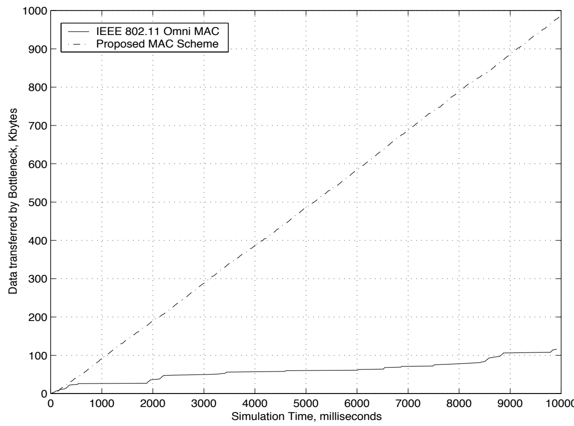

Figure 21. Data forwarded by Bottleneck: N = 10, T = 100 ms

process at an ad hoc node, thus facilitating the underlying smart antenna in using space-division-multiple access to improve performance. It does not require a global clock to synchronize nodes of the network, and is simple enough to be deployed in a wide range of scenarios. The realization of our technique is dependent on the economic feasibility of space-division multiple access for ad hoc networks. It therefore, needs to be justified by the application of ad hoc network solutions to crucial and strategic missions, such as a Future Combat System (FCS), a critical surveillance mission or a disaster-relief mission. Some aspects of our scheme need further attention. For example, the optimization of RTR transmit frequency has not been investigated in detail here. This is a problem that must be solved dynamically by a node based on information from other neighboring nodes. Another issue that needs to be explored is the physical limit on beamforming due to hardware restrictions on the number of antenna elements at a node.

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