On Broadcasting with Cooperative Diversity in Multi-hop Wireless Networks

Gentian Jakllari, Srikanth V. Krishnamurthy , Michalis Faloutsos, and Prashant V. Krishnamurthy

***Abstract*— Cooperative diversity facilitates spatio-temporal communications without requiring the deployment of physical antenna arrays. While physical layer studies on cooperative diversity have been extensive, higher layer protocols which translate the achievable reduction in the SNR per bit for a given target BER, into system wide performance enhancements are yet to mature. The challenge is that appropriate higher layer functions are needed in order to enable cooperative diversity at the physical layer. We focus on network-wide broadcasting with the use of cooperative diversity in ad hoc networks. We design a novel distributed network-wide broadcasting protocol that takes into account the physical layer dependencies that arise with cooperative diversity. We perform extensive simulations that show that our protocol can outperform the best of the non-cooperative broadcasting protocols by: (a) achieving up to a threefold increase in network coverage and, (b) by decreasing the latency incurred during the broadcast by about 50%. We also construct an analytical model that captures the behavior of our protocol. Furthermore, we show that computing the optimal solution to the cooperative broadcast problem is NP-complete and construct centralized approximation algorithms. Specifically, we construct an $O(N^{\epsilon})$-approximation algorithm with a computational complexity of $O(N^{\frac{4}{\epsilon}})$; we also construct a simpler greedy algorithm. The costs incurred with these algorithms serve as benchmarks with which one can compare that achieved by any distributed protocol.**

***Index Terms*— Cooperative Diversity, Network-Wide Broadcasting, Cross Layer Protocols.**

I. INTRODUCTION

With cooperative diversity (virtual antenna arrays) [1], [2], nodes that are in the close proximity of one another transmit the same packet at the same time to *emulate* an antenna array [1]. The robustness provided to fading due to the *diversity gain*, in turn, can translate into an increase in either (i) the achieved transmission range, (ii) the achievable data rate, or (iii) reliability.

In this paper, we focus on cooperative diversity based network-wide broadcasting in ad hoc networks. While there are many physical layer studies on cooperative diversity [2], [3], [4], very few efforts have addressed higher layer challenges in facilitating and exploiting cooperation [13], [15]. The key contribution of this paper is the design of a network-wide broadcasting protocol that exploits cooperative diversity. The protocol addresses the challenges of: (a) enabling cooperation and (b) exploiting the diversity benefits due to cooperation.

Cooperative diversity can be implemented with relays, using spread-spectrum, or with space-time codes [8]. We employ space-time block codes (STBCs) in this paper. Space-time codes have been shown to improve throughput in 802.11 networks [9], albeit not in a cooperative setting. To enable cooperation, each transmitting node should make *channel-state information (CSI)* available at its receivers; CSI provides the best performance with STBCs. In addition, cooperative broadcasting requires the sender to identify the set of cooperating nodes and make the information that is to be transmitted, available to this set. Our protocol exploits the additional transmission range achievable due to cooperative diversity to improve the broadcasting performance. In a nutshell, the scheme is based on a *counter based* approach wherein nodes decide on whether or not to broadcast based on the number of cooperative and SISO transmissions that it receives.

We construct an analytical model and perform simulations to evaluate the performance of our protocol. We demonstrate that our protocol significantly outperforms broadcasting solutions without cooperation (which we refer to as *non-cooperative broadcasting* approaches). The main performance benefits observed are: **(a) increased coverage** because of a reduction in losses due to fading and the enhanced range that helps bridge partitions; **(b) reduction in latency** by approximately 50% as compared to non-cooperative broadcasting approaches in the presence of fading and, **(c) reduced cost** which means *fewer* overall number of SISO node transmissions as compared to non-cooperative approaches.

Another significant contribution of this work is that, we show that the problem of performing network-wide cooperative broadcasting with minimum cost (We call this the **Coop-cast** problem) is NP-Complete and can be reduced to a Steiner tree problem on an appropriately constructed graph. Given this, we construct two centralized algorithms for the coop-cast problem: an approximation algorithm and a more straightforward greedy algorithm; the first is an $O(N^{\epsilon})$-approximation algorithm with $O(N^{\frac{4}{\epsilon}})$ computational complexity. We mea-

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Gentian Jakllari, Srikanth Krishnamurthy, and Michalis Faloutsos are with the University of California, Riverside (e-mail: {jakllari, krish, michalis}@cs.ucr.edu).

Prashant V. Krishnamurthy is with the University of Pittsburgh (e-mail: prashant@tele.pitt.edu).

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[1]Note that when multiple transmitters cooperate to reach a specific receiver (each using a single omni-directional antenna), the link that is formed is referred to as a *Virtual MISO* (multiple-input single-output) link. In contrast, if an omni-directional transmitter communicates with a single receiver, the link that is formed is referred to as a SISO (single-input single-output) link. The terms cooperative diversity, virtual antenna arrays or virtual MISO links are used interchangeably in this paper.

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sure the performance of these centralized approaches and use them as benchmarks for the performance of our distributed approach. The simulation results suggest that our distributed protocol is only slightly inferior in terms of cost performance, to the centralized approaches.

The rest of the paper is organized as follows. In Section II, we present the physical layer dependencies that affect higher layer protocols with cooperative diversity. In Section III, we show that the coop-cast problem can be reduced to a Steiner tree problem. We present centralized algorithms for the problem in Section IV. In Section V, we develop our distributed broadcasting protocol and analyze it in Section VI. In Section VII, we provide a performance evaluation of our protocol. Our conclusions form the final section.

II. Physical Layer Dependencies

In this section, we briefly discuss the physical layer issues related to cooperative diversity and its feasibility in ad hoc networks.

Cooperative Diversity and Space Time Codes: In a SISO system, a single transmitter sends m symbols in mT_s seconds for a symbol rate of $1/T_s$. With cooperation, there are N transmitters that transmit m complex symbols $\pm s_i, \pm s_i^*$ over kT_s seconds; here, s_i^* is simply the complex conjugate of the symbol s_i and $m \leq k$. With independently flat Rayleigh fading channels between the many transmitters and the receiver, this approach results in large diversity gains if the symbols are transmitted using space-time block codes (STBC) [20]. The receiver with knowledge of the complex channel fading coefficients h_i (the CSI) can linearly combine the multiple signals to recover the symbols with a much lower bit error rate (BER) than otherwise. The Alamouti code [19] is a well known example of STBCs with diversity of order 2. For the receiver to have CSI from each of the cooperating transmitters, each transmitter will have to send a pilot tone prior to data transmission [15]. The pilot tones consist of a known set of symbols and we assume that they can be detected as long as the average SNR exceeds a certain threshold [2].

With cooperative diversity, the symbol rate will be $\frac{m}{k}\frac{1}{T_s}$. The bandwidth utilization is the *rate* of the STBC, $R = m/k$. If $m = k$, then, $R = 1$ (full-rate) and the bandwidth is completely utilized. There are rate 1/2 and 3/4 codes that have been constructed in [21] that achieve higher orders of diversity ($N = 3$ and $N = 4$ transmitters). However, there is an associated penalty of lower bandwidth utilization (which we account for in our simulations).

To get a sense of the diversity gain, consider a *target* BER of 10^{-3}. With two cooperating nodes, for this target BER, the required SNR per bit – E_b/N_0 is 15 dB; the needed E_b/N_0 is 25 dB on a SISO link [19] [20]; E_b is the energy per bit and N_0 is the power spectral density of white noise. Thus, *with diversity gain, the signal can be recovered at a distance farther than, when there is no diversity.*

Since the receiver has to be aware of the exact space-time code that is being used, one cannot arbitrarily choose a varying number of cooperating nodes on the fly. Furthermore, choosing a varying number of transmitters could lead to effects of asymmetry (as we discuss next, the transmission and interference range depend on the total transmitted power) wherein certain broadcast links may be more far reaching than others; this could potentially increase the possibility of collisions. Thus, we fix the number of cooperating transmitters.

Impact of Transmission Power on Range and Interference: Two possibilities exist for cooperative transmissions – (a) the N cooperating nodes can all transmit with the SISO power P for a total transmit power NP and (b) they transmit with power P/N. In the former case, due to both the increased power and the diversity gain the transmission range increases; the higher power results in an increased interference range. As shown in [15], with the increase, the transmission range exceeds the interference range (due to the diversity gain). In the latter case, the diversity gain results in enhanced transmission range while the interference range remains unchanged.

Relative Differences in the Power and Delay of the Received Signals: Since the cooperating transmitters are not co-located, the signals they transmit could be received at the destination with different delays and average received powers (note that all nodes transmit at the same power level). In addition, the clocks of the transmitters may not be perfectly synchronized. This leads to the *asynchronous* reception of the multiple signals. This effect is similar to what is seen with frequency selective channels i.e., inter-symbol interference (ISI) occurs. There have been previously proposed physical layer techniques such as time-reversed space-time codes and space-time OFDM that can be used to overcome this problem [22], [23], [24], [25], [26], [27], [28]. Our previous work in [15] demonstrates that the relative delays between the signals are fairly small. In all cases, the above physical layer approaches can be used to combat the impact of lack of synchronization or *frequency selectivity*.

In [15], we have shown that the received power difference can be substantial only if the destination is at the same distance, d, equal to the SISO range of 250m, from the initiator of the transmission. In Figure 1 (from [15]), we show the CDFs of the power difference and the relative delays between two cooperative transmitters that are within the SISO reach of each other. We observe that as d increases (and these are really the scenarios where our protocols provide the most benefits), in more than 85-90% of the cases, the power difference between the signals from any two relay nodes will at most be 5 dB; in other words, the contributions from cooperating transmitters are significant in terms of achieving the overall diversity gain. The results also show that in almost 80 % of the cases, the delay difference is less than 0.6 μs, which is less than a symbol duration with the 2 Mbps 802.11 system. These results and related work on cooperative decode-and forward transmissions in [29] indicate that the diversity gain is only dependent on the number of cooperating transmitters and not on the physical location of these transmitters (as long as they are all within the SISO range)

Finally, we clarify that we do not propose any new physical layer techniques. Our objective is to design higher layer protocols for efficiently utilizing the underlying physical layer capabilities.

[2]Alternatively, differential detection can be used; this obviates the need for pilot tones. Here, we assume transmission of pilot tones by cooperating transmitters.

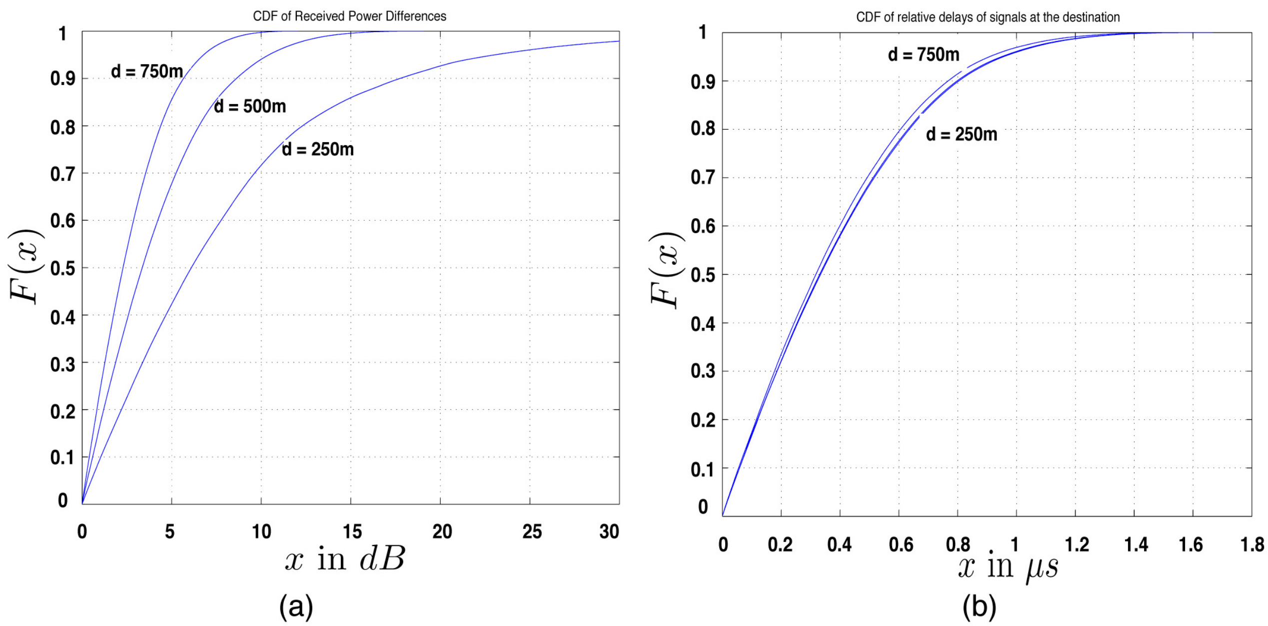

Fig. 1. CDFs of (a) the power difference and (b) relative delays

III. Optimal Cooperative Broadcasting

In this section, we study the *coop-cast* problem from a graph theoretic perspective. We show that the Coop-cast problem is NP-Complete and it can be reduced to a Steiner tree problem on an appropriately constructed graph. Note that in the next section, we use this reduction to propose an $O(N^{\epsilon})$-approximation algorithm. We defer the nuances of the physical layer dependencies for later, when we describe our *practically deployable* distributed approach in section V. Here, we consider a more general setting of the problem, wherein a node can choose the *any* sub-set of its neighbors to perform the cooperative broadcast. In contrast, our distributed protocols are restricted to using a fixed number of nodes to perform a cooperative broadcast due to implementation considerations as explained in section II. Clearly, this framework includes the more restrictive case as a special case.

Given a network, $G_o(V_o, E_o)$ our objective is to reach *all* the nodes V_0, starting from a source node $n_0 \in V_0$, while performing cooperative broadcasting, with the minimum number of SISO broadcasts [3]. We assume that all nodes can be reached with cooperative diversity; if not, we only need to consider the connected component that contains the source node. We create an auxiliary graph to reduce the problem to a Steiner tree problem. The auxiliary graph is inspired by the work in [30] which dealt with non-cooperative broadcasting. Except for this, to the best of our knowledge, there is no prior work that proves the properties described in this section or constructs centralized algorithms for cooperative broadcasting.

The initial graph: We model the network as a directed[4] graph $G_o(V_o, E_o)$, where V_o is the set of nodes with $N = |V_o|$ nodes, and E_o is the set of edges in the graph. An edge (u, w) exists if and only if u can reach w with its SISO broadcast. We denote the nodes by n_i where $i = 1, ..., N$. Each node n_i has a SISO degree of δ_i.

The auxiliary graph. Based on the initial graph, we create a new directed weighted graph $G(V, E)$. The new set of nodes V consists of : (a) the initial nodes V_0 (the **physical** nodes) and, (b) the **auxiliary** nodes v, defined below. For every physical node n_i, we add $k_i = \delta_i + 1$ auxiliary nodes, and we refer to k_i as the *maximum broadcast index* of node n_i. We define the auxiliary nodes $v_{i,l}$ to represent the broadcast with l collaborating neighbors. Thus, node $v_{i,0}$ ($l = 0$) represents the case where n_i broadcasts alone. Note that with this construction, for each physical node n_i, for a given value of l, there is only a single auxiliary node $v_{i,l}$. As discussed in section II, on average, the diversity gain of a cooperative broadcast depends only on the *number* of cooperating nodes.

Note that, in the special case (as with our distributed approach), where we impose a fixed requirement on the number of cooperating transmitters to say κ, we simply add only two auxiliary nodes $v_{i,0}$ and $v_{i,\kappa}$, for each physical node with more than κ neighbors, and only one auxiliary node $v_{i,0}$ otherwise.

There are two types of edges in the (directed) auxiliary graph: (a) **physical-to-auxiliary** edges, which are directed from physical to auxiliary nodes, and (b) **auxiliary-to-physical** edges, which are directed from auxiliary to physical nodes. First, there is an edge $(n_i, v_{i,l})$ from a physical node n_i to each of its auxiliary nodes $v_{i,l}$. Second, there is an edge from an auxiliary node $v_{i,l}$ to node n_j, if and only if, node n_j can be reached by the cooperative broadcast that auxiliary node $v_{i,l}$ represents. Note that the auxiliary graph, is a bipartite graph, since we do not have edges between two auxiliary nodes or

[3] A cooperative broadcast consists of multiple simultaneous SISO broadcasts.

[4] This initial graph is symmetric and we could have used an undirected representation. We opt for a directed representation for semantic consistency, since the final graph we construct is not symmetric.

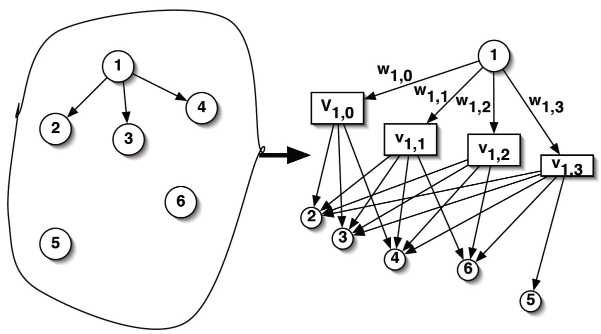

Fig. 2. An example of the initial G_0 and the auxiliary graph G showing the part that corresponds to node 1.

between two physical nodes.

We present an initial network and its auxiliary graph in Figure 2; the source node is node 1. For illustrative purposes, we make some assumptions about which nodes are reached by each cooperative broadcast: (a) broadcasting alone, node 1 can reach nodes 2, 3, and 4, (b) with one neighbor, the broadcast reaches nodes 2,3,4, and 6, (c) with two neighbors, it reaches nodes 2,3,4, and 6 (same as before), and (d) with all three neighbors, it reaches 2,3,4,5, and 6. We introduce four auxiliary nodes, $v_{1,0}, ..., v_{1,3}$. Node $v_{1,0}$ represents the case where node 1 transmits alone; thus, we connect $v_{1,0}$ with directed edges to nodes 2,3, and 4. Node $v_{1,1}$ represents the broadcast with one neighbor, and it is connected to nodes 2,3,4, and 6.

Similar connotations hold for $v_{1,2}$ and $v_{1,3}$.

The weights of the edges are set as follows. First, *the weight $w_{i,l}$ of a physical-to-auxiliary edge $(n_i, v_{i,l})$ is equal to the power required by the cooperative broadcast that node $v_{i,l}$ represents*. With $l = 0$, the weight is equal to the power incurred with a SISO broadcast of node n_i. For $l \neq 0$, the weight includes $l+2$ SISO broadcasts: (a) one SISO broadcast by n_i to its immediate neighbors, and (b) $l+1$ joint broadcasts by n_i and the l collaborating neighbors. Second, the weight of an auxiliary-to-physical edge $(v_{i,l}, n_j)$ is zero. These edges simply indicate that the nodes n_j, are reached by a cooperative broadcast at node n_i, represented by $v_{i,l}$. Note here that the cost incurred for the cooperative broadcast was already accounted for by the physical-to-auxiliary edge $(n_i, v_{i,l})$.

The problem of constructing the optimal cooperative broadcast i.e., the coop-cast problem cannot be solved exactly in polynomial time (Theorem 1 below). However, it can be reduced to a Steiner tree problem on the auxiliary graph. Note that both problems can be defined with or without an *initial source* node. For the rest of the discussion, we assume that both problems have the same source node. Let **Steiner**$(G(V,E), X)$ be the Steiner tree problem on graph G, with $X \subseteq V$ being the **terminal** nodes that the Steiner tree needs to span. There is a one to one mapping between a solution to the coop-cast problem and a solution to the Steiner tree problem on the auxiliary graph, Steiner$(G(V,E), V_0)$. The above claims are formally stated in the form of the following theorems and lemmas. We provide detailed proofs in an appendix at the end of the paper.

Theorem 1: The coop-cast problem is NP-Complete.

Lemma 1: A solution to the coop-cast problem on $G_o(V_o, E_o)$, corresponds to a solution to the Steiner tree problem on the auxiliary graph, Steiner$(G(V,E), V_0)$.

Lemma 2: A solution to the Steiner tree problem on the auxiliary graph, Steiner$(G(V,E), V_0)$, corresponds to a solution to the coop-cast problem on $G_o(V_o, E_o)$.

Theorem 2: There is a one to one mapping between a solution to the coop-cast problem and a solution to the Steiner tree problem on the auxiliary graph, Steiner$(G(V,E), V_0)$.

IV. The Centralized Approaches

Given that the coop-cast problem is NP-complete, we construct (i) an approximation algorithm *and* (ii) a greedy heuristic for solving the problem. While the approximation algorithm provides provably bounded performance, the greedy approach is simple to implement.

A. An approximation algorithm. We propose an approximation algorithm for the coop-cast problem, and call it **C-Approx**. C-Approx consists of the following three phases. **Step 1. Create the auxiliary graph:** Given the initial network $G_0(V_0, E_0)$, we create the auxiliary graph $G(V,E)$ as described in the previous section. **Step 2. Solve the Steiner tree problem:** We solve the directed Steiner tree problem Steiner$(G(V,E), V_0)$ using the approximation algorithm for directed graphs proposed by Charikar et al. [31]; we call this algorithm **Approx-Steiner**. **Step 3. Transform the solution:** We create the cooperative broadcast tree from the approximate Steiner tree, given the one to one correspondence that was shown in the previous section.

In step 2, one can select any Steiner tree heuristic appropriate for directed graphs. We choose the Approx-Steiner algorithm [31], since it has a bounded performance guarantee $O(s^\epsilon)$ with respect to the optimal cost, where s is the number of terminal nodes (defined earlier) and ϵ is a constant, $0 < \epsilon \leq 1$. The computational complexity of Approx-Steiner is polynomial and bounded by $O(m^{\frac{1}{\epsilon}} s^{\frac{2}{\epsilon}})$, where m is the number of nodes in the graph. An advantage of Approx-Steiner is that by appropriately selecting the value of ϵ we can trade off computational complexity for approximation accuracy.

Theorem 3: Given an instance of the coop-cast problem with $G_0(V_0, E_0)$, and $N = |V_0|$, the coop-cast approximation algorithm provides a broadcast tree whose cost is within $O(N^\epsilon)$ of the optimal solution.

Proof: By the construction of our coop-cast approximation, the Steiner tree problem on the auxiliary graph corresponds to a minimum cost broadcast tree on the initial graph as shown in the previous section. In the Steiner problem on the auxiliary graph, we have N terminal nodes (nodes that need to be reached by the Steiner tree). Since in the auxiliary graph, the approximation tree is within $O(N^\epsilon)$ of the Steiner tree, the broadcast tree will be within $O(N^\epsilon)$ of the optimal cooperative broadcast tree in the coop-cast problem. ■

The complexity of the algorithm can be computed, given the complexities of each phase. It is easy to see that step 2 dominates the complexity. In the Steiner tree problem on the auxiliary graph, we have $m = O(N^2)$ and $s = O(N)$ and thus, the total complexity is polynomial and bounded by $O(N^{\frac{2}{\epsilon}} N^{\frac{2}{\epsilon}}) = O(N^{\frac{4}{\epsilon}})$.

B. A greedy heuristic algorithm. We propose a greedy algorithm for the coop-cast problem, which is denoted by **C-Greedy**. Our interest here is to develop a heuristic with low complexity. Given the practical implications, C-Greedy is developed with the premise that each node can either cooperate with a fixed number of neighbors l, (if its degree is at least l) or can perform a SISO transmission. This is more restrictive than the previous schemes that allow for transmissions involving a *variable* number of cooperating nodes.

The algorithm is initiated at the source which forms the first partial broadcast tree. We say that a node is *reached*, if it has received the broadcast packet. We have three types of nodes, (a) *unvisited* nodes, which are nodes not reached by the broadcast yet, (b) *activated* nodes, which are reached nodes that have broadcasted, (c) *visited* nodes, which are reached nodes that have *not* broadcasted. At each step, we choose the best node among all the *visited* nodes. The best node denotes the node that provides the maximum additional coverage from among this set of nodes (either by performing a cooperative broadcast or a SISO broadcast). The chosen node performs the next broadcast. The algorithm terminates when all the nodes are *visited*.

V. Our Distributed Approach

In this section, we present our distributed protocol for broadcasting using cooperative diversity. We highlight physical layer implications and call forward details from Section II when appropriate. In principle, a distributed approach could be derived from any of the existing (non-cooperative) broadcast schemes. Many of these schemes require a node to have knowledge of its one-hop or two-hop neighborhood. If a distributed approach is derived from such schemes, nodes will require knowledge about the neighbors that are within their one or two *cooperative hops*. This would require additional cooperative transmissions and would make the protocol design complex. More specifically, at least $O(N)$ messages will have to be transmitted (locally) in order to facilitate this information. Here, we choose to design our protocol based on a scheme that does not need such neighborhood information, viz., the (non-cooperative) *counter-based* broadcast scheme proposed in [18]. Thus, our cooperative broadcasting protocol does not require information with regards to either the one hop or two hop *cooperative neighborhood*. Note however, that in order to facilitate cooperative broadcasts our protocol requires that each node knows its neighbors that are within a *SISO hop*. The performance of a distributed approach could be improved (to be closer to that achievable with the centralized schemes) if more information (as discussed above) is made available; however the penalty that is paid is the overhead cost. The more the information made available, the better the performance. A detailed assessment of such trade-offs is beyond the scope of this work; we have performed a preliminary study on the benefits of such information in a non-cooperative setting in [32]. We wish to point out that the design of a counter-based cooperative broadcast is not a trivial extension of the SISO counter based approach. Throughout this section, we highlight the challenges and issues that arise from the physical layer dependencies.

In the counter-based scheme, after receiving a given broadcast packet, a node sets a timer and counts the number of times it hears the same packet, prior to the expiry of its timer. If this number exceeds a preset threshold, the node does not rebroadcast the packet. Otherwise, upon timer expiry, it rebroadcasts the packet. With this approach, in sparser regions of the network, most of the nodes would participate in the broadcast while in denser regions, many of the nodes would simply quell their broadcasts [17].

Local Cooperation: In order to invoke a cooperative transmission, a node will elicit the cooperation of its neighbors. It does so by broadcasting the desired packet to its neighbors. In the packet, it also *lists* a sub-set of its neighbors (a fixed number κ) that are the nodes chosen for the cooperative transmission. To keep things simple, these neighbors are chosen at random. However, note that if the node has other information (such as GPS), it could choose this sub-set using a different criterion (as an example, it could choose its closest neighbors). If the initiator of a broadcast does not have κ neighbors, it simply invokes a SISO broadcast; its immediate neighbors then become candidates for performing cooperative rebroadcasts.

Performing the cooperative broadcast: If the chosen set of nodes were to correctly receive the transmitted packet, they participate in a cooperative broadcast of the same. In order to do so, each of the transmitters, first, is required to transmit a pilot tone. It is critical that the pilot tones do not conflict with each other; they need to be orthogonal either in time or in code. In our implementation, we separate the pilot tones in time. A simple rule, such as "minimum ID first", can establish a transmission order for the pilot tones. After the transmission of the pilot tones, the cooperating transmitters would *jointly* broadcast the packet. Note here that appropriate space-time codes are used for the broadcast (as discussed in Section II).

In practice, we cannot guarantee that all of the chosen neighbors can cooperate due to interference. The source and the participating nodes expect to hear the pilot tones and they will not follow through with the transmission of the packet, unless they hear all the expected tones. In case of failure, the source backs off and tries to instigate a cooperative broadcast later. The back off process in the above case is similar to what is done with carrier sensing. In other words, the source assumes that one of its chosen neighbors sensed the channel to be busy and hence, it backs-off and tries later.

Receiving cooperative broadcasts: An idle receiver constantly listens for pilot tones. If it receives the pilot tones, it expects a forthcoming cooperative broadcast. With the channel state information gained from the pilot tones, the receiver is then able to correctly decode the received broadcast packet.

Rebroadcasting received packets: Every node that receives a broadcast packet is a candidate for invoking a broadcast. If the node has at least κ neighbors, it will consider doing a cooperative rebroadcast; else, it seeks to perform a SISO rebroadcast. To limit the number of transmissions, each node sets a timer that expires after a uniformly chosen random time $t \in [0, T_{Max}]$, where T_{Max} is a system parameter. Before the timer expires, the node counts the number (γ) of overheard broadcasts (both SISO and cooperative) of the same packet. While computing γ, if the node is targeting a cooperative rebroadcast, it *only counts* the number of overheard cooperative

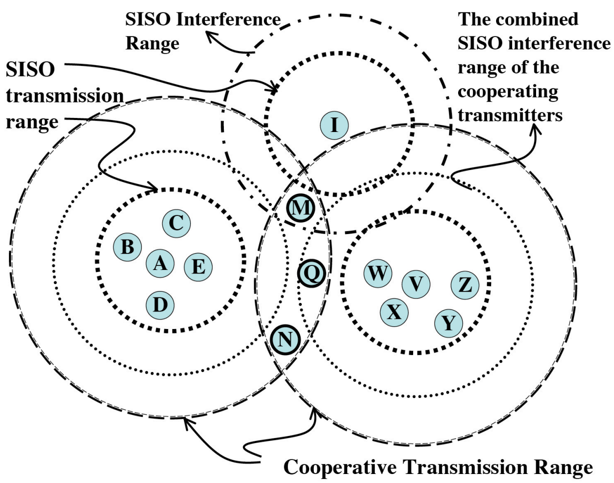

Fig. 3. A Scenario with Cooperative Broadcasting

rebroadcasts; a node that seeks to perform a SISO broadcast counts every reception (both SISO and cooperative broadcasts). If γ is above a preset threshold (say θ), the scheduled rebroadcast is aborted and the timer event is canceled. If not, when the timer expires, the node will instigate the scheduled broadcast (cooperative or SISO).

In the above policy, we distinguish between cooperative and SISO broadcasts. Our motivation is that cooperative broadcasts have larger reach. Thus, a node that is a candidate for performing a cooperative rebroadcast should not abort its broadcast, if it hears SISO broadcasts[5]. In contrast, cooperative broadcasts are counted by nodes that are considering a SISO broadcast.

Collisions: A collision occurs if a recipient node is within the interference range of any other transmission, *irrespective* of whether the interferer is performing a cooperative or a SISO transmission. If on the other hand, a node is *only within* the *transmission ranges* of multiple cooperative transmissions, *and* if it has *locked on* to the channel from one of those transmissions (acquired pilot tones), it will not experience a collision. As described in Section II, due to the diversity gain, the transmission range of a cooperative transmission could be larger than the interference range of the transmission. In order to elucidate this, we consider the scenario in Figure 3. In this figure, let us consider the following sequence of events. First, node A performs a cooperative broadcast with its neighbors (nodes B, C, D and E); the cooperating nodes transmit their pilot tones and are in the process of jointly transmitting the data packet. While the joint transmission of the data is in progress, two other transmissions are initiated. One is a cooperative transmission by node V (with its neighbors W, X, Y and Z) and the other is a SISO broadcast performed by node I. In this scenario, we consider three receivers M, N and Q as shown in the figure, that are in the process of decoding the cooperative transmission from A. We make the following observations: a) Node M is within the interference range of the SISO transmitter I; the energy from I is significant and thus, a collision occurs at M; b) Node Q is within the interference range of the *cooperative transmission* from node V. Thus, the interference from V is high and thus, a collision occurs at Q; c) Node N is within the cooperative transmission range of node V but is outside V's cooperative interference range. With the pilot tones, N has acquired the channel state information for the transmissions of A and its cooperating nodes. The interference from the cooperative broadcast from V is small, and N *is able to decode* the cooperative broadcast from A.

[5]We can have variations of this policy: such as 3 SISO broadcasts counting as one cooperative broadcast, but here we opt for simplicity. We will consider such optimizations in the future.

VI. Analysis of the Counter-Based Cooperative Protocol

In this section we present an analysis of our distributed approach. Since an exact analysis is extremely difficult if not intractable, we make some approximations. We compare the performance as predicted by our analytical model, with simulations in Section VII and discuss the implications of our approximations. We first present most of the notations and definitions that we use; other notations are introduced when needed.

- B : The event that a node broadcasts a packet either in SISO or Virtual MISO modes.
- R : The event that a node receives the broadcast packet.
- T_{SISO} : A node will abort a scheduled SISO broadcast if it overhears T_{SISO} or more copies of the broadcast packet prior to its timer expiry.
- $T_{VMISO:}$ A node will abort a scheduled VMISO broadcast if it overhears T_{VMISO} or more copies of the broadcast packet prior to its timer expiry.
- E_{SISO} The event that a node that has scheduled a SISO broadcast overhears fewer than T_{SISO} broadcasts.
- E_{VMISO} The event that a node that has scheduled a VMISO broadcast overhears fewer than T_{VMISO} cooperative broadcasts.
- B_{VMISO} : The event that a node rebroadcasts a received packet using cooperative diversity.
- B_{SISO} : The event that a node performs a SISO rebroadcast.
- k : The number of SISO neighbors needed to form a VMISO link.
- $COOP$: The event that a node has at least k neighbors; such a node can potentially perform a cooperative broadcast.
- $NoCOOP$: The event that a node has fewer than k neighbors; such a node can only perform SISO broadcasts.
- R_{VMISO} : The event that a node receives a broadcast packet that was transmitted using cooperative diversity.
- R_{SISO} : The event that a node receives a broadcast packet that was transmitted using SISO.
- q_{VMISO} : The probability that a packet transmitted using cooperation is received with an SNR per bit above a required threshold.
- q_{SISO} : The probability that a packet transmitted using SISO is received with an SNR per bit above the required threshold.
- D_{VMISO} : The event that a node receives a copy of the broadcast packet from a specific neighbor before its

timer expires. The packet copy was transmitted using cooperative diversity,

- D_{SISO} : The event that a node receives a copy of the broadcast packet from a specific neighbor before its timer expires. The copy was transmitted using SISO communications.
- N : The number of nodes in the network.
- A_{Net} : The total area of network deployment.
- R_{VMISO} : The transmission range of a cooperative transmission.
- R_{SISO} : The transmission range of a SISO transmission.

Our goal here is to compute (i) the probability that a node receives a broadcast packet ($P(R)$) and (ii) the probability that it will rebroadcast the packet ($P(B)$). These probabilities will then allow us to compute the coverage achieved and the cost incurred with our distributed approach.

The probability with which a node rebroadcasts a packet is

$$\begin{aligned} P(B) &= P(B_{VMISO} \cup B_{SISO}) \\ &= P(B_{VMISO}) + P(B_{SISO}), \end{aligned} \tag{1}$$

since the B_{SISO} and B_{VMISO} are mutually exclusive events (a node *either* performs a VMISO broadcast *or* a SISO broadcast).

For a node to broadcast using cooperative diversity, three events must occur. First, the node has to receive the broadcast packet; second, it has to have at least k SISO neighbors and third, it should not receive more than $T_{VMISO} - 1$ duplicates of the broadcast packet before its timer expires. Thus,

$$\begin{aligned} P(B_{VMISO}) &= P(R \cap E_{VMISO} \cap COOP) \\ &= P(R) \times P(E_{VMISO}|R) \times P(COOP) \end{aligned} \tag{2}$$

Similarly the probability that a node rebroadcasts the broadcast packet using SISO communications is:

$$\begin{aligned} P(B_{SISO}) &= P(R \cap E_{SISO} \cap NoCOOP) \\ &= P(R) \times P(E_{SISO}|R) \times (1 - P(COOP)) \end{aligned} \tag{3}$$

To compute the probability of the event E_{VMISO}, we make the following assumption. The specific node under consideration above and all of its one-hop neighbors receive the broadcast packet for the first time, at the same time. Furthermore, we assume that no packet collisions occur; this assumption would result in the computation of more optimistic transmit and receive probabilities. With this assumption and given that the timers are selected uniformly at random, the probability that the timer of a specific one-hop neighbor expires before that of the considered node is $1/2$. Thus, we have:

$$P(D_{VMISO}) = P\left(B_{VMISO}\right) \times q_{VMISO} \times \frac{1}{2} \times \frac{\pi R^2_{VMISO}}{A_{Net}} \tag{4}$$

Equation 4 gives the probability that a node receives a cooperative copy from a specific neighbor. The probability that a node receives fewer than T_{VMISO} such copies of the broadcast packet prior to the expiry of its timer is:

$$P(E_{VMISO}|R) = \sum_{i=0}^{T_{VMISO}-1} \binom{N-2}{i} P(D_{VMISO})^i (1 - P(D_{VMISO}))^{N-2-i} \tag{5}$$

Finally, the probability that the node has at least k SISO neighbors is given by:

$$P(COOP) = 1 - \sum_{i=0}^{k} \binom{N-1}{i} \left(\frac{\pi R^2_{SISO}}{A_{Net}}\right)^{i+1} \left(1 - \frac{\pi R^2_{SISO}}{A_{Net}}\right)^{N-i} \tag{6}$$

Using a strategy that is similar to the one above, we compute the probability of the event D_{SISO} as follows. Note here that if the node is attempting a SISO rebroadcast, it counts both the VMISO as well as the SISO packet copies that it overhears. Thus,

$$\begin{aligned} P(D_{SISO}) &= P\left(B_{VMISO}\right) \times q_{VMISO} \times \frac{1}{2} \times \frac{\pi R^2_{VMISO}}{A_{Net}} \\ &+ P\left(B_{SISO}\right) \times q_{SISO} \times \frac{1}{2} \times \frac{\pi R^2_{SISO}}{A_{Net}} \end{aligned} \tag{7}$$

and,

$$P(E_{SISO}|R) = \sum_{i=0}^{T_{SISO}-1} \binom{N-2}{i} P(D_{SISO})^i (1 - P(D_{SISO}))^{N-2-i} \tag{8}$$

Next, let P_{R1} denote the probability that a node overhears a broadcast from a specific neighbor node. This probability is:

$$\begin{aligned} P_{R1} &= P\left(B_{VMISO}\right) \times q_{VMISO} \times q^4_{SISO} \times \frac{\pi R^2_{VMISO}}{A_{Net}} \\ &+ P\left(B_{SISO}\right) \times q_{SISO} \times \frac{\pi R^2_{SISO}}{A_{Net}} \end{aligned} \tag{9}$$

In the above equation, the factor q^4_{SISO} accounts for the fact that the local communication from the initiator of a cooperative transmission to its four chosen cooperating neighbors will *all* have to be successful for the overall cooperative transmission to succeed. The probability that the above node receives the broadcast packet is:

$$P(R) = 1 - (1 - P_{R1})^{N-1} \tag{10}$$

The above set of equations (in particular, Equations 3, 2 and 10) depend on each other and it is extremely difficult to obtain closed form solutions for the desired probabilities. However, these equations can be solved iteratively to compute $P\left(B_{VMISO}\right)$, $P\left(B_{SISO}\right)$ and $P(R)$ if q_{SISO} and q_{VMISO} are known. These probabilities are dependent on the channel conditions and are computed below.

First, we set out to compute q_{SISO}. Let us assume that the average SNR per bit at a distance R_{SISO} from any transmitter is equal to the threshold β. Then, if a node u is at a distance r from v, the average SNR per bit of a packet transmitted by u at v is given by Eq. 11 below. $z = \beta \left(\frac{R_{SISO}}{r}\right)^{\alpha}$, where, α is the path-loss exponent. The SNR per bit at a distance r from the transmitter can then be approximately represented by $\gamma = z\zeta^2$, where, ζ is a Rayleigh distributed random variable with parameter σ i.e., the PDF of ζ is [14] is $f_{\zeta}(\zeta) = \frac{\zeta}{\sigma^2} e^{-\frac{\zeta^2}{2\sigma^2}}$. The probability that the received SNR is higher than the threshold is given by: This probability has been computed assuming that the node u is at a distance r from node v i.e., it is located on an annular ring of radius r and thickness dr from node v. The

$$
\begin{aligned}
P\{\gamma &> \beta\,|\text{node at } r\} = P\{z\zeta^2 > \beta\} = P\left\{\zeta^2 > \frac{\beta}{z}\right\} = P\left\{\zeta > \sqrt{\frac{\beta}{z}}\right\} \\
&= P\left\{\zeta > \sqrt{\left(\frac{r}{R_{SISO}}\right)^{\alpha}}\right\} = 1 - P\left\{\zeta < \sqrt{\left(\frac{r}{R_{SISO}}\right)^{\alpha}}\right\} \\
&= 1 - \left[1 - \exp\left(-\frac{(r/R_{SISO})^{\alpha}}{2\sigma^2}\right)\right] = \exp\left(-\frac{(r/R_{SISO})^{\alpha}}{2\sigma^2}\right) \qquad (11)
\end{aligned}
$$

probability that this is the case is given by $2\pi r dr/\pi R_{SISO}^2$ where, R_{SISO} is the maximum possible distance (given our SISO disk model) between the nodes u and v. The probability that the SNR per bit is greater than β (irrespective of where u is with respect to v) is:

$$
\begin{aligned}
q_{SISO} &= P\{\gamma > \beta\} \qquad (12) \\
&= \frac{2}{R_{SISO}^2}\int_0^{R_{SISO}} \exp\left(-\frac{(r/R_{SISO})^{\alpha}}{2\sigma^2}\right) r dr
\end{aligned}
$$

For the special case when $\alpha = 4$, q_{SISO} reduces to:

$$
\begin{aligned}
q_{SISO} &= \frac{2}{R_{SISO}^2}\int_0^{R_{SISO}} \exp\left(-\frac{r^4}{2R_{SISO}^4\sigma^2}\right) r dr \\
&= \sigma\sqrt{2}\int_0^{R_{SISO}^2/\sqrt{2}R_{SISO}^2\sigma} \exp\left(-u^2\right) du \\
&= \sigma\sqrt{\frac{\pi}{2}}\,\mathrm{erf}\left(\frac{1}{\sqrt{2}\sigma}\right) \qquad (13)
\end{aligned}
$$

Next, we compute q_{VMISO}. Since ζ is a Rayleigh distributed random variable with parameter σ, then $X = \zeta^2$ has an exponential distribution with PDF given by [14] $f_X(x) = \frac{1}{2\sigma^2}e^{-x/2\sigma^2}, x \geq 0$.

With cooperation, there are $k+1$ cooperative transmissions. Let the distances of the cooperating nodes from the receiver be r_i, for $i = 1, 2, \cdots, k+1$. The received SNR per bit will be $\gamma = \sum_{i=1}^{k+1} z_i\zeta_i^2$ where $z_i = \beta(R_{VMISO}/r_i)^{\alpha}$ and ζ_i's are $k+1$ independently distributed Rayleigh random variables. To simplify the analysis we assume that the r_i's are approximately equal to r. Note that as discussed in Section II, this is a reasonable assumption. Thus, $\gamma = z\sum_{i=1}^{k+1}\zeta_i^2$. For successful reception of the packet at the receiver, we have to compute:

$$
\begin{aligned}
q_{VMISO|r} &= P\{\gamma > \frac{\beta}{DG}\} = P\left\{z\sum_{i=1}^{k+1}\zeta_i^2 > \frac{\beta}{DG}\right\} \\
&= P\left\{\sum_{i=1}^{k+1}\zeta_i^2 > \left(\frac{r}{R_{VMISO}}\right)^{\alpha}\left(\frac{1}{DG}\right)\right\} \qquad (14)
\end{aligned}
$$

where DG is the diversity gain and $q_{VMISO|r}$ represents the probability of successful reception given r. Let $X_i = \zeta_i^2$; X_i follows an exponential distribution. We assume that all ζ_is are independent and identically distributed and under these assumptions, $Y = \sum_{i=1}^{k+1} X_i$ follows a Gamma distribution with a PDF given by $f_Y(y) = \frac{1}{2\sigma^2\Gamma(k+1)}\left(\frac{y}{2\sigma^2}\right)^k \exp\left(-\frac{x}{2\sigma^2}\right)$. The CDF of Y is given by $P\{Y \leq y\} = \frac{\gamma(k+1, y/2\sigma^2)}{\Gamma(k+1)}$. Note that $\Gamma()$ represents the Gamma function and $\gamma()$ represents the incomplete gamma function [14]. Given the above, $q_{VMISO|r}$ can be rewritten as:

$$
q_{VMISO|r} = 1 - \frac{\gamma\left(k+1, \frac{\left(\frac{r}{R_{VMISO}}\right)^{\alpha}\left(\frac{1}{DG}\right)}{2\sigma^2}\right)}{\Gamma(k+1)}. \qquad (15)
$$

Removing the dependency on r, the probability of success is then:

$$
q_{VMISO} = \frac{2}{R_{VMISO}^2}\int_0^{R_{VMISO}} \left[1 - \frac{\gamma\left(k+1, \frac{\left(\frac{r}{R_{VMISO}}\right)^{\alpha}\left(\frac{1}{DG}\right)}{2\sigma^2}\right)}{\Gamma(k+1)}\right] r dr \qquad (16)
$$

The integral in Eq(16) does not have an easy closed form. In Section VII we use numerical methods [33] to compute Equation (16) as a function of R_{VMISO}, α, k and DG.

VII. Performance Evaluation

In this section, we evaluate the performance of our distributed *cooperative* broadcasting protocol. First we present results from simulations and then we compare the results from the simulations with results from the analysis developed in Section VI. We have implemented all the protocols under consideration in an ANSI C based simulator and measure their performance in terms of the metrics defined below:

a) **Coverage:** The percentage of the nodes in the network that receive the broadcast packet; b) **Average end-to-end latency:** The duration of the broadcast (from inception to completion); c) **Cost:** The number of SISO transmissions required[6];

In our study, we compare the following approaches:

1) **C-Approx:** The centralized approximation algorithm; 2) **C-Greedy:** The centralized greedy heuristic; 3) **D-Coop:** Our distributed cooperative protocol; 4) **D-Non-Coop:** The non-cooperative counter-based broadcast algorithm [18]; 5) **C-MCDS:** An approximation of the Minimum Connected Dominating Set proposed in [34]; 6) **Flooding:** A simple flooding protocol.

The C-Approx and the C-Greedy are centralized approaches presented in Section IV. The performance of these protocols serve as benchmarks for the best achievable performance in terms of cost with cooperative diversity. D-Coop is our distributed protocol described in Section V. The counter-based D-Non-Coop is the non-cooperative broadcast protocol from which D-Coop is derived; the protocol has been shown to

[6] Recall that the cost of a cooperative broadcast is $k+2$ where k is the number of neighbors that participate in the broadcast. This accounts for the first SISO broadcast by the initiator node and the subsequent $k+1$ simultaneous broadcasts by the node and its neighbors.

achieve good coverage and cost performance in [18]. C-MCDS [34] is arguably the best centralized approximation algorithm[7] for non-cooperative broadcasts; we use it to represent the best performance in terms of cost of a non-cooperative solution. Finally, we also implement a non-cooperative *Flooding* approach, which offers the lowest latency and best coverage possible among the non-cooperative distributed protocols (data is broadcasted along the shortest possible paths and every node rebroadcasts the packet).

Simulation Models and Settings

The channel model. A transmitted signal suffers an attenuation of $d^{-\alpha}$ at a distance d from the transmitter due to path loss. We experiment with several values of α (2, 3 and 4), but here we present the results only for $\alpha = 4$ due to space limitations. As discussed in Section II, we assume that the environment under consideration reflects the use of the 2.4 GHz band. Thus, we assume that the channel is slowly varying and does not change during a packet transmission. Each SISO packet transmission is assumed to have an associated transmission range and a interference range as with the IEEE 802.11 MAC protocol. Within the transmission range the packet is subject to a random attenuation, chosen from a Rayleigh distribution, to account for fading effects. If this attenuation drives the received SNR below a threshold (of SNR_{TH} dB), the transmission fails.

Physical carrier sensing is implemented. A node can sense interference either from a SISO or a cooperative transmission, and it refrains from performing a transmission of its own.

Transmission and Interference Ranges: We compute the transmission and interference range of cooperative broadcast, derived from the corresponding diversity gain, as follows. If the diversity gain is D dB, the preset threshold SNR is now set to $(SNR_{TH} - D)$ dB. In our simulations SNR_{TH} is set to 25 dB whereas D is set to 15 dB [20] [8]. Then, with the path-loss model, we recompute a new transmission range based on this new lower threshold SNR as discussed in Section II. In our simulations, for reasons explained in section II, we limit the number of cooperating nodes to five; that is, the originating node and four of its one hop neighbors. For a path loss exponent $\alpha = 4$, the *average* transmission range is $3.54 \times d$ and the *average* interference $1.5 \times d'$; d is the SISO transmission range and d' is the SISO interference range.

Successful Reception of Packets. If ζ_i is the attenuation due to the Rayleigh fade suffered by the signal from the i^{th} transmitter, and d_i is the distance to the receiver from the i^{th} transmitter, the signal received by the receiver is now attenuated by a factor $\sum_{i=1}^{5} \zeta_i^2 d_i^4$. We compare the received SNR with the required required threshold $(SNR_{TH} - D)$ and is considered correctly received if $SNR > (SNR_{TH} - D)$. For SISO transmissions, note that the SNR is instead compared simply to SNR_{TH}. Collisions are modeled as discussed in Section V.

[7]To minimize the cost, the broadcasts are only performed by nodes that belong to a Minimum Connected Dominating Set (MCDS). Finding the MCDS is an NP-Complete problem [35]. A very efficient approximation algorithm is presented in [34].

[8]The diversity gain of 15 dB is achieved when the virtual array has four elements and the target BER is 10^{-3}. We use the same value for the diversity gain even though our virtual antenna arrays have five elements. Thus, our results are somewhat pessimistic.

Reflecting on our Models: In this paper, we use the unit disc graph and diversity gain macroscopically to evaluate the benefits of cooperation. Our goal here is to demonstrate the benefits of cooperation in ad hoc networks. A more precise way to simulate the network would be to assume a specific modulation scheme, a realistic time varying channel model between each pair of nodes (perhaps accounting for spatial correlation), checking for bit errors with each STBC transmission and thus, eventually checking for packet errors. With each transmission, it will also then be necessary to update the channel to check to see what nodes are capable of receiving packets, where there is interference (it could very well be beyond the unit disk in some cases and for much smaller ranges at other times), and so on. While this approach may give more accurate results compared to those presented here, it is beyond the scope of this paper to consider a microscopic implementation of bit level artifacts in the simulations with existing tools.

Topology: We set our unit measure of distance to be equal to the SISO transmission range. Thus, each unit corresponds to $250m$, the nominal value for the range of a transmission using a wireless card compliant with the IEEE 802.11 standard. Nodes are placed uniformly at random in a 10 unit $\times$ 10 unit flat area. We consider this a sufficiently large area since each unit corresponds to the range of a SISO broadcast.

Simulation Specifics and Parameters: Every computed value, in each performance plot, is an average computed over 100 randomly generated topologies.

We set $\theta = 3$, the number of broadcasts that a node would need to hear in order to abort its own broadcast. This value is suggested by Tseng *et al* in [18]. An appropriate value for the maximum time interval T_{Max} for which a node would wait prior to aborting its own broadcast is set to be $T_{Max} = c\ \theta\ T_p$, where T_p is the packet transmission time, and c a small constant that is scenario dependent. A value of $c = 3$ was used in the experiments reported in this paper. We have varied the value of c and observe behavioral results that are similar to those reported here.

For the centralized approaches, we construct a tree as specified in Section IV and invoke broadcasts along the tree.

We do not model mobility in this work. However, we expect that mobility will have a limited effect on the performance results for the following reasons. First, the duration of each network wide broadcast is typically much smaller than the time taken for the topology of the network to change significantly. Second, since the distributed schemes that are considered, do not rely on any topological information that could become stale due to mobility.

Impact of Pilot tones: The pilot tones are part of the distributed protocols and are implemented in the simulations as per the description in Section V. The pilot tones affects both the coverage and the overhead and this is accounted for in our simulations. In terms of coverage, if the pilot tones of one node collide with those from another, the receiver will not be able to decode the broadcast packet and hence, this would affect coverage. The optimal channel training is achieved by transmitting one symbol per transmit antenna element [36]. With the 2 Mbps 802.11 a symbol is only 2 bits while with the 11 Mbps 802.11b it is only 8 bits. Given that the broadcast

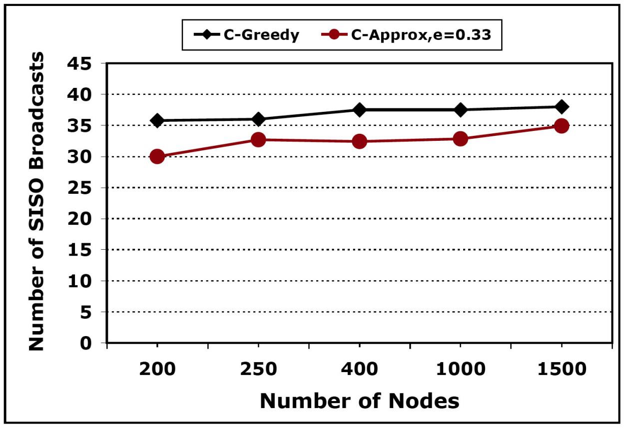

Fig. 4. Comparing the costs incurred with the Centralized Algorithms.

TABLE I
THE AVERAGE DEGREE FOR DIFFERENT NUMBER OF NODES.

Number of Nodes	Average Degree
80	3.3
150	5.26
200	6.75
250	8.19
400	12.47
1000	29.77
1500	44.17

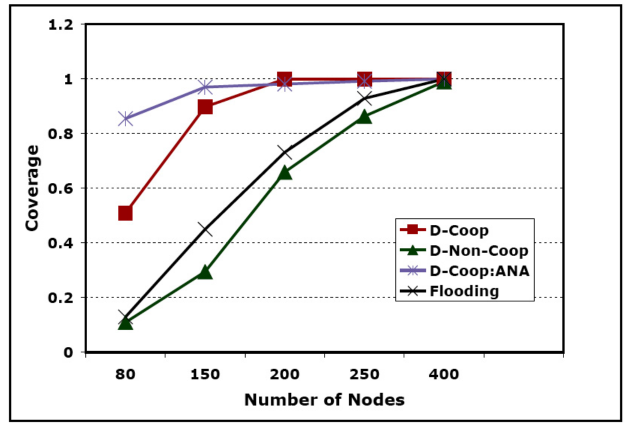

Fig. 5. Coverage vs. Number of Nodes

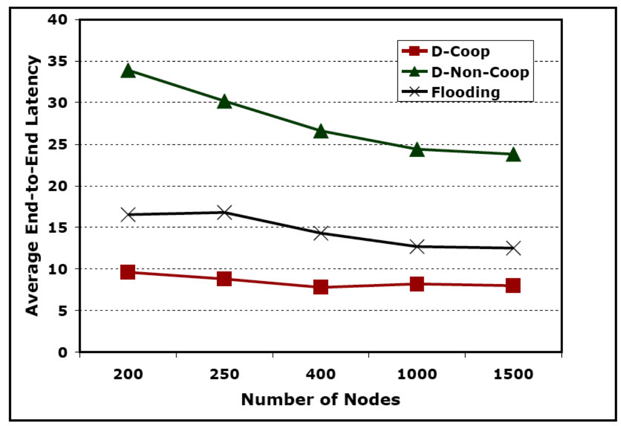

Fig. 6. Average End-to-End Latency vs. Number of nodes.

packets consist of hundreds of bytes, the overhead due to the pilot tones is thus negligible and hence is ignored in our cost computations.

A. Results and Discussion

In all our experiments, we analyze the performance of the schemes under consideration, in terms of the metrics of interest, as a function of network density. In Table I we depict the different scenarios considered (in terms of the deployed number of nodes) and reflect the average node degree for each scenario. The average node degree indicates the extent of cooperation possible in the scenario considered.

The Centralized Algorithms as Benchmarks: First, we compare the approximation algorithm, C-Approx, and the greedy heuristic, C-Greedy. In figure 4, we plot the cost incurred with the algorithms as we vary the number of nodes. Note that C-Greedy compares favorably with C-Approx with $\epsilon = 0.33$. This is an interesting observation, given that C-Greedy is much simpler to implement and less expensive computationally. Furthermore, note that while C-Approx attempts to choose the *optimal* number of cooperating neighbors, C-Greedy simply uses a fixed number (five) of cooperating transmitters. Note that the C-Approx can be made more accurate by making ϵ smaller, but this would further increase the computational complexity.

Coverage: To begin with, we measure the coverage offered by the distributed schemes under consideration. As observed in Fig. 5, when there are only 80 nodes in the network and the average node degree is as low as 3.3, the SISO based protocols perform very poorly. This is due to possible partitions in the network. However, the cooperative based scheme exploits the increase in the broadcast range to bridge many of the partitions and broadcasts the data effectively to three times as many nodes as was possible with the SISO based schemes. Note that, even with 150 nodes in the network, the cooperative approach is able to broadcast the data to over 90% of the nodes. This is twice the coverage that the best SISO algorithm, Flooding, is able to achieve. For the cooperative scheme, we depict both the simulation and analytical results; we discuss these in greater detail later.

End-to-End Latency: We plot the average end-to-end latency incurred with the distributed schemes in Figure 6. For a meaningful comparison, we consider only dense networks to ensure that all protocols deliver acceptable (higher than 90%) coverage. For sparse networks, certain schemes may provide a smaller end-to-end latency simply because they do not reach a majority of the nodes in the network. Our cooperative based algorithm (D-Coop) is able to reduce the time for data delivery by about half when compared with the fastest SISO based scheme i.e., Flooding. This is again because of the increased coverage range of each cooperative broadcast link.

Cost: Next, we measure the cost incurred in terms of the number of SISO broadcasts. Here, we also consider the cost due to the centralized schemes; note that these schemes are

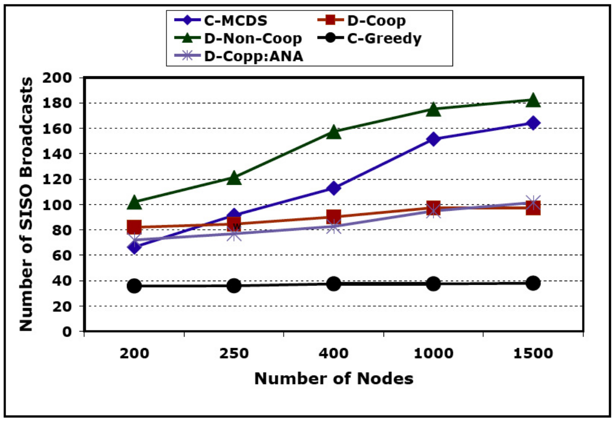

Fig. 7. Cost vs. Number of nodes.

designed to minimize the cost of the broadcast [9]. The results are depicted in Fig. 7 and reveal a somewhat counter-intuitive result. The cooperative based schemes incur a lower overhead than the SISO based C-MCDS, even though each cooperative broadcast requires 6 SISO transmissions. However, this result is reasonable since, the cooperative broadcast link, on average, has a transmission range that is 3.5 times that of the SISO range. This implies that the area covered by a cooperative broadcast is on average, $3.5^2 = 12.25$ times that covered by a SISO broadcast; so, with each broadcast, a large fraction of nodes is covered. Therefore, the number of individual broadcasts that are *quelled* with cooperative broadcasts is extremely high (with either of our centralized or counter-based approaches). As one might expect, the cost incurred with D-Coop is higher than that of the centralized schemes (due to redundant broadcasts). The results also show that the analytical model for D-Coop predicts performance that is very close to that achieved with simulations (we discuss this later).

Note that although it may seem that the cost with D-Coop is higher than with C-MCDS at extremely low densities, the result is somewhat misleading. At low densities, the broadcast with C-MCDS does not reach all the nodes (due to lapses in coverage) as seen in Figure 5. However, as noted in Figure 5, the D-Coop achieves complete coverage. Thus, one might expect that the cost would be higher with D-Coop (to account for the higher coverage).

Comparing Results from Simulations and Analysis: Finally, we compare the results from the simulations with those obtained with our analysis developed in Section VI.

We compute the probability of performing a broadcast and the probability of reception with D-Coop as detailed in Section VI and use these values to estimate the cost and coverage. The cost is computed as a sum of two terms. The first term accounts for the SISO broadcasts and the second term is due to cooperative broadcasts. In particular, $Cost = N * P_{BSISO} + N * \{P_{BVMSIO}[1 \times (1 - q_{SISO}^4) + 6 \times q_{SISO}^4]\}$. Note that when computing the cost due to virtual MISO broadcasts, we account for the fact that there is simply a single transmission if the local transmission (preceding the cooperating transmission) were to fail and six individual SISO broadcasts if the cooperative broadcast were to succeed. The coverage is essentially same as the probability of reception (it quantifies the fraction of the nodes that are covered by the broadcast).

The results from the analysis (D-Coop:ANA) are also plotted in Figures 5 and 7. We note that there is a reasonable match between the results of the simulations and the analysis. The differences between the results from the analysis and simulations are due to the assumptions made in our analysis in order to ensure mathematically tractability. In particular, it was assumed in the analysis that a node and its one-hop neighbors receive the packet simultaneously, and therefore set their count down timers at the same time. In practice (and in our simulations) this is not the case. Depending on how the broadcast packet progresses in the network, different nodes in a neighborhood will receive the packet at different times. This is turn will affect the setting of the timers and the probability of broadcast itself. Furthermore, the fact that we don't consider packet collisions in the analysis contributes to the difference between the results. In low densities, the collisions have a higher effect on the coverage than what they do in high densities. In particular, at high densities there is more redundancy in terms of the number of rebroadcasted packets to every node in the network. At low densities, a single loss could result in a significant degradation in coverage. However, the analytical results do demonstrate the behavioral nuances of cooperative communications and the benefits that may be achieved. We also note that the cost incurred in terms of the number of SISO transmissions as predicted by the analysis is higher than that with the centralized approaches; this is expected since the distributed scheme lacks global information and hence, invokes redundant broadcasts.

VIII. Conclusions

In this paper, we explore the use of virtual antenna arrays (aka cooperative diversity) for network-wide broadcasting in ad hoc networks. We design a new broadcasting protocol that is tightly integrated with the physical layer. The key property that is exploited is that cooperation can yield an extension in the transmission range, due to the diversity gain achieved in fading environments. This extension in range increases the broadcast coverage by as much as three times over what is achieved with the best SISO based approach; the latency is also reduced by up to 50%. We support the above claims with extensive simulations and with an analytical model. In addition, we also study the optimal network-wide cooperative broadcasting problem. We construct centralized approximation algorithms for the problem and simulate these as well. The performance of these approaches serve as benchmarks for evaluating any distributed approach. **Acknowledgments:** The authors wish to thank the editor Dr. K.J. Ray Liu and the reviewers for their constructive comments, which helped in improving the quality of our paper.

Appendix

Theorem 1: The coop-cast problem is NP-Complete.

Proof: One can reduce the fixed-power Minimum Broadcast problem [16] to the coop-cast problem. In the fixed-power Minimum Broadcast problem, each node can transmit

[9]Note that due to global knowledge, the centralized schemes may be expected to cover all connected components with minimal latency.

at a single fixed power level, and the goal is to reach all nodes with the minimum number of broadcasts. In more detail, in the fixed-power Minimum Broadcast problem, each node is required to choose whether to transmit or not; while in our case, a node has to do one more optimization decision: whether to do a simple or a cooperative trasmsission (and the number of cooperating nodes, assuming the more general case). The fixed-power Minimum Broadcast problem has been shown to be NP-Complete [16]. The fixed-power Minimum Broadcast problem is a special case of the coop-cast when each node is restricted to transmitting alone, that is without any cooperation. ■

Lemma 1: A solution to the coop-cast problem on $G_o(V_o, E_o)$, corresponds to a solution to the Steiner tree problem on the auxiliary graph, Steiner($G(V, E), V_0$).

Proof: Intuitively, by the construction of the auxiliary graph, each possible cooperative broadcast of a physical node n_i corresponds to an auxiliary node $v_{i,l}$, and the weight of the edge $(n_i, v_{i,l})$ corresponds to the cost of the cooperative broadcast.

In more detail, the coop-cast solution is a minimum cost tree G_T that spans the nodes in V_0 in G_0. From G_T, a solution for Steiner($G(V, E), V_0$) can be obtained in two steps. **Step 1:** for every broadcast of n_i with broadcast index l (i.e., l cooperating nodes), we include the edge $(n_i, v_{i,l})$ in the Steiner tree of the auxiliary graph. **Step 2:** for every node $v_{i,l}$ in the Steiner tree, we include the edges $(v_{i,l}, n_j)$ as long as n_j has not been reached already. We prove by contradiction that if a tree created as above in the auxiliary graph is not the Steiner tree, then, G_T is not the minimum cost tree for the coop-cast problem. Let's assume the tree created (say T) is not a Steiner tree. That means that T is not the one with the minimum cost, but a different one, say T' is the one. By definition there must be at least an edge in T', say (n_i, n_j), that has a smaller weight than the edge (n_k, n_j) in T. That would mean that in G_T, there is a cooperative broadcast from n_k that covers node n_j and this has a larger weight. This contradicts with the fact that G_T is the minimum broadcast tree. ■

Lemma 2: A solution to the Steiner tree problem on the auxiliary graph, Steiner($G(V, E), V_0$), corresponds to a solution to the coop-cast problem on $G_o(V_o, E_o)$.

Proof: Given a Steiner tree in the auxiliary graph, we can define a tree in the initial graph using the *inverse* of the process outlined in the proof to Lemma 1. Here, we show that every physical node performs at most one cooperative broadcast. In other words, there is at most one directed edge from each physical node, n_i in the solution of the Steiner($G(V, E), V_0$) problem.

We will prove this by contradiction. Let $T_1(V_{T_1}, E_{T_1})$ be a Steiner tree on $G(V, E)$ with cost $cost(T_1)$. Let us assume that, from node n_i, there are two edges $e_1 = (n_i, v_{i,l_1})$ and $e_2 = (n_i, v_{i,l_2})$ in the tree T_1. We can create a new tree T_2 by replacing these two edges e_1, e_2 with the edge e_3 that corresponds to a cooperative broadcast with the union of the collaborating nodes in e_1, and e_2. The weight of the new edge e_3 is less than the combined weight of e_1 and e_2. (Recall that by construction, the weight of e_j involves one SISO broadcast by n_i, if $l_j = 0$, and exactly two SISO broadcasts by n_i, otherwise.) Thus, e_3 is *lighter* by at least the cost of one SISO broadcast by n_i. Note that the two trees cover the same set of physical nodes. Tree T_2 is a Steiner tree with a smaller cost than that of the initial tree T_1, and thus, T_1 cannot be a Steiner tree. ■

Theorem 2: There is a one to one mapping between a solution to the coop-cast problem and a solution to the Steiner tree problem on the auxiliary graph, Steiner($G(V, E), V_0$).

Proof: The proof follows from lemma 1 and lemma 2. ■

REFERENCES

[1] J. N. Laneman, "Cooperative diversity in wireless networks: Algorithms and architectures." Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, August 2002.

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "Increasing uplink capacity via user cooperation diversity.," in *IEEE International Symposium on Information Theory (ISIT)*, 1998.

[3] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of mimo and cooperative mimo techniques in sensor networks." IEEE Journal on Selected Areas of Communications, Vol. 22, No. 6, August, 2004.

[4] I. Maric and R. D. Yates, "Cooperative multicast for maximum network lifetime." I. Maric and R. D. Yates, Cooperative Multicast for Maximum Network Lifetime, IEEE JSAC, June 2004.

[5] E. C. van der Meulen, "Three-terminal communication channels." Adv. Appl. Prob., vol. 3, pp. 120-154, 1971.

[6] T. M. Cover and A. A. E. Gamal, "Capacity theorems for the relay channel." IEEE Trans. Inform. Theory, vol. 25, pp. 572?584, Sept. 1979.

[7] A. Khandani, J. Abounadi, E. Modiano, and L. Zhang, "Cooperative routing in wireless networks.," in *Allerton Conference on Communications, Control and Computing*, October 2003.

[8] A. Nosratinia, T. Hunter, and A. Hedayat, "Cooperative communication in wireless networks.," *IEEE Communications Magazine*, 2004.

[9] A. Stamoulis and N. Al-Dhahir, "Impact of space-time block codes on 802.11 network throughput," *IEEE Transactions on Wireless Communications*, vol. 2, no. 5, pp. 1029-1039, 2003.

[10] A. Hu and S. D. Servetto, "Asymptotically optimal time synchronization in dense sensor networks," in *Proceedings of ACM WSNA '03*, 2003.

[11] Y. Hong and A. Scaglione, "Energy-efficient broadcasting with cooperative transmission in wireless sensory ad hoc networks," in *Proc. Allerton Conference*, 2003.

[12] R.Ramanathan, "Challenges: A Radically New Architecture for Next Generation Mobile Ad hoc Networks," *ACM MOBICOM*, 2005.

[13] M. Agarwal, J. Cho, L. Gao, and J. Wu, "Energy efficient broadcast in wireless ad hoc networks with hitch-hiking.," in *IEEE INFOCOM*, 2004.

[14] J. G. Proakis, "Digital communications." 4th ed. McGraw Hill,2001.

[15] G. Jakllari, S. Krishnamurthy, M. Faloutsos, P. Krishnamurthy, and O. Ercetin, "A Framework for Distributed Spatio-Temporal Communications in Mobile Ad hoc Networks," *In IEEE INFOCOM*, 2006.

[16] M. Cagalj, J. Hubaux, and C. Enz, "Minimum-energy broadcast in all-wireless networks: Np-completeness and distribution issues," in *ACM MobiCom*, 2002.

[17] B. Williams and T. Camp, "Comparison of broadcasting techniques for mobile ad hoc networks," in *ACM MOBIHOC*, pp. 194–205, 2002.

[18] S. Ni, Y. Tseng, Y. Chen, and J. Sheu, "The broadcast storm problem in a mobile ad hoc network," in *ACM MOBICOM*, pp. 151–162, 1999.

[19] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE JSAC, Vol. 16, No. 8, pp. 1451-1458*, October 1998.

[20] S. Haykin and M. Moher, "Modern wireless communications." Pearson Education, Upper Saddle River, NJ, 2005.

[21] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs.," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, 1999.

[22] G. Barriac, R. Mudumbai, and U. Madhow, "Distributed beamforming for information transfer in sensor networks," in *Proceedings of IPSN'04*, 2004.

[23] F. Ng, J.-H. Hwu, M. Chen, and X. Li, "Asynchronous space-time cooperative communications in sensor and robotic networks.," in *IEEE ICMA*, 2005.

[24] Y. Mei, Y. Hua, A. Swami, and B. Daneshrad, "Combating synchronization errors in cooperative relays.," in *IEEE ICASSP*, 2005.

[25] D. B. III, G. Prince, and J. McNeill, “A method for carrier frequency and phase synchronization of two autonomous cooperative transmitters.,” in *IEEE SPAWC*, 2005.

[26] X. Li, “Space-Time Coded Multi-Transmission Among Distributed Transmitters without Perfect Synchronization,” *IEEE Signal Processing Letters*, vol. 11, December 2004.

[27] S. Wei, D. Goeckel, and M. Valentil, “Asychnronous cooperative diversity.,” in *CISS*, 2004.

[28] E. Lindskog and A. Paulraj, “A transmit diversity scheme for channels with intersymbol interference.,” in *IEEE ICC*, 2000.

[29] A. K. Sadek, W. Su, and K. R. Liu, “Performance analysis for multi-node decode-and-forward relaying in cooperative wireless networks,” in *IEEE ICASSP*, 2005.

[30] W. Liang, “Constructing minimum-energy broadcast trees in wireless ad hoc networks.,” in *ACM MobiHoc*, pp. 112–122, 2002.

[31] M.Charikar, C.Chekuri, T. Cheung, Z. Dai, A. Goel, S. Guha, and M. Li, “Approximation algorithms for directed steiner problems.,” in *ACM-SIAM symposium on Discrete algorithms*, 1998.

[32] L.K.Law, S.V.Krishnamurthy, and M.Faloutsos, “On evaluating the trade-offs between broadcasting and multicasting in ad hoc networks,” *IEEE MILCOM*, 2004.

[33] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, “Numerical recipes in c.” Cambridge Univ. Press,1992.

[34] S. Guha and S. Khuller, “Approximation algorithms for connected dominating sets,” in *European Symposium on Algorithms*, pp. 179–193, 1996.

[35] M. Garey and D. Johnson, “Computers and intractability: A guide to the theory of np-completeness.” Freeman, San Francisco, 1978.

[36] B. Hassibi and B. Hochwald, “How much training is needed in multiple-antenna wireless links?,” *IEEE Trans. on Inform. Theory*, vol. 49, no. 4, pp. 951–963, 2003.

Gentian Jakllari is a PhD candidate at the Computer Science Dpt at the University of California, Riverside. He obtained his bachelor’s degree in computer science at the University of Ioannina, Greece and his M.Sc. in computer science at the University of California, Riverside. His research interests are in the field of wireless networking with emphasis on the design, evaluation and implementation of cross-layer protocols and algorithms.

Srikanth V. Krishnamurthy received his Ph.D degree in electrical and computer engineering from the University of California at San Diego in 1997. From 1998 to 2000, he was a Research Staff Scientist at the Information Sciences Laboratory, HRL Laboratories, LLC, Malibu, CA. Currently, he is an Associate Professor of Computer Science at the University of California, Riverside. His research interests span CDMA and TDMA technologies, medium access control protocols for satellite and wireless networks, routing and multicasting in wireless networks, power control, the use of smart antennas and security in wireless networks. Dr. Krishnamurthy has been a PI or a project lead on projects from various DARPA programs including the Fault Tolerant Networks program, the Next Generation Internet program and the Small Unit Operations program. He is the recipient of the NSF CAREER Award from ANI in 2003. He has also co-edited the book “Ad Hoc Networks: Technologies and Protocols” published by Springer Verlag in 2005. He has served on the program committees of INFOCOM, MOBIHOC and ICC and is the associate editor-in-chief for ACM MC2R.

Michalis Faloutsos is a faculty member at the Computer Science Dpt in the University of California, Riverside. He got his bachelor’s degree at the National Technical University of Athens and his M.Sc and Ph.D. at the University of Toronto. His interests include, Internet protocols and measurements, multicasting, cellular and ad-hoc networks. With his two brothers, he co-authored the paper on powerlaws of the Internet topology (SIGCOMM’99), which is in the top 15 most cited papers of 1999. His work has been supported by several NSF and DAPRA grants, including the prestigious NSF CAREER award. He is actively involved in the community as a reviewer and a TPC member in many conferences and journals.

Prashant Krishnamurthy [M] is an Associate Professor in the School of Information Sciences, University of Pittsburgh. At Pitt, he regularly teaches courses on wireless communication systems and networks, cryptography and network security. His research interests are wireless network security, wireless data networks, position location in indoor wireless networks, and radio channel modeling for indoor wireless networks. He also servedas the chair of the IEEE Communications Society Pittsburgh Chapter from 2000-2005.