ON THE EFFECTIVENESS OF COOPERATIVE DIVERSITY IN AD HOC NETWORKS: A MAC LAYER STUDY

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ABSTRACT

We investigate the effectiveness of cooperative diversity in interference limited ad hoc networks. The underlying cooperative techniques exploit space diversity through cooperative terminals' relaying signals for one another. We develop relay selection policy and channel allocation scheme to provide contention-free transmissions while acquiring capacity benefits from cooperative diversity. Extensive simulation results show that careless/selfish usage of cooperative relays yields higher connection blocking probabilities. A proper source allocation scheme is essential to balance the tradeoff between cooperative diversity and interference mitigation.

1. INTRODUCTION

1.1. Motivation

It has been shown that cooperative diversity, in particular, cooperative relay and cooperative MIMO, provide benefits of spatial diversity without need for physical arrays [1, 2, 3]. However, few studies have focus on the impact of cooperative diversity on system performance [4, 5], particularly in ad hoc networks. Cooperative relay requires more resources compared to direction transmission. While direct transmission requires a single channel or link between transmitter and receiver, cooperative diversity techniques in general require at least two links: one for direct transmission, and one for relay. This was considered in a link level study in [1] which concluded that cooperative diversity leads to lower spectral efficiency, but higher diversity. In ad hoc networks, using cooperative relay in general expands the range of signal radiation and hence the interference range. Therefore, there exists a fundamental tradeoff between cooperative diversity and interference mitigation in ad hoc networks.

1.2. Contribution

In this work, we investigate the impact of cooperative diversity on ad hoc networks. We examine the capabilities exhibited by different cooperative strategies from a system perspective. Since we only want to illustrate relevant trends by applying cooperative diversity to ad hoc networks, we use capacity to represent link performance. Analysis on a 3-node network shows that in general, cooperative diversity results in significant improvement in outage capacity by providing diversity to mitigate channel fading. We extend the results to ad hoc networks by considering three fundamental research issues which we believe are necessary to implementing cooperative diversity: choosing the appropriate relay, choosing the appropriate cooperative strategy, and resource allocation. We propose several policies for relay selection and two scheduling strategies for channel allocation. We observe that system-oriented relay selection and collaborative scheduling strategies are essential for interference limited systems.

(a) Cooperative Relay

(b) Relay in Ad hoc systems

Fig. 1. Cooperative Relays.

Throughout the paper, we assume that the network consists of nodes with slow mobility, and that transmission between any two nodes suffers slow frequency non-selective Rayleigh fading and gaussian additive noise. It should be noted that adaptation techniques to handle fast user mobility, coordination protocols for low signaling overhead and complex channel modelings are also important issues related to this work. We plan to consider them in future study.

2. COOPERATIVE DIVERSITY STRATEGIES

In this section, we provide a short description of cooperative diversity strategies proposed in literature. We consider a simple network of 3 nodes(Fig. 1(a)). As we stated, we assume that transmission between any two nodes suffers slow frequency nonselective fading and gaussian additive noise, and use ergodic capacity and outage capacity to evaluate link performance. We consider the case where node 1 communicates to node 2 with or without cooperation from node 2 (*i.e.* the relay node). In cooperative mode, a node 3 located within the transmission range of node 1 receives signals from node 1 during its transmission to 2, and forwards the signals to node 2. We will not include details of each cooperative strategy, since they have been investigated thoroughly in [1].

Let P denote the transmit power at each node (we assume that each node transmits at constant power), h_{ij} represent the channel response from node j to i at any time t that captures the effects of path-loss, shadowing and fading, n_i represent the receive noise and interference at node i. We model n_i as zero-mean, i.i.d. complex random variables with variance N_0. We define $\gamma = \frac{P}{N_0}$. We assume that there are multiple frequency bands available in the system but at any given time, each transmission can only use one frequency band. Let W denote the bandwidth in frequency associ-

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[*] This work was conducted while Yan Zhu and Cong Shen were visiting students at Microsoft Research Asia

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ated with each frequency band. We further assume that nodes are synchronized.

Direct Transmission(DT)
Node 1 transmits directly to node 2 without any help from node 3. The resulting throughput measure (bit/sec) is

$$R_{DT} = W log(1 + \gamma|h_{21}|^2). \tag{1}$$

Amplify-and-Forward(AF)
In this case, the relay simply amplifies and forwards the signal to node 2. The whole process (source to destination, source to relay and relay to destination) can happen in a single time slot where node 3 just behaves like a scatterer. In this case, source and relay can use the same channel to transmit to destination. The destination node can utilize a rake receiver to reconstruct the signals [6]. We refer to this as AF-RAKE strategy. Due to the limitations in current radio implementations, however, terminals can not transmit and receive at the same time in the same frequency (*i.e.* a radio transceiver is half duplex). Many have proposed to use a separate frequency (AF-FDD strategy[1]) or a different time slot (AF-TDD strategy[2]) for relay transmission. Next, we derive the capacity for each AF related strategy.

$$\begin{aligned} R_{AF-RAKE} &= W log(1 + \gamma|h_{21}|^2 + f(\gamma|h_{31}|^2, \gamma|h_{23}|^2), \\ R_{AF-FDD} &= W log(1 + \gamma|h_{21}|^2 + f(\gamma|h_{31}|^2, \gamma|h_{23}|^2), \\ R_{AF-TDD} &= \frac{W}{2} log(1 + \gamma|h_{21}|^2 + f(\gamma|h_{31}|^2, \gamma|h_{23}|^2), \end{aligned} \tag{2}$$

where

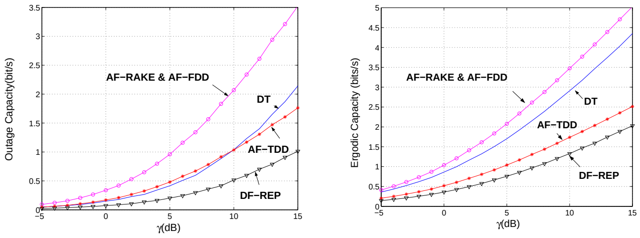
$$f(x, y) := \frac{xy}{x + y + 1}. \tag{3}$$

The factor $\frac{1}{2}$ in AF-TDD is from the fact that the transmissions between 1 to 2 (1 to 3), and 3 to 2, happen sequentially [1]. It should also be noted that AF-FDD strategy requires two channels in the system.

Decode-and-Forward with Repetition Code(DF-REP)
Noise amplification in the relay (in AF strategies) may be avoided if the message is decoded and regenerated by the relay before transmission to the destination. The performance thus depends heavily on the coding schemes utilized when regenerating the signal. In this work we consider repetition-coded decode and forward proposed in [1]. In this case, the direct and relay transmissions happen sequentially in different time slots due to the decoding delay at the relay node. The resulting throughput is given by

$$R_{DF-REP} = \frac{W}{2} \min\{log(1+\gamma|h_{31}|^2), log(1+\gamma|h_{21}|^2+\gamma|h_{23}|^2)\}. \tag{4}$$

Figure 2 illustrates the ergodic and outage (10%) capacities for different γ values, for statistically symmetric systems, i.e. $|h_{ij}| = 1$. We observe that AF-RAKE results in the best performance, but that it is difficult to implement using current hardware. We observe that among all the strategies, AF-RAKE and AF-FDD achieve the best performance, particularly in terms of outage capacity. It should be noted that AF-FDD requires radio with two transceivers while others only need one transceiver.



(a) Outage (10%) Capacity (b)Ergodic Capacity

Fig. 2. Capacity performance of different cooperative strategies for $W = 1$.

3. COOPERATIVE DIVERSITY IN AD HOC NETWORKS

In this section, we investigate the impact of cooperative diversity in ad hoc networks consisting of multiple nodes with multiple transmission requests at any given time (Fig. 1(b)). We assume that there are a number of independent frequency bands available in the network but each transmission (point to point) can only use one frequency band. Each source node can invoke collaborative neighbors as relays to provide higher throughput or to reduce transmission outage. For simplicity, we assume that each node can only invoke one neighbor as relay.

In practice, implementing cooperative diversity will take three stages. First, a source must select a cooperative neighbor within his transmission range as the relay, upon agreement from the neighbor. Second, the relay, possibly with help from the source, determines the cooperative strategy based on environmental information such as channel response and system load. Next, both direct and relay transmissions apply or compete for channel resources. We will now discuss each stage in detail.

Stage 1: Cooperative Relay Selection
Each source broadcasts its request to detect whether there are neighbors in range who would like to act as relay. Nodes available as relays can respond with a reply signal containing enough environmental information for the source to determine the quality of the relay. To reduce the number of responses, the source can include certain constraints in the request, such as minimum SINR values (from source to relay, and from relay to destination). Only nodes satisfy these constraints will respond. The source then selects the best candidate from all potential relays based on user policies. Some example policies are listed below:

Minimal distance: Choosing a nearby relay not only reduces transmission uncertainty, but also provides easy synchronization for direct and relay transmissions. We can also easily see from (3) that the distances from source to relay and relay to destination contribute equally to overall capacity.

Minimal load: Compared to direct transmission, cooperative relay scheme pushes additional traffic to relay nodes. To avoid congestion, the source can manage traffic and balance load among relays by switching to the least loaded relay at periodic intervals. In this case, heavily loaded nodes can include a measure of their load in their responses to the source, or reject the request.

Minimal interference: The source selects the relay that generates the minimum level interference to other transmissions in the local region, resulting in a balanced utilization of resources. This policy ensures cooperativeness between nodes to reduce contention and likelihood of blocked transmission.

Combination: We can compose the above rules into more com-

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[1] This requires the device to have two radio transceivers, capable of transmitting and receiving simultaneously at two channels, and receiving simultaneously from two channels.

[2] Device only needs to have one radio transceiver

plex policies to optimize impact on both users and system resources. For example, one possibility is to choose relays from only those nodes with low load and sufficiently good channel statistics (from source to relay), sorted by their likelihood of interfering with other neighbors. *Stage 2: Cooperative Strategy Selection*

The channel conditions between the relay and its surrounding nodes have a large impact on the performance of the cooperative strategy. In this work, we assume that all the nodes use the same relay strategy, and compare the impact of relay strategy on system performance.

Stage 3: Channel Resource Allocation

We consider an ad hoc network with N pairs of (direct) transmissions competing for M independent channels. For simplicity, we assume that all the channels have similar characteristics. Let $\Phi = \{n | 0 \leq n < N\}$ denote the set of direct transmissions, and $\Psi = \{m | 0 \leq n < M\}$ denote the set of all channels. Let $\Phi_r = \{l = \Re(n) | l \neq n; l, n \in \Phi\}$ denote the set of relay transmissions that represents the collection of relays chosen for each direct transmission according to a policy $\Re : \Phi \Rightarrow \Phi$. Interference between two conflicting transmissions can be characterized by a constraint set[3]. Let $C = \{c_{n,k} | c_{n,k} \in \{0,1\}, n, k \in \Phi \cup \Phi_r\}$ represent the interference constraint, where if $c_{n,k} = 1$, transmission n and k would cause interference if they used the same channel simultaneously. We define a valid channel assignment $A = \{a_{n,m} | a_{n,m} \in \{0,1\}, n \in \Phi \cup \Phi_r\}, m \in \Psi\}$ where $a_{n,m} = 1$ denotes that channel m is assigned to transmission n. A satisfies all the constraints defined by C, that is,

$$a_{n,m}\; a_{k,m}\; c_{n,k} = 0, \forall\, n, k\; \in \Phi \cup \Phi_r,\; k \neq \Re(n),\; m \in \Psi, \tag{5}$$

Let $\Lambda_{N,M}$ denote the set of valid spectrum assignments for a given set of N direct transmissions and M channels.

In this work, we intend to maximize resource utilization by providing contention-free transmissions. Since each transmission can use at most one channel and all channels are similar, this problem can be reduced to that of maximizing number of transmissions assigned to a channel, *i.e.*

$$\max_{A \in \Lambda_{N,M}} \{R_{sys} = \sum_{n \in \Phi} C_n \{(1 - C_{\Re(n)}) b(n) + C_{\Re(n)} b^r(n, \Re(n))\}\}; \tag{6}$$

where $C_n = \sum_{m \in \Psi} a_{n,m} \in \{0, 1\}$ represents the number of channel assigned to transmission n, b_n represents the reward (*i.e.* ergodic or outage capacity) acquired by using direct transmission n, and $b^r(n, \Re(n))$ denotes reward acquired by using both direct transmission n and relay transmission $\Re(n)$. For symmetric networks (e.g. grid network where nodes are within the same distance from neighbors), it is likely that $b(n) = B$, $b^r(n, \Re(n)) = \beta \cdot B$. Hence, R_{sys} can be computed as

$$R_{sys} = NB(1 - P_b) \cdot (1 + (\beta - 1) P_r), \tag{7}$$

where $P_b = 1 - \sum_{n \in \Phi} C_n / N$ denotes the blocking probability. A connection is blocked if the direct transmission can not be set up. We are also interested in the probability of relay usage, defined by $P_r = \sum_{n \in \Phi} C_{\Re(n)} / \sum_{n \in \Phi} C_n$.

The above channel allocation problem is known to be NP-hard. In this work, we extend the well-known heuristic based graph coloring solution proposed in [7] to assign channels to direct and relay transmissions. The algorithm chooses the transmission with the minimum number of conflicting neighboring transmissions, and assigns the lowest indexed channel to it without violating the constraints. The process repeats until all transmissions are assigned with a channel or there are no more channels available for assignment. Depending on the relative prioritization between direct and relay transmissions, we propose two allocation strategies.

I. Collaborative Allocation (CA)

This is the scenario where direct transmissions are prioritized over relay transmissions. Channel allocation for direct and relay transmissions are performed sequentially. Channels are first assigned to direct transmissions using the above algorithm. Next, only direct transmissions that have been assigned with a channel are allowed to set up relay using the remaining channels. Relay transmissions can not interfere with direct transmissions or other relay transmissions.

II. Non-Collaborative Allocation (NCA)

In this case, direct transmissions and relay transmissions are treated equally. That is, each direct transmission and associated relay transmissions are mapped to a transmission set that might require one or two channels depending on the cooperative strategy. Channel allocation is performed at the transmission set level. Therefore, it is possible that a direct transmission cannot be set up due to a conflict with a nearby relay transmission.

4. SIMULATION RESULTS

Our simulations are conducted under the assumption of a noiseless, immobile radio network, where nodes are distributed uniformly in a 32 by 32 grid with the same power and transmission range. Each node can only transmit to the surrounding 8 nodes. We consider two performance metrics: ergodic capacity oriented and outage capacity based system metrics, which correspond to R_{sys} in (6) by setting $\{b(n), b^r(n, \Re(n))\}$ to ergodic and outage capacities, respectively. We also examine the probability of cooperative relay usage and blocking probability, *i.e.* P_r and P_b defined in 3. We study performance with different numbers of transmission requests and available channels, using both CA and NCA strategies. Relay selection is based on the combination policy described in 3, where each source node chooses from its 8 neighboring nodes that are idle and with the least interference to other direct transmissions. The performance depends on the channel statistics. As an illustrated example, we assume that each transmission experience frequency flat, rayleigh fading with $\gamma = 0dB$, $E(|h_{ij}|) = 1$. And there are two independent channels available for transmissions, and the associated $W = 1$.

Fig. 3 illustrates the ergodic and outage capacity based system metric as a function of the number of active links in the system. We observe that similar to single user case, AF-RAKE strategy achieves the best performance, particularly in terms of outage capacity. Comparing to DT, AF-RAKE provides 10-15% gain in ergodic capacity based system metric, and at high as 90% gain in outage capacity based system metric, while AF-FDD provides 5% and 40% gain, respectively. AF-TDD does not provide any advantage.

We observe that in general, CA allocation outperforms NCA in terms of ergodic capacity based metric, but not in terms of outage capacity based metric. These can be explained by examining transmission statistics in Fig. 4. It can been seen that NCA alloca-

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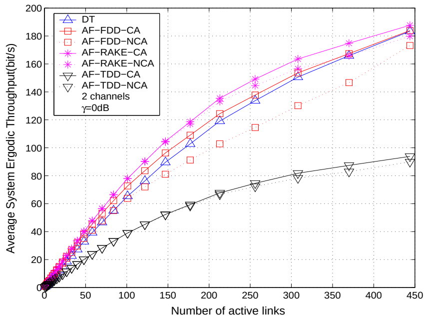
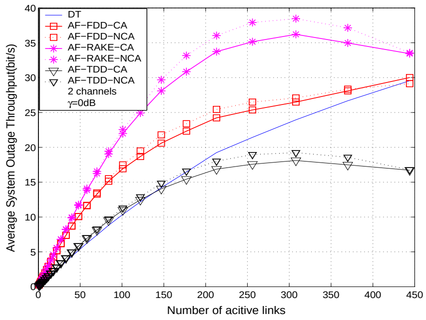
[3] In this paper, we use a binary constraint to prevent conflict transmissions to use the same channel. Interference is mainly based on distance. When two transmissions are in close distance to each other, they conflict and will both fail if using the same channel. Further complex analysis on the impact of interference will be considered in a future study.



(a) Ergodic Capacity



(b)Outage Capacity

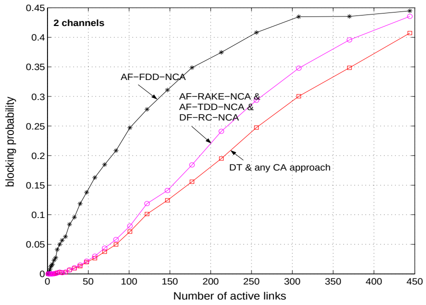
Fig. 3. System ergodic capacity and outage capacity as a function of the number of links for $\gamma = 0dB$ and two channels.

tion results in higher blocking probability P_b due to competitions from neighboring relay transmissions. On the other hand, NCA allocation enables more relay usage P_r, and enhances individual transmission through cooperative diversity. The balance between these two factors depends on β, the capacity improvement from cooperative diversity. From Fig. 2 we observe that cooperative diversity provides significant improvement ($\beta = 2$ at $\gamma = 0dB$) in outage capacity but limited improvement ($\beta = 1.2$) in ergodic capacity. Therefore, NCA outperforms CA in terms of outage oriented metric since the value of P_r is given much higher weight in R_{sys}.

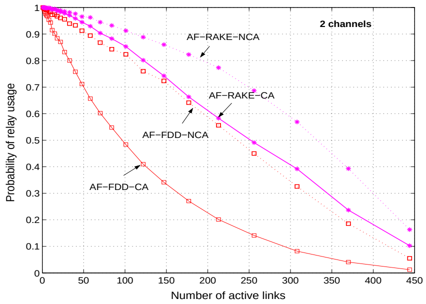
We also observe that for AF-RAKE, outage capacity drops as the number of active links exceeds 300. This is due to the tradeoff between the number of active links N, P_r and P_b. From Fig. 4 we see that both P_r and $(1 - P_b)$ decrease monotonically with N. This together with a sufficiently large β will result in inverse trend in R_{sys} as N increases.

5. CONCLUSION

In this work, we examine the performance of cooperative diversity strategies in interference limited ad hoc networks. We conclude that cooperative diversity could result in system performance improvement, but the gain depends heavily on the choice of cooperative strategy and resource allocation strategy. It is clear that careless/selfish usage of cooperative relays in an interference-limited environment will yield higher connection blocking probabilities. However, opportunistic relay usage when neighboring nodes are idle can lead to higher capacity. Only through a fair and efficient resource allocation scheme, one can reach the equilibrium of these two conflicting approaches.



(a) Probability of direct link failure



(b)Probability of relay usage

Fig. 4. Cooperation usage and link success statistics for systems with two channels

6. REFERENCES

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