Exploiting Processing Gain in Wireless Ad Hoc Networks Using Synchronous Collision Resolution* Medium Access Control Schemes

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***Abstract*—Signal spreading is used in military wireless networks to make them more difficult to detect, jam, and intercept. With signal spreading comes the opportunity to use code division multiple access (CDMA) to create multiple channels using the same spectrum. The requirement for all nodes in ad hoc networks to receive broadcast transmissions from any of their neighbors has made implementing channelization schemes impractical, especially with contention protocols. When CDMA is the method of channelization, then the near far effect must also be addressed. In this paper, we describe these challenges and then how the contention based medium access control protocol, Synchronous Collision Resolution (SCR) solves them. We describe how SCR creates a geometry of transmitters that benefits from using CDMA. We provide results of several different types of simulation experiments that demonstrate the relative benefits of different levels of processing gain. We demonstrate that tuning SCR for the available processing gain dramatically improves throughput.**

I. INTRODUCTION

CHANNELIZATION has the potential to increase the capacity of ad hoc networks. The goal of channelization in ad hoc networks is to pull hop-wise peer-to-peer communications to separate channels so that the density of the peer-to-peer communications can be increased and thus the capacity of the network. We are specifically concerned with networks with nodes that have only one transceiver that use contention protocols to statistically multiplex traffic. The requirement in ad hoc networks for these nodes to listen on common channels to discover neighbors and to enable broadcasting makes coordinating channelization difficult. The challenges are to cue destinations on which channels they should listen and to ensure that the movement of source-destination (SD) pairs to separate channels does not foil the mechanisms used to arbitrate contention. When code division multiple access (CDMA) schemes are used to make channels in the same radio frequency spectrum there is an additional issue, destinations and interfering sources must be sufficiently separated to prevent the well known near-far problem. The Synchronous Collision Resolution (SCR) MAC protocol [1], [2] provides a simple scheme to overcome these challenges. The contributions of this paper are an overview of the issues associated with channelization and using CDMA in ad hoc networks and the current state of the art in dealing with them. We explain how SCR overcomes these issues and provide an analysis using simulation to demonstrate the potential CDMA has to increase SCR's performance.

Our motivation for doing this analysis stems from the observation that spread spectrum techniques are used in military networks to reduce the vulnerability of the communications to detection, interception, jamming and multipath effects. Channelization using separate codes provides the opportunity to increase the capacity of these networks while using the same spectrum. The conclusion from our analysis is that a small amount of processing gain can dramatically increase the capacity of a network using SCR. Best performance is achieved by tuning protocol parameters for the available processing gain.

We begin our presentation in Section II with a more detailed review of the issues of implementing channelization schemes in ad hoc networks and then in Section III of exploiting CDMA in those schemes. Both sections describe the various techniques that have been proposed to resolve these issues. Then, in Section IV, we describe how SCR enables channelization and creates the SD geometry that makes exploiting CDMA possible. In Section V, we describe our simulation experiments and their results. Section VI concludes the paper.

II. CHANNELIZATION IN AD HOC NETWORKS

Channelization in ad hoc networks has three component problems: assigning channels, coordinating on which channels destinations should listen, and retaining the function of the contention arbitration mechanism.

A. Channel Assignment

Channel assignment varies in two ways, in the manner channels are associated with SD pairs and in the way channels are selected. There are three different schemes for channel association: transmitter oriented, source oriented, and pair-wise oriented. In the transmitter oriented scheme channels are assigned to transmitters and destinations are expected to receive packets using the source's channel. The opposite applies in the receiver oriented approach. Channels are assigned to receivers and sources are expected to use the channels of the destination nodes. In pairwise oriented channels, unique channels are assigned to pairs of nodes. In protocols requiring handshakes or acknowledgments, the source and destination ends of an exchange would use different transmission channels under the receiver and transmitter oriented schemes but use the same channel under the pairwise oriented scheme. All these schemes have implementation issues when used with contention MAC protocols in ad hoc networks. In the pair-wise and receiver oriented schemes, there is no allowance for broadcasting. In the transmitter and pairwise oriented schemes, it is ambiguous on which channel non-contenders should listen.

The goal of channel selection is to distribute the use of channels so that the greatest density of SD pairs can exchange packets simultaneously. The problem of assigning channels across a topology to prevent overlap is well studied. In graph theory, it is equivalent to the distance-2 vertex coloring problem which is shown to be NP-complete in [3]. Multiple heuristics have been proposed in [4], [5], and [6], however, this type of scheduling seeks to find the minimum required number of channels which is not the same problem as the most efficient distribution of resources. The available number of channels is usually fixed, possibly being fewer than the minimum required. Additionally, these algorithms are centralized in nature, requiring the tracking of to-

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* Patent pending

pology and then the dissemination of assignments, two tasks that become increasingly impractical as ad hoc networks increase in size and topologies become more variable.

The alternative is to make channel selection distributed where each node in the network selects channels. In most cases, nodes attempt to track the current use of all the channels locally and then select a channel for their own use that is not in use or is not in great demand. Distributed channel selection occurs either prior to contention or is coordinated in the contention, the latter being more common since it can also resolve the problem on which channel a non-contender should listen. As we describe next, these mechanisms provide a control channel differentiated by time or frequency on which all nodes listen to coordinate the channel use.

B. Coordinating Channel Use

We are aware of four schemes for coordinating which channel to use: touch-and-go, hop-and-stay, schedule, and implicit. In touch-and-go, sources and destinations first exchange coordination packets in a common channel to select a channel and then move to that channel for the exchange of payload. In hop-and-stay schemes, all nodes in the network hop among channels and contend as if there were only one channel, but, if successful, they stay on the channel where the contention occurred while all other nodes of the network move on. This SD pair returns to the hop sequence after they exchange their packet. In scheduling schemes, the access protocol provides nodes the opportunity to reserve channels in time for the exchange of packets or for the creation of links. In the implicit scheme, the mechanics of access arbitration indicates the channels to use. We provide examples of the first three schemes in the current work section. Our protocol, SCR, uses an implicit approach.

C. Effects of Channelization on Access Mechanisms

A goal in channelization is to prevent both primary and secondary collisions. Primary collisions occur when a node is expected to participate in more than one packet exchange at the same time. Secondary collisions occur when an exchange is interfered with by a distant exchange. CSMA based access arbitration mechanisms that use channelization are prone to primary collisions. Contenders may not know the states of their neighbors nor sense their activities since they occur on different channels and thus, may contend to send data to a node that is already busy. Even if the contention does not interfere, it has an adverse effect since the contender cannot differentiate what caused the contention failure and may act inappropriately, e.g. assume the destination is no longer in range and drop the packet.

D. Current Work in Channelization

Several MAC protocols that use channelization have been proposed. An example of a touch-and-go protocol is the Multichannel MAC (MMAC) protocol. [7] This protocol uses a modification to the 802.11 MAC that is similar to its power saving mode. The protocol has a periodic ATIM[1] window that alternates with a period for payload transmission. Nodes first contend in the ATIM window where, through a series of exchanges, they coordinate which channels to use during the payload period. Channel assignment is receiver oriented and potential receivers listen on the selected channels throughout the payload period. No provisions are specified for broadcasting other than using the ATIM window.

The Hop Reservation Multiple Access (HRMA) [8] and Receiver Initiated Channel-Hopping with Dual Polling (RICH-DP) [9] are examples of hop-and-stay protocols. The distinction between the two is that HRMA is transmitter oriented while RICH-DP is receiver oriented. In HRMA, the contender transmits first and if a successful handshake follows both stay on that frequency for the payload exchange. HRMA, however, suffers from primary collisions when contending nodes attempt to send packets to busy nodes. In RICH-DP destinations trigger contention by announcing they are ready to receive a packet. If a contender exists that has a packet for the destination it may start sending a packet to that node. Primary collisions occur if more than one destination announces its availability to receive a packet or if more than one contender has a packet for a destination and try to send it.

The Unified Slot Assignment Protocol (USAP) [10] is a scheduling protocol. USAP has both a contention and TDMA nature. The channels are time slotted but like MMAC all nodes operate on the same channel on a periodic basis. During this period, all nodes are associated with a short transmission slot called a bootstrap slot. In the bootstrap slots, contenders propose slots and channels for links during the multichannel period. Each node transmits bootstraps regardless of whether they are contending and in these bootstraps indicate their observation of channel reservations. Nodes proposing a reservation avoid channels used by the destination's neighbors for transmission and channels that will interfere with its own neighbors' receptions. USAP can create a collision free schedule, however, the lag from reservation to use makes the schedules vulnerable to node movement which can cause reservations to collide.

III. CDMA IN AD HOC NETWORKS

CDMA differs from other channelization methods in that CDMA channels are not orthogonal. Even when using orthogonal codes, the geometry of nodes in ad hoc networks prevents the necessary synchronization in the arrival of signals at the multiple destinations. The benefit of spectrum spreading is measured in the quantity of processing gain (PG). PG improves the signal strength to interference and noise strength ratio (SINR). Expressed in an equation we have

$$SINR = \frac{PG \cdot P_j \big/ d_j^{\,n}}{N \big/ K + \sum_{i \neq j} P_i \big/ d_i^{\,n}} \ . \qquad (1)$$

where j is the source that is transmitting to the destination, P_i is the effective radiated power from transmitter i, d_i is the distance that separates the destination from the transmitter i, K is a constant that accounts for the pathloss that occurs across the first distance unit of propagation from the source, N is the thermal noise power, and n is the path loss exponent. Although propagation pathloss is more complex than implied by (1), this model reasonably represents the trends for this discussion. The relative distances between the destination and the transmitters and the relative difference in the power they use in transmission determines the level of SINR. The effectiveness of CDMA channelization depends on the location of the transmitters and their effective radiated power.

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[1] ATIM stands for ad hoc traffic indication map and has a specific meaning for the power saving function. MMAC uses the same terminology although the purpose of the packets is different.

A. *Near-Far Problem*

The near far problem refers to the disadvantage that CDMA has as a channelization technique where a close-in interferer ($d_i < d_j$) causes an interfering signal that is too strong for the processing gain to overcome. Since traffic and ad hoc topologies are random, access mechanisms must insure that interfering transmitters are sufficiently separated from destinations.

B. *Power Control*

In cellular communications, the near-far problem is encountered on the uplink from the telephone transmitters to the base station. The solution has been power control where the base station adjusts the transmit power of the telephones through feedback over a control channel such that the arriving telephone signals are approximately the same strength. Transmission power is another degree of freedom available to MAC protocol designers to solve the near-far problem in ad hoc networks; however, the geometry of the problem is much more challenging than that for cellular telephones. Adjustments must be made to affect the power received at multiple destinations, not just one. Additionally, in ad hoc networks where nodes have just one transceiver, feedback to adjust power can only be given between transmissions, not during them.

C. *The Disadvantage of Asynchronous Access*

Asynchronous MAC protocols complicate solving the near-far problem. Once a set of SD pairs is found that can exchange packets concurrently, a new contention may disrupt that equilibrium. MAC protocols must manage access attempts to prevent new arrivals from interfering with ongoing exchanges.

MAC protocols use acknowledgements to mitigate the effects of unreliable wireless channels. The significance of this protocol feature is that the near-far problem must be resolved for both ends of an exchange when protocols are asynchronous. All ends must not violate the proximity limit that would cause too much interference to each other. Alternatively, if protocols are synchronous (i.e. sources send packets at the same time and destinations send acknowledgments at the same time), sources can be closer to each other as can destinations. Fig. 1 illustrates an example of the tighter compaction of SD pairs that is possible with synchronous protocols.

D. *Current Work in Exploiting CDMA in Ad Hoc Networks*

None of the channelization protocols described in Section II. D. address the near-far problem endemic of CDMA and many of the proposals for exploiting CDMA are nothing more than channelization schemes that use CDMA as the channelization technique. For example, [11 - 14] are channel assignment protocols and although [15] proposes and compares two access schemes with code assignment, there are no mechanisms in the protocols to mitigate the near-far effect.

Methods to control power to reduce interference are proposed in [16] and [17]; however, both protocols require each node to have two transceivers. In [16], one transceiver operates on a control channel that is orthogonal in frequency to the spectrum where data transmissions are multiplexed using CDMA. All nodes listen on the control channel all the time. The protocol is similar to the 802.11 MAC except the RTS-CTS exchange occurs over the control channel and the PDU-ACK exchanges occur over the data channel. The unique feature is that each node keeps track of the current level of interference by observing the RTS-CTS packets. The CTS of a destination node specifies the power the transmitter may use to send data and the amount of interference new users can offer. The RTS-CTS exchange may be used to reserve one of the available CDMA codes if this is not handled elsewhere in the protocol stack. In [17], the primary access protocol is a two phase TDMA scheduling protocol. In the first phase, the protocol attempts to create a schedule that keeps a minimum separation distance between interfering transmitters and receivers. Then, in a second phase, an iterative power level algorithm attempts to determine if all SD pairs in this schedule can achieve an appropriate SINR. If not, the process repeats itself with smaller sets of SD pairs until an admissible schedule is found. Power control is used during exchanges Neither of these protocols achieves our goal of exploiting CDMA using a single transceiver at each node and the latter requires a central controller and does not support our goal of enabling contention based access.

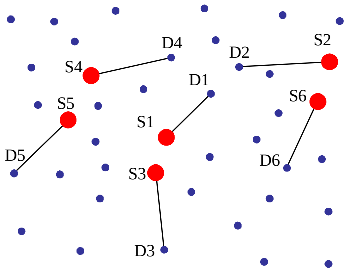

Fig. 1. Potential geometry of SD pairs using a synchronous reliable access protocol. Since transmissions from sources and destinations do not overlap in time, sources and destinations may be clustered closer together yielding a higher capacity. In asynchronous protocols, both ends of the SD pair must be separated

IV. SYNCHRONOUS COLLISION RESOLUTION (SCR)

SCR has several features that make it a complementary protocol to CDMA. It creates a node geometry that mitigates the near-far problem and it provides a channelization scheme.

A. *Description*

The basic implementation of the SCR MAC is illustrated in Fig. 2. It has four key characteristics:

1. The wireless channel is slotted.
2. All nodes with packets to transmit attempt to gain access every transmission slot.
3. Contending nodes use signaling to arbitrate their access.
4. All packet transmissions that occur during a transmission slot are sent simultaneously.

Design choices that determine the capabilities of SCR are the size and framing of transmission slots, the use of handshake packets, and the specific details of signaling.

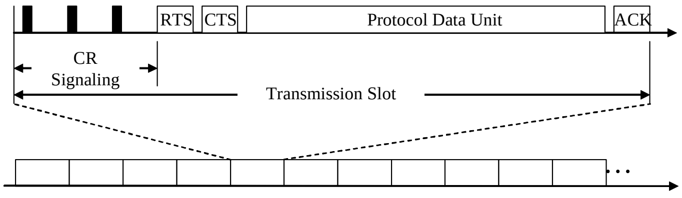

Fig. 2. Basic implementation of the Synchronous Collision Resolution MAC protocol

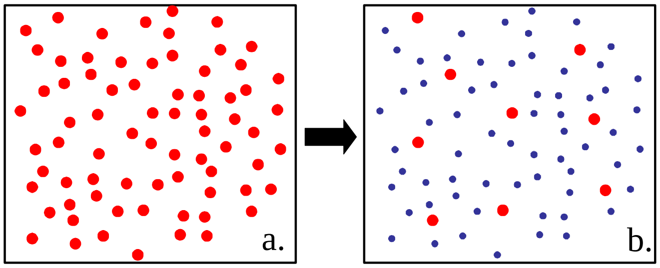

Fig. 3. The effects of signaling. All nodes are contenders in panel a and then signaling resolves a subset of these contenders in panel b, where all the surviving contenders are separated from each other by at least the range of their signals. Large nodes are contenders.

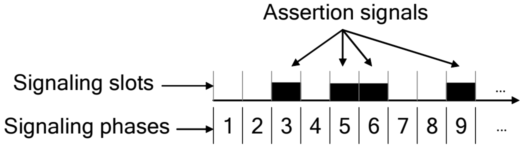

Fig. 4. Collision Resolution Signaling using single slot phases

B. *Creating a Transmitter Geometry*

Each transmission slot begins with collision resolution signaling (CRS). Its role is to determine which nodes amongst all the contenders in the network should be permitted to send a packet in the transmission slot. Fig. 3 illustrates the result. A subset of contenders from all contenders in the network is selected. Contenders in this subset are separated from each other.

CRS consists of a series of signaling slots organized into groups of slots called phases in which contending nodes may send very short signals.[2] The simplest and generally most effective at arbitrating contention is illustrated in Fig. 4, and consists of one signaling slot per phase. In this design, a probability is assigned to each signaling slot and a contending node will signal in that slot with that probability. The rules of signaling in this design are as follows.

1. At the beginning of each signaling phase a contending node determines if it will signal. It will signal with the probability assigned to the slot of that phase.
2. A contender survives a phase by signaling in a slot or by not signaling and not hearing another contender's signal. A contender that does not signal and hears another contender's signal loses the contention and defers from contending any further in that transmission slot.
3. Nodes that survive all phases win the contention.

There are two performance measures for a CRS design. The first is how well does it arbitrate contention amongst nodes in range of each other. This is purely a function of design. We provided a thorough explanation of our design approach in [1] and so only summarize the results here. Fig. 5 illustrates the performance of our design approach. If we use 4 signaling slots then there is approximately an 0.83 probability that there will be just one survivor at the conclusion of signaling with as many as 50 contenders, and probabilities of 0.91 with 5 slots, 0.96 with 6 slots, 0.97 with 7 slots, 0.985 with 8 slots, and 0.995 with 9 slots. In fact, with 9 slots, signaling can achieve a probability of one survivor > 0.99 with as many as 450 nodes contending. For most practical networks, this is probably good enough.

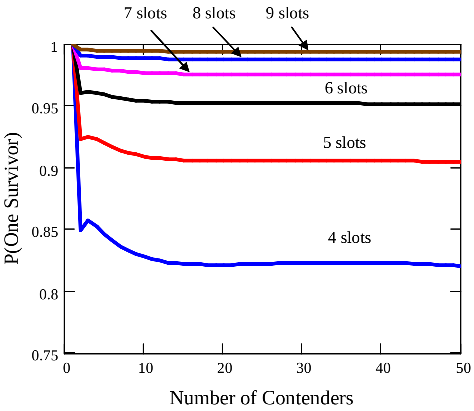

Fig. 5. 4, 5, 6 , 7, 8, and 9 single-slot phase designs optimized for a contender density of 0 to 50 contenders.

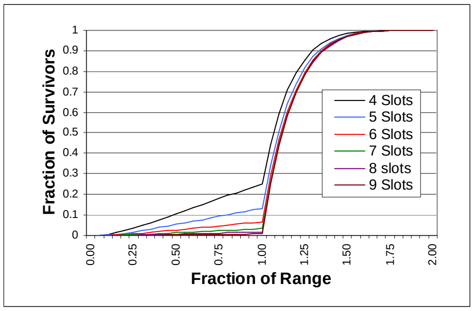

Fig. 6. Cumulative distribution of range to the nearest surviving neighbor.

The second performance measure is how well does CRS separate survivors. We used simulation to evaluate this performance. We randomly placed nodes on a toroidally wrapped surface to create a network with an average node degree of 10.[3] In the simulation, all nodes contended, and after each contention we measured the distance between each surviving contender and its closest neighboring surviving contender. We repeated this for all the signaling designs depicted in Fig. 5. Fig. 6 is a cumulative distribution of this separation distance. In this graph, 1.0 on the abscissa is the maximum range at which signals can be detected. The probability that the closest neighboring survivor is beyond this range is the P(One Survivor) predicted in the design. Most closest survivors were separated by less than 1.5 times the range of the radio. This performance was the same for more dense networks.

The separation above does not prevent collisions. This is intentional since we want to create an arrangement of contenders that can benefit from using CDMA. We are allowing destinations to cluster. In some cases; however, contenders can block each other from gaining access. This is detectable by repeated successful contentions but then failed handshakes. Signaling can be designed to create a greater separation through the use of echoing. Echo signaling phases consist of two slots. Non-contenders that hear a contender's signal in the first slot echo that signal in the second

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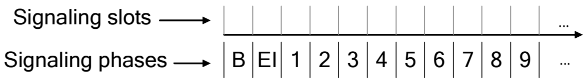
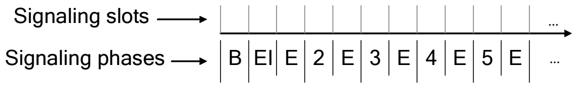
[2] The size of the signaling slots and the duration of the signals are selected to prevent ambiguity as to when signals are sent that may result from propagation delays or potential inaccuracies in synchronization.

[3] The purpose of toroidally wrapping a simulation area is to remove edge effects. On a toroidally wrapped surface, transmissions can reach across borders and be received on the opposite side of the surface. Nodes close to the border can exchange packets across to the opposite side and nodes near corners can exchange packets across to the opposite corner.



a. The standard signal design



b. The signaling design after echoing is invoked

Fig. 7. Adaptive signaling design to resolve contention blocks and to create two hop separation among contenders.

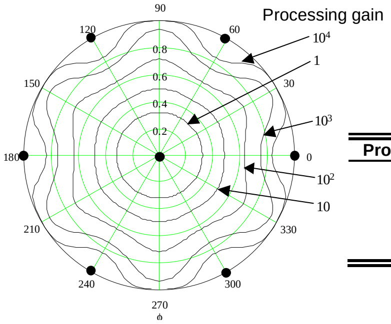
slot thus extending the effect of a contender's signal two hops. Our signal design enables contenders to invoke echoing. Fig. 7 illustrates a 9 "single slot" phase design that can be dynamically converted to a 4 phase echoing design. If a contender detects the condition that a possible block is occurring, in our implementation the criteria is three consecutive failed handshakes to the same destination, it invokes echoing by signaling in the EI slot. The signaling design in Fig. 7b. is the design used by all nodes that hear the EI signal.

Creating a two-hop separation may be motivated for other reasons. Echoing may be invoked as part of broadcasting to ensure more neighbors receive broadcasts. The more interesting possibility is to use it to create separations around nodes so that like a base station in a cellular network, they can send packets to multiple destinations simultaneously. Here is the opportunity to exploit orthogonal CDMA. Orthogonally spread signals transmitted from the same source will remain orthogonal at their destinations. The relative power of the orthogonally spread signals will be the same.

C. *Channelization*

SCR uses a receiver oriented channel assignment for peer-to-peer communications and a common channel for broadcast. Peer-to-peer channel selection is distributed. The nodes initialize the process by randomly selecting a channel from the pool. Then, on a periodic basis, nodes announce the channels they have selected and the channels used by their one-hop neighbors. If there is a conflict with a node's own selection and that of any of its two-hop neighbors, it chooses a new channel. It chooses an unused channel if there is one or, if not, it randomly selects a channel from the least used channels in the pool. It broadcasts its channel selection before using it. We limit the rate at which random changes can be made, e.g. one change every 5 seconds. Due the physical separation result of the contention there are rarely more than three contenders in range of any destination, so despite the reuse of channels, secondary collisions on the same channel are rare.

Channel coordination is implicit. Contenders indicate the type of packet they are sending in the contention. This is incorporated into a prioritization mechanism which is described in [2]. Here, and in our experiments, we use the simpler design shown in Fig. 7. The first signaling slot is used to indicate what type of packet is being sent. A contender will signal in the signaling slot marked B if and only if the node has a broadcast packet. A non-contender listens on the broadcast channel if this signaling slot is used in the contention, otherwise it listens on its peer-to-peer channel. This channelization scheme supports the multiple output approach described in the previous section.



Processing Gain	Coverage
1	0.0996
10	0.2333
100	0.4379
1000	0.6855
10000	0.8617

Fig. 8. The effect of processing gain on signal coverage in interference. Transmitters (the dots) are placed on a continuous triangular tessellation (only a portion is shown) separated by the 10 dB SNR range of the radios. Contours are the threshold for a 10 dB SINR from the center transmitter for the different processing gains when all transmitters are active. The table shows the fraction of the maximum range circle that is enclosed by the contours.

V. SIMULATION RESULTS AND ANALYSIS

A. *The Effect of Processing Gain on Coverage*

Processing gain increases the area to which a contention survivor in SCR can send a packet. Fig. 8 illustrates the idea. Here we have identified the 10 dB contours predicted by (1) (using $n = 4$ and all transmit powers the same) about a contender that exists in a continuous triangular tessellation of transmitting nodes. The separation distance between the nodes on the tessellation is the distance at which the transmitted signals are 10 dB above N. More processing gain increases the area.

Perfect tessellations are unlikely in real networks. Nodes will be separated by greater than the radio range and the density of survivors will be much less. Our experiments in [1] showed the density of CRS survivors to be just 40% that of the tessellation. Our experiments below attempt to determine at what level processing gain provides a benefit and whether changing the range of CRS signal detection or the effectiveness of the signaling will have an effect on the results.

B. *The Simulation Environment*

We evaluated the effect of processing gain on the performance of SCR using simulations executed in OPNET. The model of each node included an explicit representation of the SCR protocol together with a perfect router. All transmitters used the same transmit power. The perfect router assumes links exist between pairs of nodes if the arriving signals can achieve a specified SNR when there is no interference. Routes were minimum-hop. Path-loss was determined using the 2-ray propagation model with vertical polarization on flat earth without terrain features. 156 nodes were randomly placed on a square surface, seven transmission ranges[4] on a side, which we toroidally wrapped. This results in an average node density of 10 nodes per transmission area.[5] Nodes were stationary throughout the simulation. Packet arrivals at each node were exponentially distributed and each arrival was randomly routed to one of the other nodes in the network. The radio is assumed to have transmission capabilities similar to those of an 802.11 modem using its 1 Mbps modulation scheme, so we use

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[4] We define the transmission range as the distance that a signal has propagated when its strength drops to 10 dB above the thermal noise.

[5] A transmission area is the surface area covered by a transmission from a radio. It is the area of a circle with a radius of one transmission range.

the bit error rate curves of binary phase shift keying.. We sized the transmission slots to send 506 byte payload packets and assume headers sizes and RTS, CTS, and ACK packet sizes the same as those used in the 802.11 MAC. Signaling (using 9 signaling phases), handshake packets, headers and interframe spaces account for 34% of a transmission slots duration and there are approximately 163 transmission slots per second. We used a single scenario, i.e. identical node placement and traffic, and observed the effects of changing processing gain and various protocol parameters. We do not simulate channel assignment so all interference is from nodes using different codes. This network was fully connected with a 10 dB SNR criteria for links.

The best measure of the MAC performance in this scenario and the measure that we use is MAC throughput which is the rate packets are exchanged with neighbors. All other performance measures are correlated with this rate. The following information is provided to help the reader interpret the results. The spatial reuse of the channel in the scenario is the MAC throughput (pkts/sec) divided by the slots in a second, ~163. The total area of the network is 15.6 transmission areas so a MAC throughput of 2543 pkts/sec corresponds to a throughput of one packet per transmission slot per transmission area.

C. *Experiments*

We conducted several sets of experiments comparing the effects of varying the processing gain, the signaling designs, the range of the CRS signals, and the routing strategies. The standard experiment used a 10 dB SNR for signal detection and for link detection, it used the same 9 phase signal design which performance is shown in Fig. 5, and allowed three failed attempts for sending a packet before invoking echoing. Table I lists the details of the modifications for each experiment. The ID numbers in this table are used to identify the experiment performances in the graphs.

Fig. 9 compares the MAC throughput of the standard scenario with the four different processing gains. Processing gain dramatically improved the throughput but there is a limit in the standard scenario. This is expected since there is a finite number of survivors after signaling. Once conditions allow most survivors to be successful sending their packets, increasing processing gain had little effect. These observations led to further experiments.

The poor performance of SCR when there is no processing gain is attributed to the standard scenario deliberately allowing large interference. SCR reacted to this environment by frequently invoking echoing since there were a lot of collisions. We tried to improve SCR's performance when not using processing gain by extending the range of signaling through the reduction of the detection SNR (ID 5), reducing the number of collisions by reducing the criteria for calling echoing (ID 13), by increasing the effectiveness of echoing by increasing the number of phases used in signaling (ID 15), and by changing the link detection criteria to a 10 dB SNR above the signal detection criteria (IDs 16 and 17). Fig. 10 illustrates a comparison of their MAC throughput performances. All cases improved performance in some load regime; however, it never achieved the performance of even a modest amount of processing gain (i.e. 10 dB). It appears that the techniques that increase the SNR criteria for links improved the performance best, but this was done at a cost. Increasing the criteria reduced the number of links resulting in partitions. A large number of packets were dropped since there were no routes to their destinations. This is why the plot for ID 17 increases but with less throughput than load. Most traffic was not routable.

The strong performance of the high processing gain scenarios caused us to consider less efficient physical separation to increase the number of signaling survivors. We accomplished this by decreasing the number of CRS signaling phases in one set of experiments (ID 7, 8, 9) and by decreasing the range of signaling by halving the transmission power of the signals (ID 10, 11, 12). Fig. 11 illustrates the results. These techniques increased the throughput of the high processing gain environments by nearly 20% but decreased the performance when just 10 dB processing gain was used. This demonstrates that in the high processing gain envi-

TABLE I

EXPERIMENT SETTINGS

ID	PG	Description
1	0	Standard
2	10 dB	Standard
3	20 dB	Standard
4	30 dB	Standard
5	0	5 dB SNR for signal detection
6	10 dB	5 dB SNR for signal detection
7	10 dB	5 phase signaling design
8	20 dB	5 phase signaling design
9	30 dB	5 phase signaling design
10	10 dB	Half power CRS signal strength
11	20 dB	Half power CRS signal strength
12	30 dB	Half power CRS signal strength
13	0	1 retry before invoking echoing
14	10 dB	1 retry before invoking echoing
15	0	11 phase signal design and 1 retry before invoking echoing
16	0	5 dB SNR for signal detection and 15 dB SNR for link detection
17	0	20 dB SNR for link detection

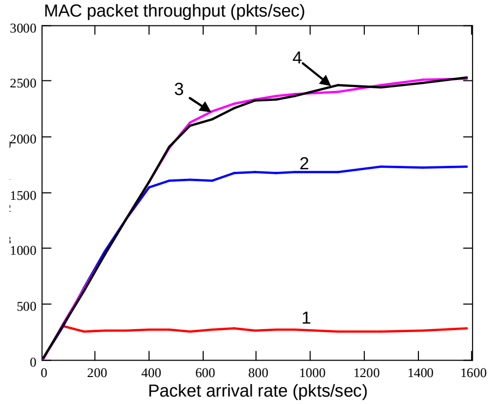

Fig. 9. Performances of processing gains with standard CRS settings

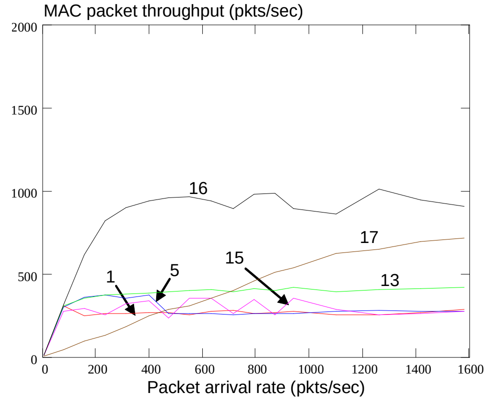

Fig. 10. Performances of 0 dB processing gain with modified CRS settings to increase separation of survivors

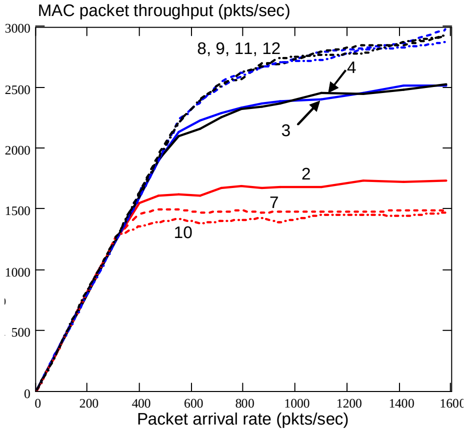

Fig. 11. Performances of using processing gain with modified CRS settings to decrease the separation of survivors

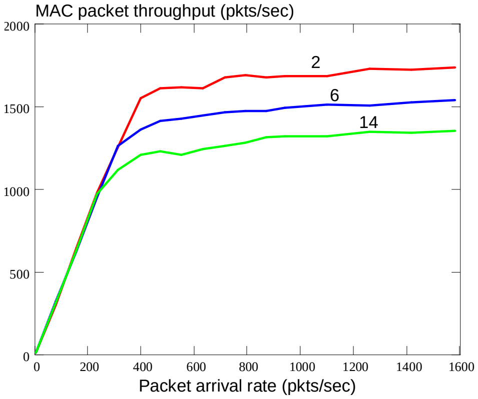

Fig. 12. Performances of 10 dB processing gain with modified CRS settings to increase separation of survivors

ronments the role of signaling is as much to thin out the set of contenders so that there are destinations available to receive packets as it is to separate the contenders and that the best throughput performance is achieved by accepting collisions for the sake of more contention survivors.

The fact that the performance with modest processing gain was not increased with less efficient signaling caused us to try some of the techniques we used to improve the no processing gain environment. Fig. 12 displays the results. Both increasing the range of CRS signals (ID 6) and decreasing the retry limit (ID 14) decreased its performance.

D. *Observations*

We found that SCR performance can be tuned for different physical layers. When there is no PG then increasing separation of contenders is warranted. When the PG is high, then smaller separation distances and less efficient signaling can improve performance. When the PG is moderate then a signal range close to the maximum link range performs well. Overall, there is a limit to how much PG can improve the performance of SCR. In our experiments, maximum performance occurs at least by 20 dB PG.

VI. CONCLUSION

We have reviewed the challenging problems in exploiting processing gain in ad hoc networks with contention-based access protocols: channelization and resolving the near-far effect. Channelization requires mechanisms to assign channels and to coordinate their use to simultaneously support peer-to-peer and broadcast communications. There are many proposals for channelization but few meet all these criteria. Nevertheless, even those that do would be unsuitable if CDMA is used as the channelization scheme since they do not resolve the near-far problem. Schemes proposed to exploit CDMA either ignore the near-far problem or use multiple transceivers and power control techniques to manage it. Our solution, Synchronous Collision Resolution, is a contention based access protocol that uses a single transceiver at each node. SCR's signaling resolves contentions and inidcates the type of packet that a winning contender will send so destinations know on which channels they should listen. The core effect of signaling is a physical separation of contenders that can be tuned to mitigate the near-far effect for the level of processing gain. SCR and CDMA are complementary protocols that together dramatically increase the MAC throughput of an ad hoc network.

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