Clustering in Cooperative Networks

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***Abstract*—Low power ad hoc wireless networks operate in conditions where channels are subject to fading. *Cooperative diversity* mitigates fading in these networks by establishing virtual antenna arrays through clustering the nodes. A cluster in a cooperative diversity network is a collection of nodes that cooperatively transmits a single packet. There are two types of clustering schemes: static and dynamic. In static clustering all nodes start and stop transmission simultaneously, and nodes do not join or leave the cluster while the packet is being transmitted. Dynamic clustering allows a node to join an ongoing cooperative transmission of a packet as soon as the packet is received. In this paper we take a broad view of the cooperative network by examining packet flows, while still faithfully implementing the physical layer at the bit level. We evaluate both clustering schemes using simulations on large multi-flow networks. We demonstrate that dynamically-clustered cooperative networks substantially outperform both statically-clustered cooperative networks and classical point-to-point networks.**

I. INTRODUCTION

Low power ad hoc wireless networks typically operate in channel conditions that are subject to time-varying signal degradation known as fading. Diversity mitigates fading by establishing multiple independent channels from source to destination. Unfortunately, radios in extremely low-power ad hoc networks (e.g. sensor networks) use narrow band channels and are unable to employ temporal and frequency diversity. Furthermore, their small size and reliance on batteries have precluded the use of antenna arrays for providing spatial diversity. Thus, *cooperative diversity*, a realization of a multi-antenna array using a *cluster* of single-antenna devices, was proposed as a solution for mitigating fading in ad hoc wireless networks [1]–[3].

A cluster in a cooperative network is a collection of nodes that cooperatively transmits a single packet. There are two types of clustering schemes: static and dynamic. In static clustering [1]–[11] all nodes within a cluster start and stop transmission simultaneously and nodes do not join or leave the cluster while the packet is being transmitted. Dynamic clustering [12]–[15] allows a node to join an ongoing cooperative transmission of a packet as soon as the packet is received. Until now, a comparison of these clustering schemes has not been made. In this work we show that, while the capacity of statically-clustered cooperative networks in our multi-flow scenario is at least 1.5 times the capacity of the classical point-to-point networks (i.e. isolated nodes communicating via point-to-point links), the capacity of the dynamically-clustered cooperation exceeds the capacity of static clustering by at least 2.5 times under the same conditions.

Prior to our work, two communities have studied cooperative networks. The fundamental knowledge of the physical layer in wireless networks, including cooperation, comes from the communications community [16], [17]. While dynamic clustering was proposed by this community [12]–[15], most of its work on cooperative diversity focuses on information propagation using static clusters [1]–[6]. Laneman surveys physical layer aspects of cooperation [18]. The networking community generally studies routing multiple packet flows in large statically-clustered cooperative networks [7]–[11]. Kramer et al. [19] provide an exhaustive survey of cooperation, including networking concerns. We have not encountered any previous study of dynamically-clustered cooperation by the networking community.

While previous studies demonstrate the superiority of cooperation over classical point-to-point schemes, a direct performance comparison of the two clustering methods for cooperation is missing and both communities generally have limited evaluation frameworks. Communications research on cooperation is usually conducted in a setting with a single-packet transmission through a network limited to a source, several relays, and a destination. However, networks generally operate with multiple packet flows. While the networks community studies the flows of packets in large networks, the physical layer in its work is often greatly simplified, and we show that such a model can significantly underestimate the capacity achieved by cooperative diversity. Furthermore, previous work has not accounted for interference from other packet transmissions within the same flow. We demonstrate that ignoring such interference can lead to network performance overestimate of as much as a factor of 2.

In this paper we evaluate the performance of the two cooperative diversity methods using simulations that employ multiple flows and hundreds of nodes with the physical layer faithfully implemented at the bit level. Thus, we peer deep into the physical layer, while examining large networks, and are able to accurately compare cooperation schemes under identical channel conditions and energy constraints.

This paper is structured as follows: in the next section we present background on the physical layer. In Section III we describe our system as well as the details of static and dynamic clustering. We analyze the performance of clustering schemes using simulation in Section IV. Section V concludes.

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II. WIRELESS COMMUNICATIONS BACKGROUND

In our system, at time t, a complex-valued signal $s_s(t)$ transmitted by sender s is corrupted by an AWGN process $n(t)$ with (two-sided) power spectral density $N_0/2$ and interference from the set $\mathcal{I}$ of interfering transmitters. The channel is subject to path loss and frequency non-selective Rayleigh fading that is independent for different transmitter-receiver pairs. Consequently, the multipath fading gain on a link from a transmitter s to receiver j is a complex zero-mean Gaussian random variable $h_{s,j}$. Thus, the signal $r_{s,j}$ at receiver j is expressed as follows:

$$r_{s,j}(t) \quad = \quad \frac{h_{s,j}(t)s_s(t)}{\sqrt{d^{\alpha}_{s,j}}} + \sum_{i\in\mathcal{I}} \frac{h_{i,j}(t)s_i(t)}{\sqrt{d^{\alpha}_{i,j}}} + n(t) \qquad (1)$$

where $d_{a,b}$ is the Euclidian distance between nodes a and b and α is the path-loss exponent.

Since fading is a random process, it can be mitigated by using multiple independent channels between transmitter and receiver. This technique is called diversity. We focus on *cooperative diversity*, a technique that utilizes multiple transmitters to establish a virtual antenna array [1]–[3]. With a set of transmitters $\mathcal{S}$ spaced at least a half-wavelength apart, we can establish a cooperative link to the receiver, where the receiver is able to use coordinated, but mutually-independent faded signals from all of the transmitters to decode the message. This is known as a multiple-input single-output (MISO) channel. Diversity in MISO systems is commonly obtained through space-time coding (STC) [17]. Provided that the power of all transmitters in the network is fixed at P_0 and bandwidth is normalized to 1 Hz, the following equation expresses the ergodic capacity of this channel in bits per second (bps) when STC is used [17]:

$$\mathcal{C}(j) \quad = \quad \log_2\left(1 + \frac{P_0\sum_{s\in\mathcal{S}}|h_{s,j}|^2 d^{-\alpha}_{s,j}}{N_0 + P_0\sum_{i\in\mathcal{I}}|h_{i,j}|^2 d^{-\alpha}_{i,j}}\right) \qquad (2)$$

For the Rayleigh model, $|h_{a,b}|^2$ is distributed exponentially with mean one. We follow the accepted practice and use (2).

III. SYSTEM DESCRIPTION

A. General Network Framework

We study large ad hoc wireless networks where nodes operate identical half-duplex peak-power limited[1] radios. We are interested in *network capacity*, or the maximum throughput between source and destination that different networks allow under a power constraint, with the throughput normalized by the number of nodes in the network.

The network operates as follows. Each node transmits each packet for b seconds, known as the *transmission period*. The source has an infinite supply of packets, each of size z. The source injects packets into the network by broadcasting a new packet for b seconds and then idling for rb seconds before broadcasting the next packet, where r is termed the *idle-to-busy ratio*. Idling at the source is designed to space out the packets and mitigate intra-flow interference. Parameters b and r control the rate of packet injection into the network.

By (2), node j receives $\mathcal{C}(j)$ bps when the set of nodes $\mathcal{S}$ is transmitting information about the packet desired by j and the set of nodes $\mathcal{I}$ is transmitting different packets. We now discuss two clustering methods enabling cooperative diversity.

B. Statically-clustered Cooperation

Nodes in a static cluster start and stop transmission simultaneously and do not join or leave the cluster while the packet is being transmitted. Statically-clustered cooperation generally outperforms classical point-to-point transmission [7]–[9]. Static clusters alternate between "receive" and "transmit" phases. In its cluster's receive phase, each node listens to the upstream cluster for the packet. The receive phase ends when the upstream cluster stops transmitting. Then the nodes that received the packet transmit it cooperatively downstream for b seconds.

C. Dynamically-clustered Cooperation

Dynamic clustering relaxes the constraint on when nodes join and leave the actively-transmitting cluster. A node is allowed to join an ongoing cooperative transmission as soon as it receives the packet. Figs. 1 and 2 illustrate an example where a node that is left out of the statically-clustered cooperative transmission is included when dynamic clustering is used.

Dynamic clustering is implemented using mutual information accumulation (MIA). To enable this, the information in the packet is encoded into a set of codewords and transmitted. MIA is the process where the receiver collects codewords until the mutual information of the collected codeword set exceeds the entropy of the packet and it can be decoded. Code combining is used to sum mutual information across symbols [20]. Once the node decodes the packet, it can encode the packet into codewords and join the dynamic cluster by starting transmission. A node transmits each packet for b seconds.

The work that introduced dynamic clustering [15] implemented MIA using a conventional incremental redundancy fixed-rate coding scheme [21]. The drawback of fixed-rate codes is that they may not easily adapt to changes in network conditions and are inefficient when operating outside of their fixed design. Rateless codes [22], [23] have been proposed as a flexible alternative [12]–[14]. However, analysis in [12]–[14] is based on a deterministic channel model and does not account for fading. Furthermore, the analysis in [12]–[15] focused on a single-packet transmission in small networks. Our work is oblivious to the specific implementation of MIA as long as it allows nodes to join cooperative transmission of a packet as soon as the packet is decoded.

IV. EXPERIMENTAL RESULTS

We start by describing our experimental setup. We then motivate our bit level simulations of cooperative networks and present the comparison between cooperative clustering schemes in single and multiple flow settings.

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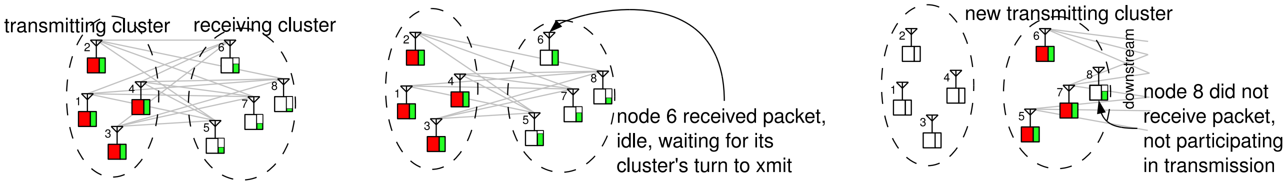
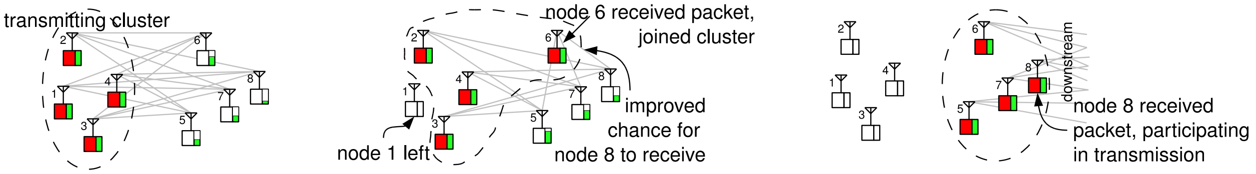
[1] While we can impose an average power constraint instead, low-power wireless transmitters are often peak power limited, and, in networks dominated by interference (such as the ones we study), the impact of the distinction between average and peak power constraints is minimal. We repeated many of the experiments in this work using an average power constraint and reached similar conclusions.



(a) $t = 1$ (b) $t = 2$ (c) $t = 3$

Fig. 1. An example of the evolution of statically-clustered cooperative transmission. See legend in Fig. 3.



(a) $t = 1$ (b) $t = 2$ (c) $t = 3$

Fig. 2. An example of the evolution of dynamically-clustered cooperative transmission. See legend in Fig. 3.

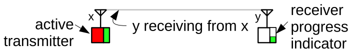


Fig. 3. Legend for Figs. 1 and 2.

A. Simulation Setup

We developed a network simulator in C that implements the physical layer on the bit level using a block Rayleigh fading channel model. Due to space limitations, we report the experiments on strip networks (however, we observed similar results with randomized network topologies [24].) A strip is a narrow rectangular $l \times w$ 2D lattice of nodes, with one unit of distance separating neighbors along the east-west and north-south axes. Our approach allows us to compare the performance of the clustering schemes independent of routing. In a more realistic setting, we envision a routing protocol connecting the source and the destination that would include a mechanism to ensure cooperation of the nodes along the path (similar to braided routing [25]).

We fix the strip length at $l = 100$ nodes and vary the width w. Thus our networks have hundreds of nodes, like prior simulation studies [7]–[9]. For statically-clustered cooperation, we report results for single-column clusters since they outperform other arrangements. The source and destination are at opposite ends of the strip. In statically-clustered cooperation the source node disseminates each packet to its cluster in zero time just before the cluster starts to transmit. The packet length is $z = 500$ bits, and $\alpha = 4$ is the path-loss exponent.[2]

Each transmitter has peak power P_0; for a given signal-to-noise ratio P_0/N_0, we adopt the standard convention of letting $N_0 = 1$ and vary P_0. We compute network capacity for values of P_0 between 10 dB and 20 dB and various strip widths w by maximizing the throughput over the transmission period b and source idle-to-busy ratio r. We report total network capacity divided by strip width w to match the normalization of the multiple flow case. Each simulation is run for 10^6 seconds to ensure that network performance reaches steady state.

B. Limitations of Previous Cooperative Diversity Analysis

To motivate the bit level simulation of cooperative networks, we present two limitations of previous cooperation studies.

1) Cluster modeled as a single node with multi-antenna array: In [7], [8] the authors use an off-the-shelf simulator to model a statically-clustered cooperative diversity network of randomly located nodes with 4-node clusters. Since cooperative diversity is not directly supported by the simulator, one node per cluster actually transmits the packet with an additional power gain of $D = 15$ dB (spatial diversity gain from using 4 antennas at bit error rate of 10^{-3} [16]); other cluster members are idle. We call this method of using uniform diversity gain to model static clusters the *power boost approximation* (PBA). Because PBA fixes the diversity order of every transmission to be equal, we would expect it to be most accurate in regular (as opposed to random) topologies. Here we apply PBA in our structured networks. We estimate the capacities of two statically-clustered single-flow networks with clusters containing two and four nodes ($w = 2$ and $w = 4$) using PBA, and compare with the capacities obtained via full simulation of the corresponding networks on Fig. 4. The PBA curves represent the capacities of point-to-point networks where all transmitters are operating at D dB above the peak power of the corresponding cooperative networks, with $D = 10$ dB for PBA of the network with 2-node clusters and $D = 15$ dB for 4-node clusters. PBA capacities are normalized by the cluster sizes of the corresponding networks. Fig. 4 shows that PBA significantly underestimates the capacity as the transmitter power increases.

2) Ignoring interference: Fig. 5 shows the effect of ignoring intra-flow interference on the capacities of two single-flow dynamically-clustered cooperative networks of width $w = 2$ with path-loss exponents $\alpha = 3$ and $\alpha = 4$. As expected, omitting interference results in a substantial overestimate of capacity. The figure also shows that the small difference in path-loss exponent α does not result in significant capacity changes.

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[2] We experimented with $\alpha = 3$ and obtained similar results (see Fig. 5).

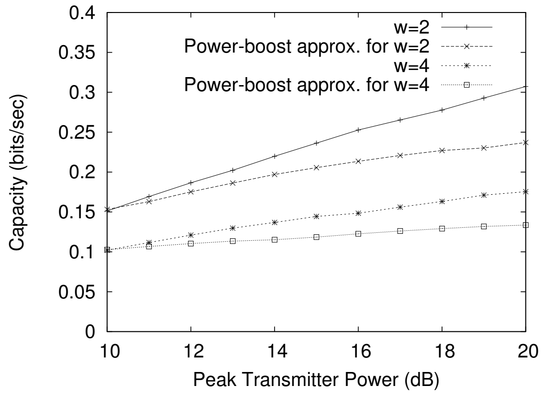


Fig. 4. Capacities of statically-clustered single-flow networks vs. PBA.

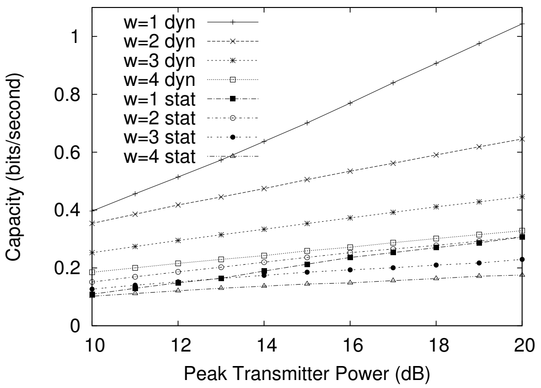


Fig. 6. Effect of changing the w in single-flow cooperative networks.

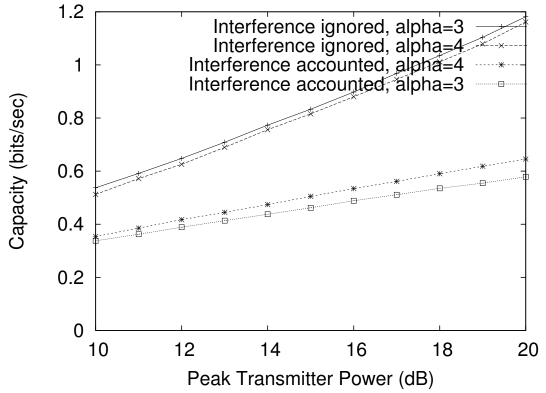


Fig. 5. Omission of interference (dynamic clusters, $w = 2$)

TABLE I
PARAMETERS YIELDING MAXIMUM CAPACITY

	Dynamic, $w = 1$		Static, $w = 2$	
P_0 (dB)	b (sec)	r	b (sec)	r
10	510	1.02	360	3
11	460	1.00	330	3
12	420	1.00	300	3
13	350	1.12	280	3
14	320	1.16	260	3
15	290	1.14	240	3
16	250	1.22	230	3
17	220	1.42	220	3
18	200	1.50	210	3
19	180	1.48	160	4
20	160	1.58	150	4

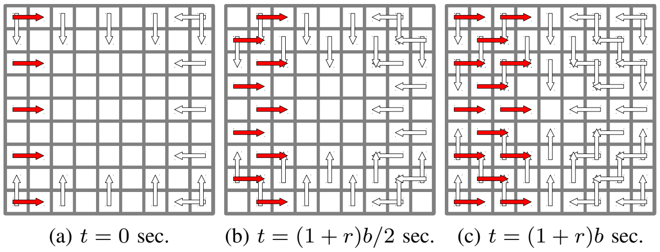
C. Comparison of Cooperative Schemes

We evaluate the normalized network capacities of statically and dynamically-clustered single-flow networks for strip widths $w = \{1, 2, 3, 4\}$ and report the results in Fig. 6. In [24] we also provide analytical models that quickly determine reasonable estimates of the capacity and the parameters that achieve it.

The reason for the substantial gain from using dynamic clustering is its opportunistic approach to utilizing network resources. A node in the dynamically-clustered network joins the cluster by starting packet transmission as soon as it receives the packet. This node is usually on the frontier of the cluster, and has a better channel (on average) to nodes that have not yet received the packet. By the time that node stops transmitting, the frontier has moved on, and the node is no longer needed to move that packet downstream. Table I lists parameters that yield maximum capacities in statically and dynamically-clustered networks. Smaller idle-to-busy ratios r in dynamic networks illustrate that the dynamic clusters are faster and tighter-packed than static. In our experiments the best dynamically-clustered network, while employing half as many nodes, delivered 40% more packets than the best statically-clustered network.

D. Impact of Multiple Flows

Finally, we examine multiflow cooperative networks. We consider a grid of identical nodes with flows traversing the grid vertically and horizontally in either direction, as illustrated in Fig. 7. Such a grid can be embedded in a network of randomly placed nodes [26]. We are interested in the per flow capacity of a grid network with flows traveling horizontally left to right (highlighted flows in Fig. 7), since TDMA can divide this capacity among flows running in both directions vertically and horizontally [27]. Thus, we simulate flows on parallel strips of length $l = 100$ nodes at least one unit distance apart. We report the total capacity per flow divided by the number of rows w used by the flow plus s additional units distance separating each flow from the neighboring flow, normalizing the capacity by the *area* the flows occupy. The parameters b and r are the same for all flows. We assume that the adjacent sources synchronize their transmissions and inject packets $(1+r)b/2$ seconds apart, thus alternating phases of their busy cycles. This is reasonable since it takes a source $(1 + r)b$ seconds to detect its neighbor's busy cycle. We thus reduce interference without sacrificing network capacity and produce a checkerboard flow pattern in Fig. 7.



(a) $t = 0$ sec. (b) $t = (1 + r)b/2$ sec. (c) $t = (1 + r)b$ sec.

Fig. 7. Flows on the grid. We compute the capacity of the highlighted flows.

Fig. 8 reports the per flow capacity for dynamically- and

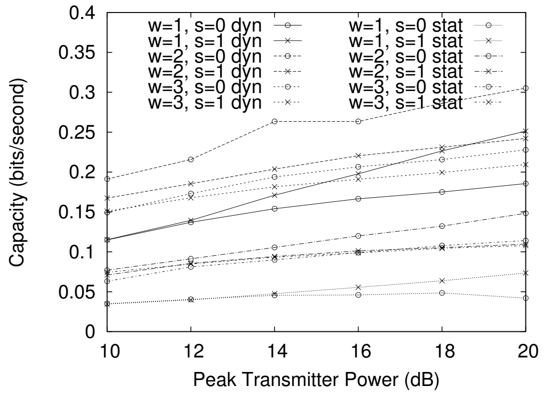


Fig. 8. Effect of changing the strip width w and the separation s in a multiflow cooperative networks.

statically-clustered multiflow networks. As in single-flow networks, dynamic clustering outperforms static clustering. Neither clustering scheme requires additional separation ($s = 0$) between the flows to maximize the capacity. For static clustering, two-node clusters ($w = 2, s = 0$) maximize capacity, as in the single-flow case. For dynamic clustering, two-node wide strips ($w = 2, s = 0$) maximize the capacity. The increase in strip width over the single-flow scenario is sensible, since a narrow cooperative cluster is more vulnerable to interference from the other flows.

V. CONCLUSION

The objective of this work is to directly compare the two clustering methods for cooperative networks. Our main contribution is the demonstration of substantial performance gain from using dynamic instead of static clustering in large cooperative networks. We also show the importance of accounting for the intra-flow interference. Finally, we provide comprehensive evaluation of the cooperative network performance using a simulation engine that both accurately implements the physical layer at the bit level and supports large multiple-flow networks. In the future we would like to develop scalable protocols to deal with changing workload conditions in cooperative networks.

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