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14. ABSTRACT
Future tactical networks will be complex, with severe constraints on energy and bandwidth, operating in dynamic and unpredictable environments. By exploiting the broadcast nature of a wireless medium and spatially dispersed nodes, some of the advantages of using multiple antennas can be realized through cooperation among nodes in a network. Recent work has demonstrated that cooperation can provide increased range, improved efficiency, and more reliable and longer lasting connectivity. However, in large, complex networks, centralized control will likely be infeasible, and the overhead required for communications between the cooperating nodes could be excessive. To address these issues, we focused on developing and analyzing cooperative strategies which work well without centralized control or inter-node communications, and which are based on locally obtained information. In particular, we devised several decentralized techniques for relay selection and demonstrated the efficacy of these approaches in terms of outage, spectral efficiency, and energy efficiency. We also developed and evaluated several techniques for decentralized cooperative routing. Finally, we initiated a structured study, based on rate-distortion theory, to quantify the overhead-performance trade-off, and to develop optimal algorithms based on source-coding solutions.

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Final Report
Decentralized Cooperative Networking

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1. Introduction

Future tactical networks will operate in dynamic, unpredictable, and heterogeneous environments, and will have severe constraints on energy and bandwidth. The use of multiple antennas, which has provided significant improvements in performance for single-link communications, should also provide similar advantages in such networks. By exploiting the broadcast nature of the wireless medium and spatially dispersed nodes, some of these advantages can be realized through cooperation among single-antenna nodes in a network.

In cooperative systems, a group of nodes can transmit together as a virtual antenna array to obtain diversity gains. Previous work has demonstrated that cooperation can significantly improve the performance of wireless networks; in particular, cooperation can provide increased transmission range, improved energy and bandwidth efficiency, and more reliable and longer lasting network connectivity. However, in large, complex, dynamic networks, centralized control will likely be infeasible, and the overhead required for communications between the cooperating nodes could be excessive. To address these issues, we focused on developing and analyzing cooperative strategies which work well without centralized control or full inter-node communications, and which are based as much as possible on locally obtained information.

2. Objectives

This research program was aimed at developing a broad suite of cooperative strategies that can provide reliable network performance in highly dynamic environments, with severe constraints on energy and bandwidth. The original program proposal included the following goals:

- Devise and analyze decentralized, cooperative strategies based as much as possible on locally obtained information, and which are relatively insensitive to uncertainties in the environment.
- Evaluate the implications of decentralized decision making in cooperative networking, including identification of the overheads at the PHY, MAC, and network layers and the bottlenecks to improving performance, as well as an evaluation of the dynamics of these algorithms.
- Determine the minimum set of parameters and conditions that are necessary to make decisions.
- Develop an OFDMA-based routing strategy for cooperation in multihop networks. The required flow of CSI throughout the network and the effects of interference will be quantified.
- Using a utility-based model of cooperation, develop an algorithm for joint routing and cooperation using only local decisions.
- Investigate the use of evolutionary algorithms to achieve global networking objectives for

cooperation based only on local information and decisions.

3. Summary of Research Results

During the term of this grant, we have made progress on several aspects of the program as described above, as well as in several new directions. One student (Lu Zhang) received his PhD and now works at Alcatel-Lucent Bell Labs in Shanghai. Three students (Hao Feng, Gubong Lim, and Yao Xiao) joined the project in September 2009, and all three passed their PhD Qualifying Exams in June 2010. A post-doc, Hongzheng Wang, was in my group from August 2010 through July 2011. The results and accomplishments from the work supported by this grant are summarized below; detailed descriptions can be found in the publications listed in Section 5 (hyperlinks to the papers are included). The work has culminated in fifteen conference papers, as well as two journal articles and two dissertations. We are also preparing two manuscripts for submission. To better organize the discussion, the work has been divided into four categories with several sub-categories.

A. Decentralized Cooperation in a Networking Context

Our goal is to devise an efficient cooperative protocol that uses distributed control, has low overhead, and provides good performance in a realistic networking context. Based on the complexity of the problem, neither simulation nor theoretical optimization alone can provide the solution. Rather, a methodology combining *analysis* and *synthesis* seems to offer more potential for success. It is often easier to first consider a heuristically derived protocol and then, using simulation, evaluate its performance under realistic conditions. The lessons learned from this exercise should lead to new heuristic protocols. This approach permits the evaluation of complicated protocols in realistic environments, but the conclusions are protocol-specific. Alternatively, we could consider a *synthesis* approach, in which we define an optimization problem that, if solvable, can provide some general "truths." The solutions to these problems, however, are often difficult to obtain without unrealistic simplifying assumptions. The best approach, then, should be a combination where the lessons learned from the analysis provide the essential features that should be the focus of a new optimization problem; and, in turn, the lessons learned from the synthesis should provide the insight needed to develop better heuristic solutions. Our work involved activities in both analysis and synthesis, as well as a few new twists and turns.

Analysis: Evaluation in a Realistic Networking Context

In collaboration with Prof. C.-C. Shen, CIS, University of Delaware, we developed a *strawman* cooperative protocol and evaluated its performance in realistic networking scenarios, taking into account the overheads incurred at the physical, MAC, and network layers. The strawman was evaluated for scenarios with multiple simultaneous data flows, and compared with non-cooperative communications, as well as other cooperative protocols. Based on the *lessons learned*, we devised a new heuristic protocol.

Synthesis: Overhead Constraints

Ideally, we should be able to synthesize, motivated by minimal-overhead considerations, a *best* cooperative networking protocol. However, developing these solutions is limited by the tractability of the optimization and the mathematical representation of reality. In particular, the main challenge is how to include the overhead within the definition of a solvable problem. The objective is to define an optimization problem that reflects reality, but is simple enough to solve. Then, we can use the structure of the solution to derive heuristic algorithms to evaluate in a realistic environment. In our work so far, we have only considered very simple scenarios. For example, consider the simple relay selection problem where the objective is to minimize the end-to-end outage. Assume the same transmission power for all nodes and the availability of instantaneous CSI at each node. Since each node uses the same fixed transmit power, the CSI at the first hop plays no role. The optimization only requires CSI at the second hop, and, thus, the metric can be chosen as the SNR at the destination. If we also add the constraint that only one node acts to relay the source information, the solution is obvious: Pick the node with the largest instantaneous path gain. This approach, called *Best-Select cooperation*, was used heuristically in previous work and has been incorporated into a networking context. Similarly, if only average CSI is available, we would pick the node with the largest mean path gain to the destination. The performance of this algorithm was also previously studied. Alternatively, if several nodes can transmit, maximal-ratio transmission is optimal. When there is no control information exchanged between nodes and Space-Time Block Coding (STBC) is used for transmit diversity, M-group cooperation provides the minimum outage. More generally, we could define an internode communication matrix for control traffic whose elements correspond to the *usage status* of a link.

Synthesis: Optimality of M-Group Cooperative Relaying

With M-group, the nodes that have already successfully decoded the information from the source node will independently and randomly divide themselves into M groups and each group then emulates one antenna of an M-antenna system. By applying a pre-determined STBC scheme, cooperation among the relays, and the resulting performance gain, can be obtained. It has been shown that M-group can achieve almost the same outage performance as a true multiple-antenna STBC system, with very low complexity. Moreover, M-group demands the least amount of overhead compared with other distributed STBC schemes: it requires neither inter-relay channels nor a central control unit. In our work, we proved that, in a pure Rayleigh fading environment, M-group Dis-STBC is the optimal transmission strategy. The optimal strategy for more realistic environments, including path loss, was also derived. Simulation results showed that M-group can achieve a near-optimal performance without incurring additional overhead.

Interference Characterization

In this ambitious project, a multihop cooperative network was studied, and the impact of cooperation among nodes on the performance of the network was analyzed. With cooperation, each single wireless link of the network can be greatly enhanced, which in turn leads to a potential improvement of the network's performance. On the other hand, multiple-node cooperation results in a higher level of spatial interference, thereby degrading the performance of the network. In this work, we assumed the locations of the nodes form a Poisson process on the plane, and the interference caused by all concurrent cooperative transmissions was characterized using stochastic geometry. Our long-term goal is to better understand the trade-off between the two opposing effects of cooperation; this study is facilitated by characterizing the spatial interference.

Spectral Efficiency of Distributed Cooperative Relaying

Many cooperative relaying strategies have been proposed over the last ten years. One strategy is to select a single node and utilize decode-and-forward relaying. The selection of the “best” relay can be done easily if there is a central controller or if inter-node information exchange is permitted. This might require a significant amount of control overhead; performing relay selection in a distributed manner requires much less overhead. Among several distributed relay selection schemes, timer-based selection provides an elegant approach to select the “best” relay. In this approach, every cooperating node that can successfully decode the signal from the source sets up a timer so that the best node has the shortest timer. For example, if higher channel power gain to the destination is better, the individual timer can be set as inversely proportional to the channel power gain. Once the timer expires, this node begins transmitting, and the other nodes back off. In another relaying strategy, proposed in the literature, all the nodes that can decode the source information to transmit. One possible approach uses a STBC to coordinate the simultaneous transmissions from the multiple relays. Distributed STBC (Dis-STBC) can provide full spatial diversity in the number of cooperating nodes. To implement Dis-STBC, either a central controller or full inter-node communication is required to (i) determine the number of potential relays and then construct the appropriate STBC matrix and (ii) assign each relay a unique column of the matrix to transmit. In M-group Dis-STBC, each potential relay randomly chooses one column of the underlying M-column STBC matrix to transmit. All the relays that use the same column comprise a group, and all M groups transmit simultaneously.

To understand the trade-offs, we evaluated the performance of these distributed relaying strategies in terms of spectral efficiency. We showed that, in general cases, 2-group Dis-STBC is more spectrally efficient than timer-based Best-Select, especially when the node mobility is high and the size of the system is large. Although 2-group Dis-STBC performs better in terms of spectral efficiency, it consumes much more energy than timer-based Best-Select, especially when the size of the decoded set is large. We also investigated the spectral efficiency of cooperative relaying with consideration of the overhead to acquire essential channel state information, as well as that required to select the relay(s).

Energy Efficiency of Distributed Cooperative Relaying

From the perspective of spectral efficiency, M-group Dis-STBC All-Select relaying outperforms Best-Select relaying; however, when every node in the decoded set retransmits the source message, much more power will be consumed. We determined the energy efficiency of these two relaying strategies to provide a more comprehensive guide for system designers to determine which strategy fits a specific application. Numerical results indicate that, although Best-Select relaying conserves transmit power, in some cases, it is also less energy efficient than M-group Dis-STBC All-Select relaying. In addition, we obtained some general conclusions on energy efficiency of cooperative relaying schemes: (1) the selection process degrades the performance, and, (2) in some cases, the energy consumed by nodes not in Transmit mode is comparable to or even higher than that consumed by those nodes that are transmitting.

Optimum Number of Hops in a Multi-Hop Linear Network

We proposed a novel linear network model to characterize the randomness in the node locations. Unlike most previous work which usually assumes that the nodes are uniformly distributed on a line, we considered a linear network with randomly located nodes. We modeled the randomness in distance and showed that the proposed model is a reasonable approximation. We evaluated a performance bound on spectral efficiency, and then calculate the optimum number of hops.

B. Cooperative Routing

To implement cooperative communication in wireless networks, cooperative path discovery, or cooperative routing, is a very important but very difficult step. In previous work, the problem has often been broken into two stages: first find a primary route and then select relays, hop by hop, to construct the cooperative path. This approach is relatively easy to implement and scalable, but it cannot guarantee the optimal performance. Two-stage algorithms have several other drawbacks. First, most distributed two-stage cooperative routing algorithms consider networks as dense and/or uniformly deployed, and, so, they assume every node has sufficient neighbors (in dense scenarios) and/or equal capability (in uniform scenarios) to form a cooperative path. In practice, cooperative networks can be sparse or randomly clustered due to the mobility of nodes and the competition between multiple source-destination pairs. Second, as the network increases, there will be more unnecessary route requests to discover the primary route in the first stage.

Distributed Route Discovery

To address these problems, we proposed a new two-stage cooperative routing algorithm, NDCPD (Neighborhood-based Distributed Cooperative Path Discovery), which takes cooperation into account in both stages and makes use of this information to significantly reduce the number of route requests. In NDCPD, we use a new algorithm, NDSR (Neighborhood-Based Dynamic Source Routing), to find the primary route, taking into account the local topology in selecting nodes to broadcast the route request. The number of decoded neighbors is a meaningful indicator of the capability to cooperate; and, if several decoded nodes are very near to each other, intuitively, we can select one as a representative to reduce the number of unnecessary transmissions. In the second stage, we use of the local topology obtained in the previous stage to construct a cooperative path with a flexible number of relays in each hop.

Location-Aware Cooperative Routing

Geographic routing provides a scalable solution for wireless networks. Compared to proactive/table-driven routing, geographic routing does not have to maintain a routing table at each node to track the global topology since every node makes routing decisions based on local topology, usually the position of its own one-hop neighbors. In addition, compared to flooding-based reactive/on-demand routing, e.g., DSR, geographic routing significantly reduces the route discovery overhead and thus conserves energy. Generally speaking, geographic routing makes routing decisions based on a distance-based metric, which captures the long-term performance of wireless links. However, this metric cannot keep track of the instantaneous status of the channel because of the lack of information about fading and shadowing.

We proposed Location-Aware Cooperative Routing (LACR) which is the first effort, to the best of our knowledge, to incorporate cooperation into *geographic* routing. To make the routing protocol scalable, M-group Dis-STBC is applied, and an analysis of the cooperative transmission range is provided to guide the design of LACR. A theoretical analysis of the impact of cooperative transmissions on the range extension is presented to guide the measurement of the potential performance of each node. Through simulation, we show that LACR performs better in terms of higher probability to find a route and higher throughput in comparison to a Single-Input-Single-Output (SISO) based routing protocol. On the other hand, because LACR is designed to provide a higher probability of route discovery with little overhead, a discovered cooperative route might have poor performance. An interesting topic for further work is to compare LACR with SISO-based cooperative routing schemes with respect to the performance-overhead tradeoff.

Cooperative Source Routing

In cooperative transmission, a virtual antenna array is created using nodes in the neighborhood of the source; we call this Virtual Multiple-Input Single-Output (MISO). It is a non-trivial task, however, to effectively convert the performance gain of virtual MISO at the physical layer to the performance improvement at the higher layers of the protocol stack, due to the fact that overheads are introduced to coordinate the simultaneous transmissions of the distinct antenna elements. To make the best use of the potential improvements in range and/or rate facilitated by the physical layer, both routing and medium access control protocols must be adapted to benefit the performance of higher-layer protocols.

Most existing routing protocols designed to incorporate virtual MISO first discover a SISO route as a primary route using conventional ad hoc routing protocols (such as DSR and AODV) where route request (RREQ) and route reply (RREP) control packets are transmitted via SISO transmissions. Then, specific nodes along the primary route are selected to establish virtual MISO links. Thus, the quality of virtual MISO links highly depends on the primary SISO route discovered. We proposed *Cooperative Source Routing* (CSR), which does not require a SISO route to be discovered first, but instead transmits RREQ and RREP messages cooperatively, which better exploits the cooperative gain facilitated by the physical layer and the network topology. Via extensive simulations, we showed that CSR can operate in network scenarios where SISO routes do not exist, and the cooperative gains can be utilized to improve network performance in terms of lower end-to-end delay and higher route discovery success ratio.

Maximal Throughput Routing

To design an efficient wireless routing scheme, both the physical characteristics of the wireless links and the related networking activities must be taken into account. Simply applying the routing algorithms used in wired networks has been shown to be a suboptimal approach because of the fundamental differences between wireless and wired links. Here, we focused on the end-to-end throughput of equidistant routes in wireless linear networks. Applying a practical wireless network model, in which we consider the physical-layer characteristics as well as the interactions with the upper layers, optimization problems were formulated to derive the best routing and scheduling scheme. Simulation results illustrated the performance gains of the proposed algorithm.

C. Cooperation in the Presence of Imperfect CSI

Reduced-Feedback Cooperative Beamforming

In the literature, it has been shown in that, under ideal channel and system conditions, cooperating nodes can effectively beamform to a destination, and the maximum directivity, on the order of the number of cooperating nodes, can be achieved asymptotically. However, in order to achieve the potential benefits from cooperative beamforming, it is necessary to deal with the practical challenges caused by the distributed nature of the nodes. For example, to create a beam, it is necessary for the phases of the received signals to be aligned at the destination. In the literature, several techniques have addressed this issue. In particular, a phase synchronization algorithm was proposed using RSS (Received Signal Strength)-based one-bit feedback from the destination. Each node randomly perturbs the transmit phase at each iteration and updates the perturbation if it improves the RSS at the destination. By selecting nodes whose channel gains from the cooperating nodes to the destination are sufficiently large, the transmitted signals can be added in a quasi-coherent manner to obtain considerable beamforming gain, even if there is moderate phase misalignment. An alternative approach divides the total number of nodes into two subsets. At every iteration, the nodes randomly select subset A or subset B. After the random selection of a subset, nodes in each subset transmit the same signal in different time-slots. At the receiver, a composite phase is measured for subset A and fed back to subset B to offset the phase difference between the two subsets. We showed that this algorithm always converges to the maximum gain.

We also proposed and evaluated a new phase synchronization algorithm which converges faster than the original one-bit feedback algorithm, at the cost of downlink bandwidth expansion and estimation of the composite phase. It was shown that as the number of subsets and the total number of nodes increases, the performance advantage of the algorithm improves. We also investigated the effect of a phase estimation error and showed that moderate phase estimation error does not significantly degrade the performance of either system.

Robust Cooperative Relaying

Most of the previous work in cooperative relaying has assumed that perfect CSI is available. However, if the channel estimation is not accurate, for example, due to feedback delay, the system performance might severely degrade. Thus, a robust design for a cooperative communication system is desirable. In the literature, a robust relay selection scheme for a decode-and-forward network was previously proposed that takes advantage of both the location information about relay nodes and the instantaneous channel estimates, and is based on the level of estimation uncertainty. We considered a similar communication scenario and concept of robustness, but applied to an amplify-and-forward network. An amplify-and-forward protocol is more practical in terms of system complexity, but it is also more complicated to analyze. We proposed three robust relay selection schemes, based on the best-select protocol, that effectively utilize both the position information of the relay nodes and instantaneous imperfect CSI. We showed that the proposed schemes outperform the non-robust approaches in average received SNR and outage probability. We also showed that the maximum performance can be achieved when the relays are between 0.6 and 0.7 of the distance from the source to the destination. Finally, we explored the effect of the radius of the relay set and showed that the performance decreases with increasing radius.

Spectral Efficiency of Cooperative Relaying with Imperfect Channel Estimation

It is well known that cooperative relaying has the potential to improve the performance of end-to-end wireless communications. However, compared to point-to-point communications, implementing cooperative relaying requires much more overhead. For example, more complicated coordination and transmission schemes are required. We investigated the spectral efficiency of cooperative relaying, taking into account the overhead to acquire essential channel state information, as well as that required to select the relay(s). As before, we compared three cooperative relaying schemes (Timer-based Best-Select relaying, Dis-STBC All-Select relaying, and *M*-group All-Select relaying), and numerical results illustrate the impact of the overhead on the spectral efficiency.

D. Overhead-Performance Trade-off Using Multiterminal Rate Distortion Theory

I started a collaboration with John Walsh and Steven Weber (Drexel), and Javier Garcia-Frias (Delaware) to develop a systematic theory for the design and evaluation of distributed wireless networks, specifically using distributed source coding theory to study the fundamental trade-off between collaboration overhead and performance (e.g., spectral efficiency). Our goals are to establish fundamental limits explicitly describing this trade-off, and use the insights we obtain to design efficient practical distributed resource allocation algorithms. These fundamental trade-offs should also provide a basis for evaluating the effectiveness of existing allocation algorithms. So far, we have results for very simple scenarios, but it appears that the approach has potential. In recent work, we investigate the overhead-performance trade-off for relay selection in cooperative communications. Existing research is usually highly dependent on the specific implementation approaches. Our analysis, instead, addressed the general and fundamental question: how much extra information is required for relay selection? We derived the rate-distortion function and its asymptotic properties, and simulation results verify our analysis.

4. Personnel Supported

Prof. Leonard J. Cimini, Jr. (Principal Investigator)
Justin Yackoski (Research Assistant, Dr. C.-C. Shen) – Ph.D. Spring 2009 – Provided travel support through this grant
Lu Zhang (Research Assistant/Post-doc, PhD granted August 2009)
Hao Feng (Research Assistant, started September 2009)
Yao Xiao (Research Assistant, started September 2009)
Gubong Lim (Research Assistant, started September 2009, part-time support)
Hongzheng Wang (Post-doc, August 2010-July 2011)

5. Technical Publications

A. Conference Papers

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B. Journal Articles

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C. Dissertations

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6. Honors

None.

7. Patents

None.

8. Transitions

The research described here is still in the early stages of development. However, future tactical networks will be deployed in highly dynamic environments, with severe constraints on energy and bandwidth. The results of these investigations, based on the concept of cooperative networking, will have the most impact precisely in these applications. The approach described here, the techniques devised, and the understanding obtained will be invaluable in meeting the objective of reliably communicating in highly dynamic environments.