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Cooperating with Smartness: Using Heterogeneous Smart Antennas in Ad-Hoc Networks

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***Abstract*— The ability of smart antennas to improve performance in a typically constrained ad-hoc network environment, has helped them garner significant attention over the last few years. However, not much light has been shed on wireless ad-hoc networks that have nodes with varying antenna capabilities. While homogeneous ad-hoc networks with all nodes having the same antenna capabilities will have certain applications, we argue that ad-hoc networks with nodes having heterogeneous antenna capabilities are more likely to be the norm due to a variety of motivating factors.**

In the context of such heterogeneous smart antenna networks (HSANs), we investigate and motivate the need for a simple form of node cooperation called *retransmit diversity*. We show that while such a simple form of node cooperation cannot bring significant benefits to *homogeneous* omni-directional and smart antenna networks, they can bring several folds improvement to *heterogeneous smart* antenna networks. We then present several key properties pertaining to node cooperation in HSANs. In the process, we identify a fundamental trade-off between exploiting smart antenna gain and cooperation gain, that undermines the ability of HSANs to leverage node cooperation to their maximum potential. To address this tradeoff, we then present an adaptive cooperation mechanism and incorporate this mechanism through the design of a simple but efficient MAC protocol. The performance of the MAC protocol is evaluated through *ns2* simulations.

I. Introduction

Smart antennas, due to their unique signal processing capabilities, are considered to hold promise for use in wireless ad-hoc networks. While their properties have been well understood at the physical layer, their relevance to higher layers of the protocol stack is still being explored. This has motivated several researchers to design MAC and routing protocols [1], [2], [3], [4] that exploit the capabilities of the underlying smart antenna technology. A common underlying assumption of all such work is that all nodes in the network have antenna technology with the same degree of sophistication, namely switched beam in [1], [2] and MIMO in [3], [4].

While such homogeneous networks form an essential first step towards understanding the true performance gains that can be delivered by each of the specific antenna technologies, there are several reasons why it is important to consider a heterogeneous wireless antenna network: (i) *Economic Feasibility:* Since most of the existing wireless networks operate with omni-directional antennas, revamping entire networks as a whole and equipping all the nodes with a smart antenna technology may not be economically feasible. However, incremental deployments are highly desirable. (ii) *Mesh Networks:* In mesh networks, one has control over the deployment of mesh routers in the network, which serve as stationary relay points for traffic for other nodes. Hence, it is possible to conceive such "special" nodes to be vested with smart antennas capabilities to improve the overall network performance. Other applications would include digital battlefields envisioned by DARPA, zero-configuration community networks, etc.

In this context, the focus of this work is to consider multi-hop wireless networks where the nodes are equipped with varied antenna technologies. We investigate and motivate the need for a simple form of node cooperation, also popularly referred to as *retransmit diversity*, in HSANs. We first show that while such a simple form of node cooperation cannot bring significant benefits to *homogeneous omni-directional and smart* antenna networks, they can bring great gains (several folds improvement) to *heterogeneous smart* antenna networks, thereby motivating the need for their exploitation. We consider two forms of practical HSAN's in studying the performance gains attainable from node cooperation: (i) random networks - traffic as well as node placement are random; and (ii) arbitrary* networks - traffic is random but node placement is controllable atleast for some nodes - a popular example being mesh networks. Our contributions and results can be summarized as follows:

- We show that the gains from cooperation are always more for random networks than for arbitrary* networks, indicating that random networks have a much larger potential for leveraging cooperation. This makes node cooperation a natural tool for exploitation in random networks.
- For random networks, we show that with increasing number of smart nodes, the (SNR/throughput) gain from cooperation increases initially when the degree of heterogeneity increases, peaks and then starts to decrease when the network tends towards a *homogeneous* smart antenna network. We identify that the increasing spatial sensitivity of transmissions due to increasing number of smart nodes is responsible for decreasing the potential for cooperation, thereby resulting in a tradeoff between exploiting smart antenna gain and cooperation gain.

- We then present a strategy that attempts to leverage both the cooperation and antenna gains appropriately based on fading conditions, without requiring the estimation/knowledge of fading statistics. We also present a distributed, localized MAC protocol that addresses all challenges arising in the implementation of the proposed strategy.

The paper is organized as follows. In Section II, we provide some background material on the smart antenna capabilities. Section III presents the impact of node cooperation in HSAN's. Sections IV and V present the proposed cooperation mechanism and a MAC protocol to incorporate the mechanism respectively. Section VI evaluates the proposed MAC protocol under varied network settings, followed by the related work and conclusions in Sections VII and VIII respectively.

II. Preliminaries

In this work, the term "smart" refers to nodes capable of spatially sensitive transmissions, namely nodes with directional or adaptive array antennas.

A. Capabilities and Gains

In a multiple element array (MEA), the signal that is sent to each of the antenna elements is weighted in both magnitude and phase before being transmitted. The specific set of weights is responsible for the antenna (radiation) pattern formed.

In switched beam antennas, a pre-determined set of weights is used, each of which results in a beam pointing to a particular direction with a high SNR gain. This is suitable for strong LOS environments. However, for strong multipath scattering (NLOS) environments, it is the adaptive array antennas that are capable of adapting their weights and hence beam pattern to maximize the resulting SNR. When the appropriate antennas are used in respective environments, the resulting SNR gain (directional/array) can be bounded by $G = K^2$, where K is the number of antenna elements on either side of the link.

B. Exploiting Gains

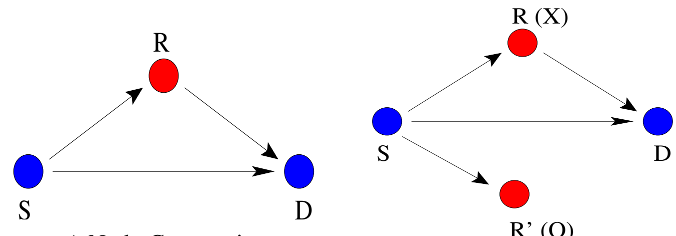
By default, the SNR gains resulting from the smart antennas contribute to increased communication reliability on the link. However, they can also be alternatively used for (i) increasing rate (capacity), (ii) increasing communication range, or (iii) reducing power consumption. We do not focus on routing and assume no power control for the nodes. Hence, we focus on the first possibility of exploiting the available SNR gain on the links to increase the data rate of transmissions.

For a given modulation scheme, the BER on the link is determined by its SNR. A gain in SNR (G) due to directional (G_d) and array gains (G_a) in switched beam and adaptive arrays respectively, is used to perform adaptive modulation, increasing the number of bits transmitted per symbol, while maintaining the BER at its original value. The increase in capacity can be asymptotically bounded as C_g, where

$$C_g \approx \log_2(1 + \rho G) \quad (1)$$

where the SNR (ρ) increases by a factor of G in the presence of smart antennas, thereby contributing to a relative logarithmic increase in capacity.

III. Node Co-operation in HSANs



a) Node Cooperation

b) Node Cooperation in HSAN

Fig. 1. Illustrations

In this section, we introduce and study the impact of node cooperation in (random) HSAN's. By node cooperation, we refer to the process of neighboring node(s) of a transmitter assisting the receiver in successful reception of packets in the event of losses resulting from fading. Consider the simple topology in Figure 1(a) where transmitter/source S tries to send a packet to receiver/destination D. Let R be an intermediate node within communication range of both S and D. Assuming omni-directional transmissions, node R is capable of receiving the packet from node S when it transmits to D due to the *wireless broadcast advantage*. Let the transmission from S to D fail due to fading while R successfully receives the packet. It is possible for S to try retransmitting the packet. On the other hand, node R can assist in the retransmission. There are two advantages to node R re-transmitting instead of node S: (i) R may be closer to D and hence has a possibly lower path loss and higher link gain, (ii) if fading is time-correlated (existing over several consecutive packets) it is futile for node S to retransmit; however the channel between R and D is independent of that between S and D. Hence, it is possible for R to succeed with a higher probability than S. What essentially happens here is that retransmit diversity is indirectly built into the system by way of exploiting neighboring nodes that possibly have a better channel gain in the event of fading.

A. Motivation

Note that, such a simple form of retransmit diversity may not necessarily provide performance improvement in homogeneous omni-directional networks if the relay does not have a better link gain to the destination than the source, and if the fading is fast and independent from one packet to another. This has motivated researchers to consider more sophisticated forms of cooperation diversity such as distributed space-time codes, virtual MIMO, etc. [5], [6], [7] in omni-directional networks. While such approaches are warranted in omni-antenna networks, we show that even the simple form of retransmit diversity presented in the example above can provide significant performance improvement and hence has incentives to be exploited in HSANs.

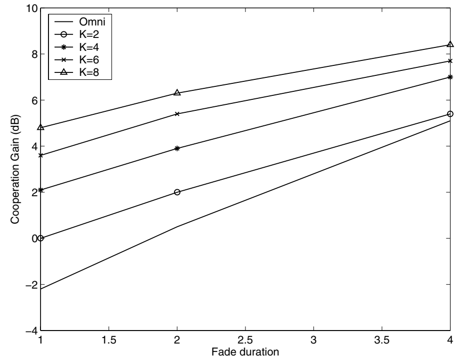


Fig. 2. Cooperation Gain

The key elements in a HSAN are the smart nodes that contribute a SNR gain on their links and hence serve as sources of diversity gain that can be exploited by omni-directional nodes during conditions of fading. Whenever links involve omni-directional transmitters and have a smart node as their neighbor, exploiting the neighboring smart node for cooperation delivers significant gains than when an omni-directional neighbor is used for cooperation. The choice of high gain smart links over the low gain omni links for retransmission also ensures gains during conditions of fast fading. In Figure 1(b), when the link S-D suffers from fading losses (S being an omni transmitter), the smart node R is exploited for cooperation rather than the omni node R'. Further, the cooperation mechanism exploits only one relay for cooperation, keeping the coordination mechanism simple and easily deployable. The gain in SNR from the cooperation mechanism (over non-cooperation) in a homogeneous omni antenna network and a heterogeneous smart antenna network with 20% smart nodes is presented in Figure 2 as a function of fade duration and number of elements. *While homogeneous omni networks degrade in performance under typical fade durations, the result clearly highlights the incentive for exploiting retransmit diversity in HSANs.*

B. Network Model

We consider a mixture of smart and omni nodes in the network, the fraction of smart nodes being given by p_x. We consider two forms of networks: random and arbitrary*. In arbitrary* networks, a small set of nodes, whose location can be controlled, form a routing backbone infrastructure (as in mesh networks) and all flows route their data through the backbone. We assume that the number of smart nodes available in the network is sufficient such that all forwarders in the routing backbone are smart nodes.

We consider block (time-correlated) Rayleigh fading, where the fading (and hence channel coefficients) is Rayleigh from block to block but remains the same within a block. The length of the block could vary from a single packet to several packets (order of several tens of milliseconds [8]). We consider a practical version of loss recovery at the MAC layer where a data packet is retransmitted during fading losses for only a fixed number of times F (eg. four in IEEE 802.11 DCF). We also assume that any available antenna gain is used for reliability. Exploiting antenna gain for rate is considered later on in Section IV. The two basic versions of communication that we consider are:

No Cooperation (NC): The transmitter continues to (re)transmit the packet on fading loss using its normal strategy of operation without any change for a maximum of F trails. If the link involves a smart node then the smart antenna gain on the link would contribute to reliability.

Cooperation (C): The transmitter transmits using its normal strategy of operation. On experiencing a fading loss, if there is a neighbor within the communication pattern of both the transmitter and receiver, then that node can potentially receive the packet from the transmitter due to wireless broadcast advantage and hence relay the packet (on successful decoding) to the receiver. In any case, the number of retransmissions for the packet (including transmitter and relay) is bounded by F, after which the packet is dropped. In the absence of a relay, the operation is the same as that of non-cooperation.

We use outage probability as a measure to compare the different schemes. Outage probability refers to how often (probability) does the BER (or equivalently SINR) experienced falls below a certain threshold. It is both a popular and practical measure for robustness to fading [7], [5] especially for block fading where it can directly be related to frame/packet error rate. Since most applications require a specific outage probability to be satisfied, we also compare the mechanisms based on the SNR required to achieve a desired outage probability. Closed form expressions for the outage probabilities and transmit SNRs for the different schemes in random and arbitrary* networks have been obtained and presented in [9]. Based on the analytical results, we now establish the following key properties of cooperation along with the numerical results.

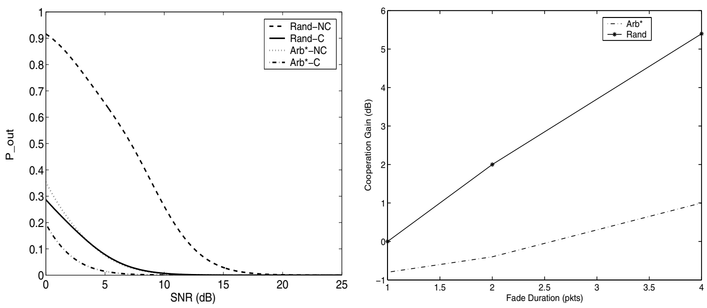
C. Properties

The main metric we use to evaluate the cooperation mechanism is the cooperation gain, which represents the amount of SNR gain (dB) obtained over the non-cooperation scheme. Let G_{c_R} and G_{c_A} represent the cooperation gain in random and arbitrary* networks respectively. For a desired outage probability, the gains are given as $G_{c\_R} = SNR_{nc\_R} - SNR_{c\_R}$ and $G_{c\_A} = SNR_{nc\_A} - SNR_{c\_A}$. Due to space constraints, the proofs for the lemmas and propositions are omitted but are available at [9].

Lemma 1: $\mathbf{G_{c\_R} \geq G_{c\_A}}$

Property 1: The gains from cooperation are always more for random networks than for arbitrary networks, indicating that random networks have a much larger potential for leveraging cooperation.*

Note that the gains from cooperation must not be confused with the absolute performance. It is straight-forward that arbitrary* networks will provide a much better (throughput) performance than random networks owing to their control over node placement and routing. However, when it comes to exploiting cooperation, the smart nodes are already exploited to the best possible extent in arbitrary* networks and hence there is not much room left for improvement through cooperation. Thus, leveraging cooperation also provides random networks a means to bridge the performance gap between the two networks without resorting to any autonomous control over node placement.



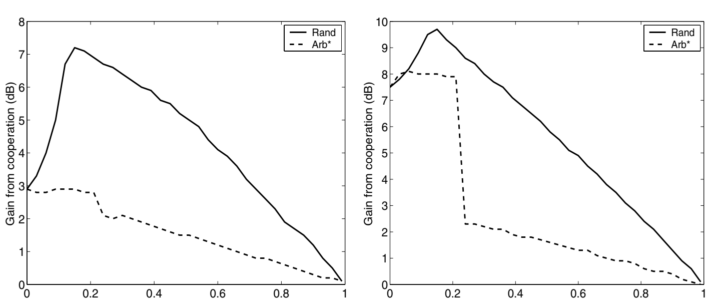
a) P_out: p=30, f=1 b) Gain: p=20, K=2

Fig. 3. Outage and Gain Results

This can also be verified from the numerical result for outage probability presented in Figure 3(a), where the number of elements considered at each of the nodes is four. While there is a huge gap in performance between the non-cooperation schemes of arbitrary* and random networks, the gap is significantly reduced for the cooperation schemes. The cooperation gain as a function of fade duration for $K = 2$ and $p = 20\%$ in Figure 3(b) indicates the significant potential of random networks to exploit cooperation, which increases with increasing fade duration. Note that, all the numerical results presented in this paper are averaged over numerous possible geometric configurations of the source, destination and relay.

Lemma 2: **$\mathbf{G_{c\_R}}$ is a concave function in the (fractional) number of smart nodes in the network, $\mathbf{p_x} \in (\mathbf{0}, \mathbf{1}]$.**

Property 2: The higher the degree of heterogeneity in the network, the higher is the potential for cooperation. Thus, with increasing number of smart nodes, the cooperation gain increases initially. But beyond a certain fraction of smart nodes, the network tends towards a homogenous smart antenna network, thereby resulting in a decrease of cooperation gain.



a) f=1 b) f=3

Fig. 4. Cooperation Gain Results

This can be seen from the cooperation gain results for random networks presented in Figure 4 as a function of increasing fraction of smart nodes for $K = 6$. For arbitrary* networks, the gain from cooperation increases initially where some of the omni nodes acting as forwarders of traffic in the backbone can still try to exploit nearby smart nodes for cooperation. However, the probability of finding a nearby smart node and hence the gain is small since the available smart nodes are already made to act as forwarders. Once the fraction of smart nodes is such that every forwarder in the backbone is a smart node, the disadvantage of not being able to exploit cooperation owing to spatially sensitive transmissions becomes significant, resulting in a large drop in gain.

Focussing on random networks, one of the key points to note is that the gain from cooperation in a homogeneous smart antenna network ($p_x = 1$) is much lesser than the gain from a homogeneous omni antenna network ($p_x = 0$). While the absolute performance of homogeneous smart antenna networks is much higher than that of omni networks, the potential for cooperation is much smaller owing to the spatially sensitive transmissions that increases with increasing elements. Thus, while increased antenna gain helps cooperation from the perspective of a node acting as a smart relay, it inhibits cooperation from the perspective of the node serving as a smart source and the inhibition dominates with increasing number of smart node sources. In order to favor cooperation, the smart node transmitters would have to sacrifice antenna gain to reduce the spatial sensitivity of transmissions. This leads to a fundamental tradeoff between exploiting antenna and cooperation gains, the relative importance of the two gains varying with the fading conditions and fraction of smart nodes available. Since both these network parameters cannot be estimated by a node in a distributed manner, we proceed to identify an adaptive cooperation mechanism that attempts to strike a balance between the two gains in random networks.

IV. Adaptive Co-operation Mechanism

We begin by considering two versions of cooperation in random networks: (i) basic cooperation mechanism considered thus far (C_{ant}), which favors antenna gain and leverages cooperation only if a relay can be found within the communication pattern of the transmitter; and (ii) modified cooperation mechanism (C_{coop}), where a smart transmitter after experiencing a fading loss, switches to omni-directional mode of transmissions to favor cooperation. The tradeoff between the two gains is pronounced when $p_x \rightarrow 1$, under which conditions we have the following lemma.

Lemma 3: When $p_x \rightarrow 1$,

$$\begin{aligned} G_{C_{ant}} &\geq G_{C_{coop}}, \quad f = 1 \\ G_{C_{coop}} &\geq G_{C_{ant}}, \quad f = F \end{aligned} \tag{2}$$

Thus, we see that exploiting antenna gain and hence scheme C_{ant} is the best strategy under fast fading ($f = 1$) conditions. However, C_{coop} serves to be the best strategy under conditions of time-correlated fading ($f \geq 2$)) by virtue of exploiting cooperation. We shall also observe this subsequently in the results. Hence, what we ideally need is a strategy that can adapt between these two schemes based on the fading conditions. However, since this information is a dynamic network parameter that cannot be estimated, we cannot have a strategy that switches between the two schemes. Hence, we will have to devise a strategy that serves as a middle-ground between the two schemes but will deliver reasonably good performance gains irrespective of the nature of fading conditions. In this regard, we propose the following adaptive cooperation mechanism, which operates as follows.

A. Mechanism

The proposed adaptive cooperation mechanism is referred to as C_{adap}. If the transmission from S fails due to fading, and if there is a neighbor (R) that has successfully received the packet and is within transmission range to D, then R will cooperate to retransmit the packet to D. If there are multiple such neighbors, the one with the largest link (antenna) gain (eg. smart node as opposed to an omni node) will take part in the cooperation. If there are no such neighbors, the source continues to retransmit the packet until the maximum number of trials possible. Further, if the transmitter is exploiting any available antenna gain on the link for increased rate, then it reduces its rate to omni rate and starts exploiting the antenna gain for reliability from the second trial onwards. If the transmitter is a smart node (directional or adaptive), then the spatially sensitive (optimized beam patterns) transmission will inhibit any available neighbors from cooperating. In this case, the transmitter first switches from using its antenna gain for rate to reliability using all available elements (if not doing so already). If this transmission also fails, then it switches to using three elements for reliability (if $K > 3$) before eventually resulting in omni-directional transmission on further failure to enable cooperation. Using the intermediate stage of operating on three elements would help retain some antenna gain while also ensuring that a neighbor within the range of both S and D receives the packet with a probability comparable to that of an omni transmission.

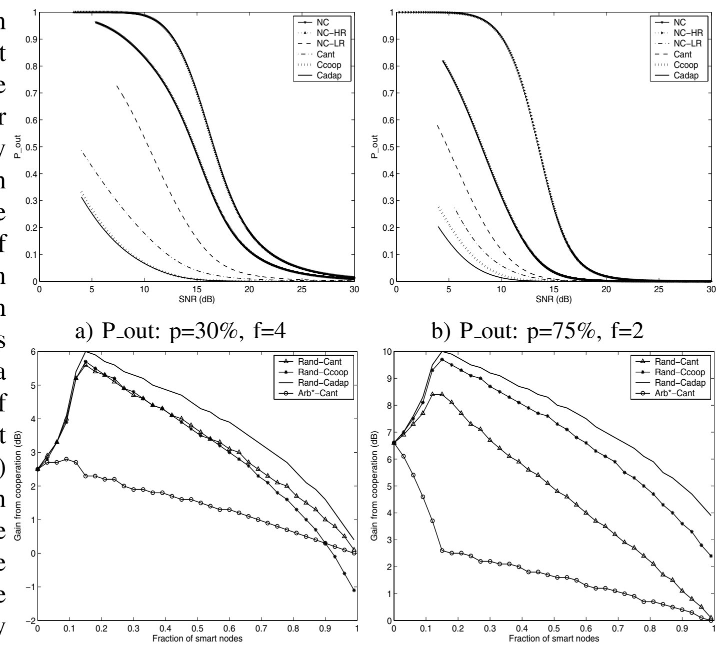
Proposition 1: If q_o and q_3 are probabilities of finding a relay in the case of an omni transmission and a spatially sensitive tranmission made with three elements respectively, then $\frac{1}{3} \leq \frac{q_3}{q_o} \leq 1$. [Proof in [9]]

Once a neighbor takes part in cooperation it assumes responsibility for the packet instead of S. In any case, the total number of trials for the packet (including those made by the cooperating node) is limited by the specification of MAC protocol (F).

Note that all the above cooperation mechanisms considered can be easily extended to the case when the smart nodes are initially using their antenna gain for increased rate instead of reliability. In such cases, on experiencing a fading loss, the transmitter would first switch back to omni rate and use the available antenna gain for reliability. Thereafter, the procedure outlined in the cooperative mechanisms can be directly applied. Since most applications would tend to use the available antenna gain for increased rate, we present numerical results evaluating the different cooperative schemes under this scenario. In the comparison, we also consider two basic rate based mechanisms to counteract fading, namely:

Non-cooperative High Rate (NC-HR): Here, the antenna gain, exploited for increased data rate on a smart link, is retained even after experiencing a fading loss. While this is not a wise idea in the presence of (time) correlated fading, it still minimizes the amount of transmit SNR consumed in every trial due to lower transmission time.

Non-cooperative Low Rate (NC-LR): Here, on experiencing a fading loss, the transmitter reduces its transmission rate to a low value which helps improve BER performance. Any available antenna gain on the link contributes to reliability as well. However, this increases the average SNR consumed per transmission and also the delay (which impacts throughput directly).



a) P_out: p=30%, f=4 b) P_out: p=75%, f=2

c) Gain: f=1 d) Gain: f=3

Fig. 5. Performance of Different Strategies

The results are presented in Figure 5 with the smart nodes employing four elements each. From the outage results in Figures 5(a) and (b) it can be clearly seen that NC-HR performs the worst in the presence of fading since it continues to use up its available antenna gain for increased rate and hence has no protection to fading loses. Though the reduced transmission time can contribute to a potential throughput increase, this is outweighed by the large outage error to result in its worst performance. NC-LR uses a rate reduction factor of two on experiencing a fading loss in our experiments. It performs better than the NC scheme but worse than the simple cooperative (C) scheme for small fractions of special nodes. However, for large fractions of special nodes, it performs slightly better than the C strategy owing to the low rate coupled with the antenna gain on most of the links (being smart). However, the increase in delay by a factor of two and hence the reduction in throughput will make the simple cooperative scheme clearly outperform the NC-LR scheme. Thus, the results clearly indicate that rate adaptation mechanisms cannot provide gains as significant as those resulting from cooperation.

It can be clearly seen from the cooperation gain results in Figures 5(c) and (d) that while C_{ant} and C_{coop} perform the best in fast fading and time-correlated fading respectively, the adaptive cooperation mechanism strikes a balance in exploiting the antenna and cooperation gains to provide the best performance under all fading conditions. Further, the degradation in cooperation gain for a homogeneous smart antenna network ($p_x = 1$) is much more graceful in the adaptive cooperation mechanism (C_{adap}) than in the other cooperative schemes.

We now proceed to propose a simple MAC protocol called *MACH* (MAC for HSAN's) that incoporates the adaptive cooperation mechanism.

V. The MACH Protocol

A. Design Challenges

There arise several challenges in realizing the adaptive cooperation mechanism outlined above in a purely distributed manner.

(i) First, in order for the transmitter S to be able to change strategies and enable cooperation, it needs to be able to distinguish a contention packet loss from a wireless fading packet loss. (ii) If there is a fading loss during a transmission, it becomes necessary for neighbors to identify this to take part in cooperation even if S has appropriately changed strategies to enable cooperation. Further, they must also identify if they are within communication range of D. (iii) Assuming, that the neighbors have a means to figure out if they can aid in cooperation, one still needs to have a distributed channel access mechanism that will ensure that only one of the neighbors assumes responsibility for retransmission and it is the one that can contribute maximum gain towards retransmission. (iv) Also, S needs to make sure that if no feasible cooperating neighbor is available then it continues to assume responsibility for the packet. (v) Finally, we also need to have an efficient channel access mechanism that can maximize utilization by exploiting the available smart nodes in the network well.

B. Channel Access

Before deciding on the MAC mechanism, one needs to decide on the fairness model desired by the protocol operation. While max-min fairness has been shown to be unsuitable for ad-hoc networks from an efficiency perspective [10], proportional fairness proves to be a good compromise between efficiency and fairness and a suitable candidate for use in ad-hoc networks [11], [10]. Hence, the fairness model that we adopt for our MAC protocol is proportional fairness. Note that, one can also adopt other fairness models and our mechanisms are not specific to the fairness model. Further, since some links in our network contribute more to the channel capacity than others, we adopt a weighted proportional fairness model to maximize the aggregate network capacity where the smart links access the channel with a higher probability than the non-smart ones. The higher priority (frequency) of the smart links in accessing the channel is needed to compensate for their reduced duration of usage of channel bandwidth, consequently resulting in a notion of fairness with respect to the channel access time.

We use the distributed persistence algorithm for omni-directional antenna networks in [11] as the basic contention resolution mechanism in our MAC protocol. It has been shown in [11] that if the persistence adaptation of each flow follows,

$$\dot{a_i} = \alpha w_i - \beta p_i a_i \tag{3}$$

then the system will converge to the optimal point of maximizing aggregate network utilization while ensuring a proportional fairness model. α and β are system parameters corresponding to a utility constant and a penalty constant respectively. p_i is the loss probability experienced by the flow i; w_i is the weight assigned to the flow, which in our case is proportional to its SNR gain contribution, and a_i is the persistence probability with which the flow decides whether to contend for a slot or not with $\dot{a_i}$ representing the rate of change of persistence. The state maintained at each node consists of the persistence probability, the system constants α and β and the flow's (link's) weight w_i. Every node i having a packet to transmit, first decides to contend for the channel with a probability of a_i. If the node succeeds, it chooses a waiting time uniformly distributed from the interval (0,B_{max}) where B_{max} is a constant. The node then waits for the backoff period (in mini-slots), after which it tries to access the channel to see if the channel is busy. If the node finds the channel to be busy (a transmission has already begun), it gives up the slot and decrements its persistence by β. Similarly, if the channel is idle but if the node undergoes a collision, it decrements its persistence by β. On the other hand, if the node finds the channel to be idle, and does not experience any collision then it has a successful transmission. At the end of the slot, all the nodes having a packet to transmit in the next slot increase their persistence by αw_i. Thus, the links that contribute more gain will increment their persistence values more aggressively and hence contend with higher persistence to provide a larger gain, while maintaining a fair channel access time. The values for α and β are empirically set to 0.07 and 0.3 in our simulations.

Every node maintains persistence values and weights for all the links on which it is a transmitter. The weights used in the persistence mechanism must be chosen appropriately. While the weights are based on the link gains ($w_i \propto \{1, K, K^2\}$) thereby giving smart links higher priority in accessing the channel, we also need to ensure that the cooperating links obtain higher priority on an average in accessing the channel than the source links. Further, among the cooperating links, the one with the higher link gain must have the highest expected priority. This is achieved by associating two constants with the weight of a link. When a link operates as a normal source (transmitting) link, it uses a weight of $c_1 w_i$ while it uses a weight of $c_2 w_i$ when it operates as a cooperating link.

Proposition 2: If $c_2 > c_1$, the desired channel access priorities will be achieved. [Proof in [9]]

C. Protocol Details

MACH uses persistence for channel access and follows a four way handshake (RTS-CTS-DATA-ACK) as in the CSMA/CA protocol. Further, it does not require any synchronization between the nodes. We now explain the sequence of operations at the source (S), destination (D) and cooperating (R) node, pseudo codes for which are available in [9].

Fading Loss Detection: The source S appends a short preamble to the DATA packet that is transmitted at a very low rate compared to the actual DATA transmission. This is similar to the short preamble in IEEE 802.11 which is transmitted at a default low rate of 1 Mbps while the DATA packet itself can be transmitted at 11 Mbps, 54 Mbps, etc. so that the preamble has a higher probability of being decoded since it contains valuable information for channel access. A similar strategy is used here although for a different purpose (for identifying fading loss). Hence, if the destination D is able to decode the short preamble but not the data, then the loss is due to fading and not due to contention. However, if fading is extremely severe resulting in loss of preamble as well, then this would not affect the correctness of operation of the protocol, but would make the protocol fall back to default operation, thereby not exploiting cooperation. However, the rate of the preamble is kept low enough to help identify a large fraction of fading loses while at the same time the preamble size is kept small enough (as required for minimal detection and decoding) to avoid excessive overhead.

Source and Destination Operations: (1) The control packets (RTS, CTS) are transmitted omni-directionally to avoid hidden terminal problems. The reason CTS needs to be omni (apart from hidden terminal problem) is because, for a neighboring node to identify if it is within communication range of D, it needs to be able to receive the CTS from D. Also, the omni-directional transmission will increase the probability of locating a relay. Hence, if a neighboring node receives both RTS and CTS, it can assume itself to be a relay.

(2) DATA and ACK packets are transmitted using the mode (smart/omni) of the transmitting node. If S is an omni node, then its DATA transmission would automatically favor cooperation. However, if the communication nodes are smart, then during fading losses alone, the mode used for transmitting DATA and ACK packets changes to enable cooperation gains. This is because, to decide if the relay should actually cooperate in retransmitting the packet, it needs to identify if the packet was lost in the first place due to fading.

(3) This is made possible by D transmitting ACK in the omni directional mode (to foster cooperation) along with the nature of loss information during "fading" losses alone. Thus, if the DATA was not decoded due to fading but the fading loss itself was detected through decoding of the preamble, then an ACK is still sent in the omni mode. The fading loss information in the ACK informs relays to participate in cooperation, while also informing the source to change strategy to provide more reliability and consequently enable cooperation. Thus, a neighboring node can both identify if it is a relay and if it should cooperate. Note that, in the absence of a fading loss, an ACK will be sent using the mode of D if DATA data was successfully received but will not be sent if DATA was lost due to contention (collision).

(4) On experiencing and being notified of a fading loss, S switches strategy from exploiting available antenna gain for increased rate to reliability (if not already using gain for reliability) first on all K elements; then on three elements and eventually to omni-directional transmission to enable cooperation. However, if it still experiences a fading loss in omni-directional mode with the number of trials not exhausted and no relay being found, then it switches back to exploiting all the available antenna gain (K elements) for reliability. In most practical cases, the maximum number of trials is three or four for the DATA packet. The loss/absence of CTS and ACK are detected through the use of timeouts.

Relay Operations: (1) Once a neighbor is aware that it is a relay through the CTS, it stores the DATA packet (if received successfully) until it receives the ACK. If ACK is not received or if it does not indicate fading then the packet is dropped. Otherwise, the relay decides to cooperate in retransmission.

(2) It then stores the DATA packet at the head of line of its MAC queue to give it the same priority as in the source node. It then contends for the packet with persistence but using c_2 constant in its weight unlike the source that uses c_1. The appropriate choice of persistence values helps the relay with the largest link gain obtain channel access with a higher probability. The relay uses its link gain only for reliability and does not switch strategy for future trials unlike the source S.

(3) R sends RTS omni-directionally, while DATA and ACK are transmitted using the mode of S and D respectively.

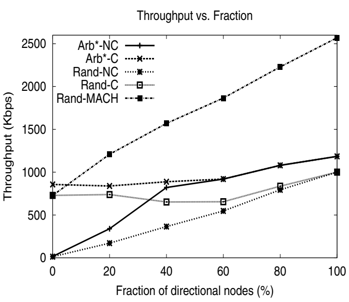
(4) When D responds back to R with a CTS, the CTS is always made omni so that S as well as other contending relays (R') are made aware of R assuming responsibility for the packet for the remaining trials (F'), and consequently drop the packet from their queue.

(5) After the first of the remaining F' trials for the packet (if needed), R falls back to using c_1 in its link weight since it becomes the virtual source for that packet.

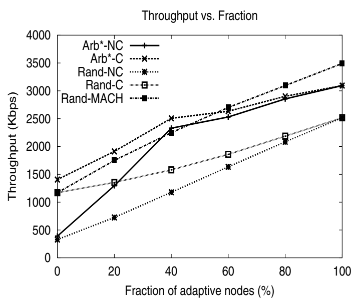
VI. Performance Evaluation of MACH

We use *ns2* network simulator for all our simulations. The topologies considered are static consisting of 100 nodes in a 1000m by 1000m grid. The transmission range used is 100m. The sources and destinations are chosen at random. UDP is used as the transport protocol. Every source generates traffic on a channel of 2 Mbps at a high rate (20-50 pkts/s with 1 KB packet size) to remain back-logged for the entire simulation duration. We consider the basic non-cooperative (NC) and cooperative (C_{ant} or simply C) schemes in random and arbitrary* networks as baselines for comparison with MACH in random networks. The simulations are run for 100 secs and each of the data point in the graphs presented is averaged over 10 seeds.

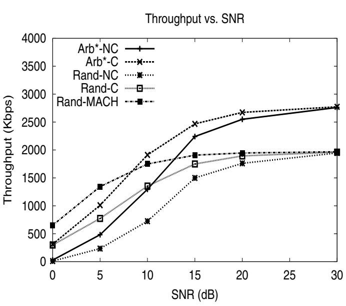
We consider two environments of study: LOS and NLOS environments. In NLOS environments, we consider a combination of adaptive and omni nodes while in LOS we consider a combination of directional and omni nodes. We use the two ray propagation physical model available in *ns2* for the LOS environment. However, for the NLOS environment with multipath scattering, we emulate the link characteristics by running Matlab simulations for the scenarios considered with different types of smart antenna processing at the nodes and incorporate them in the form of link-level packet loss statistics. The SINR threshold on every link is set to 5 dB. The number of trials for packet retransmission is limited to four. The duration of fade (in packets) is assumed to be a random variable even within a single simulation run, taking in values $\{1, 2, 3, 4\}$ with decreasing probability in that order.



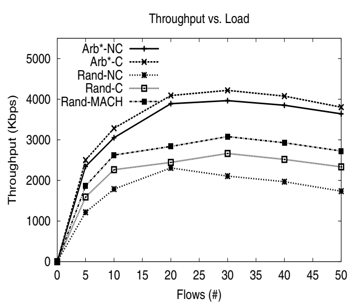
a) LOS: Fraction (x,4,5,30)



b) NLOS: Fraction (x,6,10,30)



c) NLOS: SNR (20,6,x,30)



d) LOS: Load (40,4,15,x)

Fig. 6. Throughput Results: (Fraction,Elements,T_SNR,Flows)

A. Throughput

The throughput results are presented in Figure 6. Figure 6(a) presents the throughput results for LOS environments with four elements and a transmit SNR of 5 dB as a function of the number of smart nodes in the network. It can be seen that the simple cooperative scheme is able to provide better gains in random networks than in arbitrary* networks. Further, MACH is able to provide significant gains over the simple cooperative scheme upto about 100%, especially when the fraction of directional nodes is large due to its ability to exploit cooperation efficiently and hence scale well in the presence of increasing fraction of smart nodes. Similar trends can be observed in Figure 6(b) for the NLOS case.

Figure 6(c) presents the throughput results measured as a function of increasing transmit SNR. It can be seen that the gain from cooperation is maximum at low SNR's where the impact of fading is maximum and then starts to decrease with increasing SNR's. MACH is able to provide a two fold performance improvement over the naive cooperative scheme.

Figure 6(d) presents throughput results as a function of load - increasing flows in the network. The throughput increases with increasing flows initially and then starts to decrease at high loads due to increased contention in the network. Since (i) the transmit SNR is moderate and (ii) fraction of smart nodes is almost half, most of the links in the network have a high link gain and sufficient protection against fading losses thereby reducing the potential for cooperation. However, even in this case MACH provides a gain of about 50% over the no cooperation scheme and about 25% over the simple cooperation scheme.

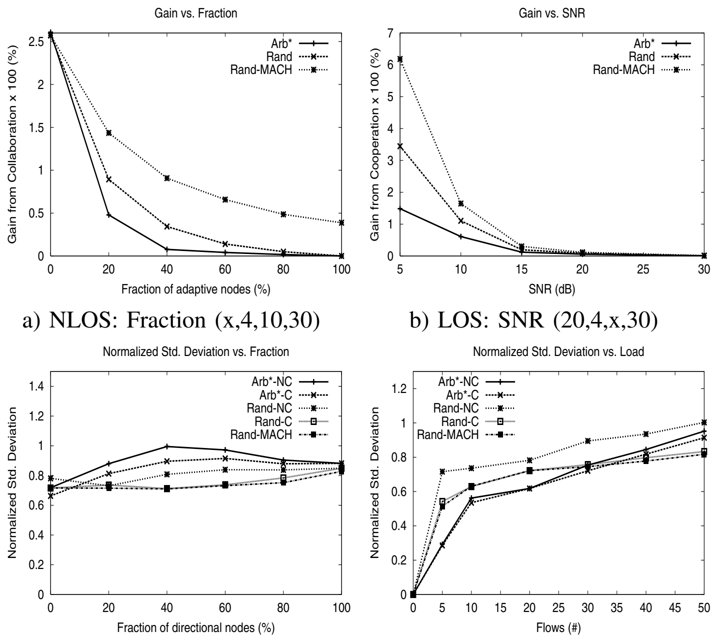
B. Cooperation Gain

Figures 7(a) and (b) present results profiling the gain in throughput (different from SNR gain) obtained from cooperation. This is measured by the difference in throughput between the cooperative and non-cooperative schemes, as a fraction of the throughput of the non-cooperative scheme. Figure 7(a) presents the gain as a function of the number of smart nodes in the network for NLOS environments. It can be seen that the gain from cooperation decreases with increasing fraction of smart nodes for all the schemes in both random and arbitrary* networks. While MACH helps even the smart nodes to exploit cooperation, it does so at the cost of reducing the number of antenna elements being used for beamforming, thereby losing out on some of the antenna gain. Hence, as the fraction of smart nodes increases, the price to pay for exploiting cooperation increases, thereby decreasing the net throughput gain.However, the gain from cooperation in MACH is still about 40% in the worst case and several folds in the best case (lower fractions).

Figure 7(b) presents the gain as a function of transmit SNR for LOS environments. It can be seen that as transmit SNR increases, the gain from cooperation decreases rapidly since the received SNR would also increase and thereby provide greater protection against fading losses. The gain from cooperation is large at small SNR, which makes cooperation a highly useful mechanism in energy constrained applications (eg. sensor networks). The gain from simple cooperation can be as high as a factor of two while the gain from MACH over simple cooperation can be as high as a factor of three.

C. Fairness

While MACH does provide significant gains in throughput, we need to ensure that the improvement comes purely from cooperation and does not come from aggressive channel access by the smart links over the omni links than that existing in non-cooperation. Hence, we consider deviation in the distribution of throughputs obtained by MACH and simple cooperation schemes with respect to that of the non-cooperation scheme. The normalized standard deviation (NSTD) results are presented as a function of the fraction of smart nodes and load in Figures 7(c) and (d) for the LOS and NLOS environments.



a) NLOS: Fraction (x,4,10,30) b) LOS: SNR (20,4,x,30)

c) LOS: Fraction (x,4,10,30) d) NLOS: Load (40,4,10,x)

Fig. 7. Gain and Fairness Results: (Fraction,Elements,T_SNR,Flows)

Increasing the fraction of smart nodes does not impact the NSTD significantly, indicating that the smart nodes are not exploited more aggressively than in non-cooperation scheme (Figure 7(c)). In fact, the measure is lower for the cooperative schemes than the non-cooperative scheme by about 10% in both random and arbitrary* networks. Further, the NSTD measures for MACH are similar to that of the simple cooperation scheme, indicating that the gain of MACH over simple cooperation is also purely due to leveraging cooperation efficiently for the smart nodes. Increasing the load increases contention in the network causing the unfairness index to increase with load (Figure 7(d)). However, the cooperative schemes still provide a lower NSTD than the non-cooperative ones by about 25%.

VII. Related Work

Most of the MAC and routing protocol design for ad-hoc networks with smart antennas have focused primarily on directional antennas [1], [2], [12], with recent interest in adaptive arrays [13] and MIMO links [4], [3]. The focus of all these works has been on networks where all nodes posses the same antenna technology. In addition, none of these solutions consider the benefits of node cooperation in their protocols. In fact, our MAC solution for node cooperation in HSAN's can be used in conjunction with these existing protocols for smart antennas for the purpose of exploiting node cooperation.

In the context of node cooperation, there are different versions considered in physical layer literature, where the popular term is *collaborative/cooperative diversity*. The goal of most of these works [5], [6] has been to emulate the transmit diversity gains of space-time codes in a distributed manner through node cooperation without the use of MEAs. On the other hand, [7] considers both transmit and receive diversity schemes. However, [7] considers power control and rate control at the cooperating nodes which is a difficult optimization in a purely distributed environment. The cooperative notion that we consider falls under the category of receive diversity exploiting a single relay, which is simple but easily realizable as a distributed mechanism since it does not require synchronization, distributed space-time code design, power control, or rate control between the cooperating nodes.

VIII. Concluding Remarks

In this work, we have considered the problem of ad-hoc networks with heterogeneous antenna technologies. We have attempted to bridge the significant performance difference existing between random and arbitrary* networks by exploiting node cooperation without assuming control over the placement of smart nodes. We have identified an inherent limitation in exploiting cooperation with directional and adaptive transmitters and have identified an efficient strategy among several potential candidates to overcome the limitation. We have also proposed a simple MAC protocol to incorporate the proposed cooperation mechanism.

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