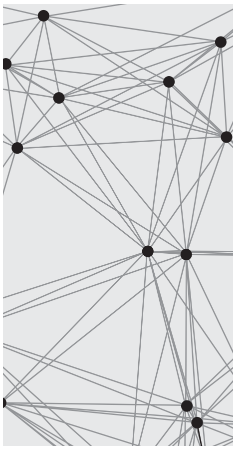
TOPOLOGY CONTROL IN MOBILE AD HOC NETWORKS WITH COOPERATIVE COMMUNICATIONS

QUANSHENG GUAN, SOUTH CHINA UNIVERSITY OF TECHNOLOGY
F. RICHARD YU, CARLETON UNIVERSITY, OTTAWA
SHENGMING JIANG, SOUTH CHINA UNIVERSITY OF TECHNOLOGY
VICTOR C. M. LEUNG, UNIVERSITY OF BRITISH COLUMBIA
HAMID MEHRVAR, CIENA INC.



The authors propose a Capacity-Optimized COoperative (COCO) topology control scheme to improve the network capacity in MANETs by jointly considering both upper layer network capacity and physical layer cooperative communications.

ABSTRACT

Cooperative communication has received tremendous interest for wireless networks. Most existing works on cooperative communications are focused on link-level physical layer issues. Consequently, the impacts of cooperative communications on network-level upper layer issues, such as topology control, routing and network capacity, are largely ignored. In this article, we propose a Capacity-Optimized Cooperative (COCO) topology control scheme to improve the network capacity in MANETs by jointly considering both upper layer network capacity and physical layer cooperative communications. Through simulations, we show that physical layer cooperative communications have significant impacts on the network capacity, and the proposed topology control scheme can substantially improve the network capacity in MANETs with cooperative communications.

INTRODUCTION

The demand for speed in wireless networks is continuously increasing. Recently, cooperative wireless communication has received tremendous interests as an untapped means for improving the performance of information transmission operating over the ever-challenging wireless medium. Cooperative communication has emerged as a new dimension of diversity to emulate the strategies designed for multiple antenna systems, since a wireless mobile device may not be able to support multiple transmit antennas due to size, cost, or hardware limitations [1]. By exploiting the broadcast nature of the wireless channel, cooperative communication allows single-antenna radios to share their antennas to form a virtual antenna array, and offers significant performance enhancements. This promising technique has been considered in the IEEE 802.16j standard, and is expected to be integrated into Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) multihop cellular networks [2].

Although some works have been done on cooperative communications, most existing works are focused on link-level physical layer issues, such as outage probability and outage capacity [3, 4]. Consequently, the impacts of cooperative communications on network-level upper layer issues, such as topology control, routing and network capacity, are largely ignored. Indeed, most of current works on wireless networks attempt to create, adapt, and manage a network on a maze of point-to-point noncooperative wireless links. Such architectures can be seen as complex networks of simple links. However, recent advances in cooperative communications will offer a number of advantages in flexibility over traditional techniques. Cooperation alleviates certain networking problems, such as collision resolution and routing, and allows for simpler networks of more complex links, rather than complicated networks of simple links [5].

Therefore, many upper layer aspects of cooperative communications merit further research, e.g., the impacts on topology control and network capacity, especially in mobile ad hoc networks (MANETs), which can establish a dynamic network without a fixed infrastructure. A node in MANETs can function both as a network router for routing packets from the other nodes and as a network host for transmitting and receiving data. MANETs are particularly useful when a reliable fixed or mobile infrastructure is not available. Instant conferences between notebook PC users, military applications, emergency operations, and other secure-sensitive operations are important applications of MANETs due to their quick and easy deployment.

Due to the lack of centralized control, MANETs nodes cooperate with each other to

---

This work was in part supported by the National Fundamental Research and Development Programs of China (i.e., 973 Program, no. 2011CB707003), the Fundamental Research Funds for the Central Universities of China (no. 2012ZM0021), the National Natural Science Foundation of China under Grant 61101113, and the Natural Sciences and Engineering Research Council (NSERC) of Canada.

1536-1284/12/$25.00 © 2012 IEEE

achieve a common goal. The major activities involved in self-organization are neighbor discovery, topology organization, and topology reorganization. Network topology describes the connectivity information of the entire network, including the nodes in the network and the connections between them. Topology control is very important for the overall performance of a MANET. For example, to maintain a reliable network connectivity, nodes in MANETs may work at the maximum radio power, which results in high nodal degree and long link distance, but more interference is introduced into the network and much less throughput per node can be obtained. Using topology control, a node carefully selects a set of its neighbors to establish logical data links and dynamically adjust its transmit power accordingly, so as to achieve high throughput in the network while keeping the energy consumption low [6].

In this article, considering both upper layer network capacity and physical layer cooperative communications, we study the topology control issues in MANETs with cooperative communications. We propose a Capacity-Optimized Cooperative (COCO) topology control scheme to improve the network capacity in MANETs by jointly optimizing transmission mode selection, relay node selection, and interference control in MANETs with cooperative communications. Through simulations, we show that physical layer cooperative communications have significant impacts on the network capacity, and the proposed topology control scheme can substantially improve the network capacity in MANETs with cooperative communications.

The remainder of the article is structured as follows. We introduce cooperative communications and the topology control problem in MANETs. Network capacity and the proposed COCO topology control scheme are presented. We give the simulation results and discussions. Finally, we conclude this study.

Mobile Ad Hoc Networks with Cooperative Communications

In this section, we first introduce cooperative communications. Then the topology control problem in MANETs with cooperative communications is presented.

Cooperative Communications

Cooperative communication typically refers to a system where users share and coordinate their resources to enhance the information transmission quality. It is a generalization of the relay communication, in which multiple sources also serve as relays for each other. Early study of relaying problems appears in the information theory community to enhance communication between the source and destination [7]. Recent tremendous interests in cooperative communications are due to the increased understanding of the benefits of multiple antenna systems [1]. Although multiple-input multiple-output (MIMO) systems have been widely acknowledged, it is difficult for some wireless mobile devices to support multiple antennas due to the size and cost constraints. Recent studies show that cooperative communications allow single-antenna devices to work together to exploit the spatial diversity and reap the benefits of MIMO systems such as resistance to fading, high throughput, low transmitted power, and resilient networks [1].

Cooperative communication typically refers to a system where users share and coordinate their resources to enhance the information transmission quality. It is a generalization of the relay communication, in which multiple sources also serve as relays for each other.

In a simple cooperative wireless network model with two hops, there are a source, a destination, and several relay nodes. The basic idea of cooperative relaying is that some nodes, which overheard the information transmitted from the source node, relay it to the destination node instead of treating it as interference. Since the destination node receives multiple independently faded copies of the transmitted information from the source node and relay nodes, cooperative diversity is achieved. Relaying could be implemented using two common strategies,

- Amplify-and-forward
- Decode-and-forward

In amplify-and-forward, the relay nodes simply boost the energy of the signal received from the sender and retransmit it to the receiver. In decode-and-forward, the relay nodes will perform physical-layer decoding and then forward the decoding result to the destinations. If multiple nodes are available for cooperation, their antennas can employ a space-time code in transmitting the relay signals. It is shown that cooperation at the physical layer can achieve full levels of diversity similar to a MIMO system, and hence can reduce the interference and increase the connectivity of wireless networks.

Most existing works about cooperative communications are focused on physical layer issues, such as decreasing outage probability and increasing outage capacity, which are only link-wide metrics. However, from the network's point of view, it may not be sufficient for the overall network performance, such as the whole network capacity. Therefore, many upper layer network-wide metrics should be carefully studied, e.g., the impacts on network structure and topology control. Cooperation offers a number of advantages in flexibility over traditional wireless networks that go beyond simply providing a more reliable physical layer link. Since cooperation is essentially a network solution, the traditional link abstraction used for networking design may not be valid or appropriate. From the perspective of a network, cooperation can benefit not only the physical layer, but the whole network in many different aspects.

With physical layer cooperative communications, there are three transmission manners in MANETs: direct transmissions (Fig. 1a), multi-hop transmissions (Fig. 1b) and cooperative transmissions (Fig. 1c). Direct transmissions and multi-hop transmissions can be regarded as special types of cooperative transmissions. A direct transmission utilizes no relays while a multi-hop transmission does not combine signals at the destination. In Fig. 1c, the cooperative channel is a virtual multiple-input single-output (MISO) channel, where spatially distributed nodes are coordinated to form a virtual antenna to emulate multi-antenna transceivers.

Topology Control

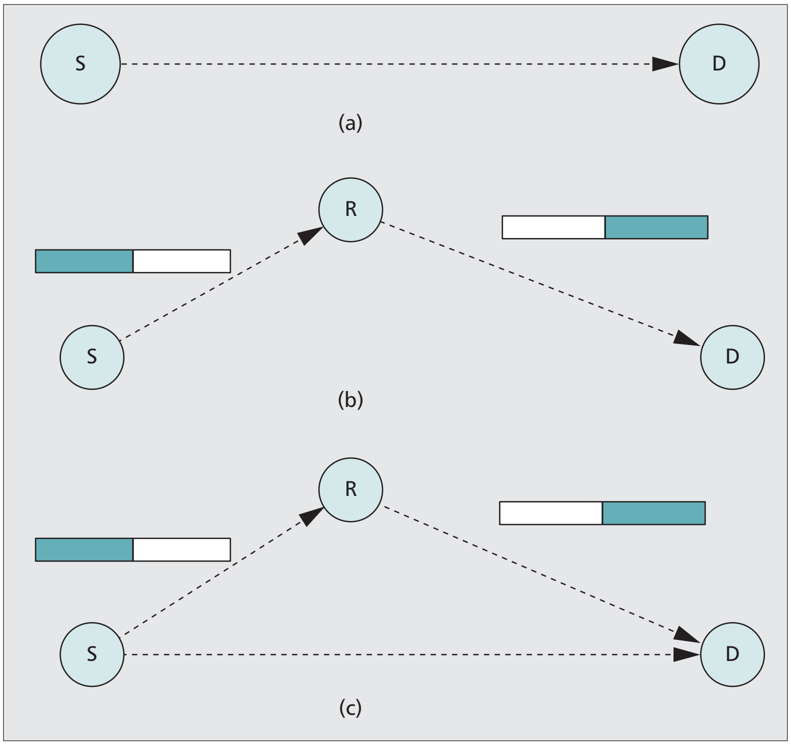


Figure 1. *Three transmission protocols: a) direct transmissions via a point-to-point conventional link; b) multi-hop transmissions via a two-hop manner occupying two time slots; and c) cooperative transmissions via a cooperative diversity occupying two consecutive slots. The destination combines the two signals from the source and the relay to decode the information.*

The network topology in a MANET is changing dynamically due to user mobility, traffic, node batteries, and so on. Meanwhile, the topology in a MANET is controllable by adjusting some parameters such as the transmission power, channel assignment, etc. In general, topology control is such a scheme to determine where to deploy the links and how the links work in wireless networks to form a good network topology, which will optimize the energy consumption, the capacity of the network, or end-to-end routing performance. Topology control is originally developed for wireless sensor networks (WSNs), MANETs, and wireless mesh networks to reduce energy consumption and interference. It usually results in a simpler network topology with small node degree and short transmission radius, which will have high-quality links and less contention in medium access control (MAC) layer. Spatial/spectrum reuse will become possible due to the smaller radio coverage. Other properties like symmetry and planarity are expected to obtain in the resultant topology. Symmetry can facilitate wireless communication and two-way handshake schemes for link acknowledgment while planarity increases the possibility for parallel transmissions and space reuse.

Power control and channel control issues are coupled with topology control in MANETs while they are treated separately traditionally. Although a mobile node can sense the available channel, it lacks of the scope to make network-wide decisions. It therefore makes more sense to conduct power control and channel control via the topological viewpoint. The goal of topology control is then to set up interference-free connections to minimizes the maximum transmission power and the number of required channels. It is also desirable to construct a reliable network topology since it will result in some benefits for the network performance.

Topology control focuses on network connectivity with the link information provided by MAC and physical layers. There are two aspects in a network topology: network nodes and the connection links among them. In general, a MANET can be mapped into a graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of nodes in the network and $\mathcal{E}$ is the edge set representing the wireless links. A link is generally composed of two nodes which are in the transmission range of each other in classical MANETs. The topology of such a classical MANET is parameterized by some controllable parameters, which determine the existence of wireless links directly. In traditional MANETs without cooperative communications, these parameters can be transmit power, antenna directions, etc. In MANETs with cooperative communications, topology control also needs to determine the transmission manner (i.e., direct transmission, multi-hop transmission, or cooperative transmission) and the relay node if cooperative transmission is in use.

As topology control is to determine the existence of wireless links subject to network connectivity, the general topology control problem can be expressed as

$$\mathcal{G}^* = \arg\max f(\mathcal{G}), \qquad (1)$$
$$\text{s.t. } \textit{network connectivity}.$$

The problem Eq. 1 uses the original network topology $\mathcal{G}$, which contains mobile nodes and link connections, as the input. According to the objective function, a better topology $\mathcal{G}^*(\mathcal{V}, \mathcal{E}^*)$ will be constructed as the output of the algorithm. $\mathcal{G}^*$ should contain all mobile nodes in $\mathcal{G}$, and the link connections $\mathcal{E}^*$ should preserve network connectivity without partitioning the network. The structure of resulting topology is strongly related to the optimization objective function, which is $f(\mathcal{G})$ in Eq. 1.

It is difficult to collect the entire network information in MANETs. Therefore, it is desirable to design a distributed algorithm, which generally requires only local knowledge, and the algorithm is run at every node independently. Consequently, each node in the network is responsible for managing the links to all its neighbors only. If all the neighbor connections are preserved, the end-to-end connectivity is then guaranteed. Given a neighborhood graph $\mathcal{G}_N$ $(\mathcal{V}_N, \mathcal{E}_N)$with N neighboring nodes, we can define a distributed topology control problem as $\mathcal{G}_N^* = \arg\max f(\mathcal{G}_N)$, s.t. connectivity to all the neighbors.

The objective function $f(\mathcal{G})$ in Eq. 1 is critical to topology control problems. Network capacity is an important objective function. Our previous work [8] shows that topology control can affect network capacity significantly. In the following section, we present a topology control scheme with the objective of optimizing network capacity in MANETs with cooperative communications.

TOPOLOGY CONTROL FOR NETWORK CAPACITY IMPROVEMENT IN MANETS WITH COOPERATIVE COMMUNICATIONS

In this section, we first describe the capacity of MANETs. Then, we present the proposed COCO topology control scheme for MANETs with cooperative communications.

THE CAPACITY OF MANETS

As a key indicator for the information delivery ability, network capacity has attracted tremendous interests since the landmark paper by Gupta and Kumar [9]. There are different definitions for network capacity. Two types of network capacity are introduced in [9]. The first one is transport capacity, which is similar to the total one-hop capacity in the network. It takes distance into consideration and is based on the sum of bit-meter products. One bit-meter means that one bit has been transported to a distance of one meter toward its destination. Another type of capacity is throughput capacity, which is based on the information capacity of a channel. Obviously, it is the amount of all the data successfully transmitted during a unit time. It has been shown that the capacity in wireless ad hoc networks is limited. In traditional MANETs without cooperative communications, the capacity is decreased as the number of nodes in the network increases. Asymptotically, the per-node throughput declines to zero when the number of nodes approaches to infinity [9]. In this study, we adopt the second type of definition.

The expected network capacity is determined by various factors: wireless channel data rate in the physical layer, spatial reuse scheduling and interference in the link layer, topology control presented earlier, traffic balance in routing, traffic patterns, etc. In the physical layer, channel data rate is one of the main factors. Theoretically, channel capacity can be derived using Shannon's capacity formula. In practice, wireless channel data rate is jointly determined by the modulation, channel coding, transmission power, fading, etc. In addition, outage capacity is usually used in practice, which is supported by a small outage probability, to represent the link capacity.

In the link layer, the spatial reuse is the major ingredient that affects network capacity. Link interference, which refers to the affected nodes during the transmission, also has a significant impact on network capacity. Higher interference may reduce simultaneous transmissions in the network, thus reduce the network capacity, and vice versa. The MAC function should avoid collision with existing transmission. It uses a spatial and temporal scheduling so that simultaneous transmissions do not interfere with each other. Nodes within the transmission range of the sender must keep silent to avoid destroying ongoing transmissions. In addition, there are some factors that prevent the channel capacity from being fully utilized, such as hidden and exposed terminals, which need to be solved using handshake protocols or a dedicated control channel in wireless networks.

Routing not only finds paths to meet quality of service (QoS) requirements, but also balances traffic loads in nodes to avoid hot spots in the network. By balancing traffic, the network may admit more traffic flows and maximize the capacity. Since we focus on topology control and cooperative communications, we assume an ideal load balance in the network, where the traffic loads in the network are uniformly distributed to the nodes in the network.

The study in [3] shows that cooperative transmissions do not always outperform direct transmissions. If there is no such relay that makes cooperative transmissions have larger outage capacity, we rather transmit information directly or via multi-hops. For this reason, we need to determine the best link block (Fig. 1) and the best relay to optimize link capacity. On the other hand, other nodes in the transmission range have to be silent in order not to disrupt the transmission due to the open shared wireless media. The affected areas include the coverage of the source, the coverage of the destination, as well as the coverage of the relay.

Routing not only finds paths to meet QoS requirements, but also balances traffic loads in nodes to avoid hot spots in the network. By balancing traffic, the network may admit more traffic flows and maximize the capacity.

IMPROVING NETWORK CAPACITY USING TOPOLOGY CONTROL IN MANETS WITH COOPERATIVE COMMUNICATIONS

To improve the network capacity in MANETs with cooperative communications using topology control, we can set the network capacity as the objective function in the topology control problem in Eq. 1. In order to derive the network capacity in a MANET with cooperative communications, we need to obtain the link capacity and inference model when a specific transmission manner (i.e., direct transmission, multi-hop transmission, or cooperative transmission) is used.

When traditional direct transmission is used, given a small outage probability, the outage link capacity can be derived. Since only two nodes are involved in the direct transmission, the interference set of a direct transmission is the union of coverage sets of the source node and the destination node. In this article, we adopt the interference model in [9], which confines concurrent transmissions in the vicinity of the transmitter and receiver. This model fits the medium access control function well (e.g., the popular IEEE 802.11 MAC in most mobile devices in MANETs). Herein, interference of a link is defined as some combination of coverage of nodes involved in the transmission.

Multihop transmission can be illustrated using two-hop transmission. When two-hop transmission is used, two time slots are consumed. In the first slot, messages are transmitted from the source to the relay, and the messages will be forwarded to the destination in the second slot. The outage capacity of this two-hop transmission can be derived considering the outage of each hop transmission. The transmission of each hop has its own interference, which happens in different slots. Since the transmissions of the two hops cannot occur simultaneously but in two separate time slots, the end-to-end interference set of the multi-hop link is determined by the maximum of the two interference sets.

When cooperative transmission is used, a best relay needs to be selected proactively before transmission. In this study, we adopt the decode-and-forward relaying scheme. The source broadcasts its messages to the relay and destination in the first slot. The relay node decodes and re-encodes the signal from the source, and then forwards it to the destination in the second slot. The two signals of the source and the relay are decoded by maximal rate combining at the destination. The maximum instantaneous end-to-end mutual information, outage probability, and outage capacity can be derived [3]. For the interference model, in the broadcast period, both the covered neighbors of the source and the covered neighbors of the relay and the destination have to be silent to ensure successful receptions. In the second slot, both the covered neighbors of the selected relay and the destination have to be silent to ensure successful receptions.

After obtaining the link capacity and interference models, the network capacity can be derived [8] as the objective function in the topology control problem in Eq. 1. By considering direct transmission, multihop transmission, cooperative transmission, and interference, the proposed COCO topology control scheme extends physical layer cooperative communications from the link-level perspective to the network-level perspective in MANETs. The proposed scheme can determine the best type of transmission and the best relay to optimize network capacity.

Two constraint conditions need to be taken into consideration in the proposed COCO topology control scheme. One is network connectivity, which is the basic requirement in topology control. The end-to-end network connectivity is guaranteed via a hop-by-hop manner in the objective function. Every node is in charge of the connections to all its neighbors. If all the neighbor connections are guaranteed, the end-to-end connectivity in the whole network can be preserved. The other aspect that determines network capacity is the path length. An end-to-end transmission that traverses more hops will import more data packets into the network. Although path length is mainly determined by routing, COCO limits dividing a long link into too many hops locally. The limitation is two hops due to the fact that only two-hop relaying is adopted.

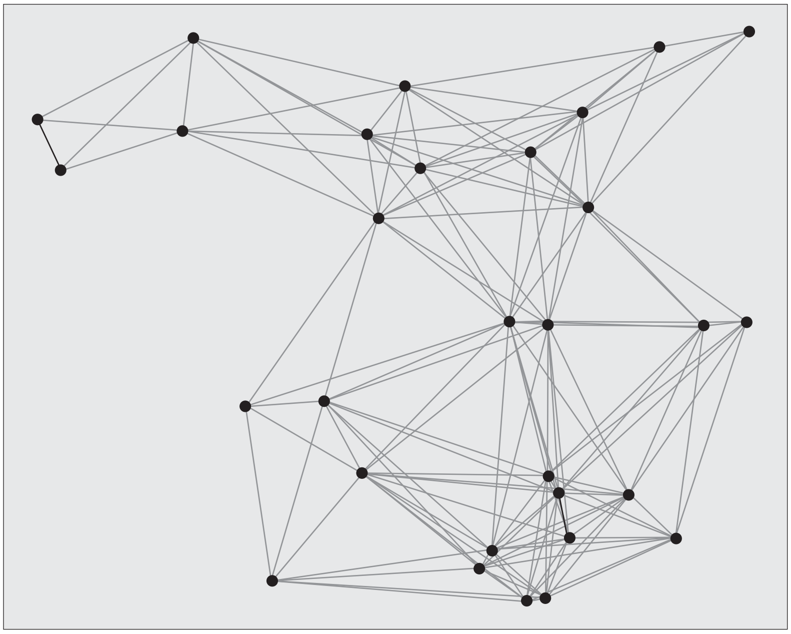


Figure 2. *The original topology: a MANET with 30 nodes randomly deployed in a 800 × 800 m*² *area.*

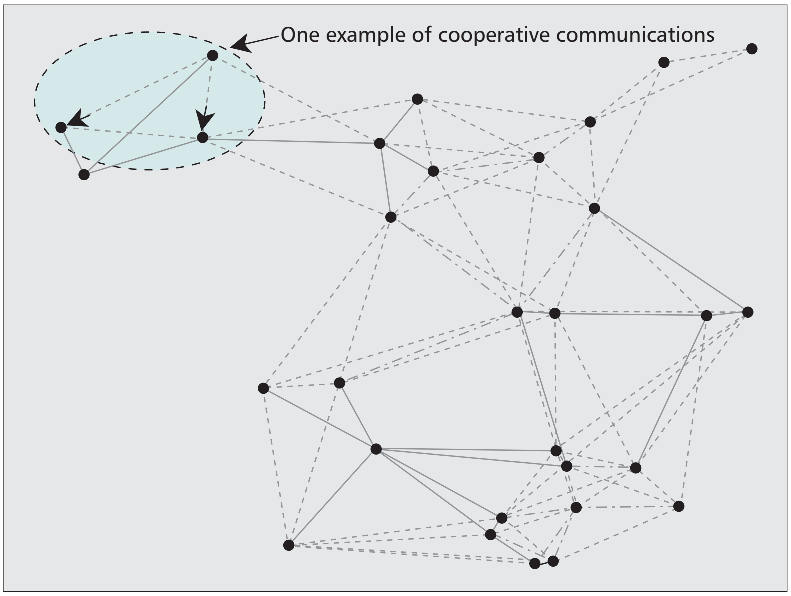


Figure 3. *The final topology generated by COCO. The solid lines denote traditional direct transmissions and multihop transmissions. The dashed lines denote the links involved in cooperative communications.*

SIMULATION RESULTS AND DISCUSSIONS

In this section, the performance of the proposed scheme is illustrated using computer simulations. We consider a MANET with 30 nodes randomly deployed in a 800 × 800 m^2 area. The number of nodes is changed in the simulations. The channels follow a Raleigh distribution. We compare the performance of the proposed scheme with that of an existing well-known topology control scheme [10], called LLISE, which only considers traditional multi-hop transmissions without cooperative communications and preserves the minimum interference path for each neighbor link locally. We also show the worst network capacity among all the topology configurations for comparison. The original topology is shown in Fig. 2, where links exist whenever the associated two end nodes are within transmission range of each other. It is clear that this topology lacks any physical layer cooperative communications. Figure 3 shows the resulting topology using the proposed COCO topology control scheme. In Fig. 3, the solid lines denote traditional direct transmissions and multi-hop transmissions, and the dash lines denote links involved in cooperative communications. As we can see from Fig. 3, to maximize the network capacity of the MANET, many links in the network are involved in cooperative communications. One example of two-phase cooperative communications is shown in the top left corner of the figure. Figure 4 shows the network capacity per node in different topology control schemes with different numbers of nodes in the MANET. As we can see from the figure, the proposed COCO scheme has the highest network capacity regardless of the number of nodes in the network. Similar to COCO, LLISE is executed in each node distributedly. It preserves all the edges on the minimum interference path for each link in the resulting topology, thus minimizes the interference to improve network capacity. Nevertheless, COCO can achieve a much higher network capacity than LLISE, since LLISE only considers multihop transmissions. The performance gain of the proposed scheme comes from the joint design of transmission mode selection, relay node selection, and interference minimization in MANETs with cooperative communications.

CONCLUSIONS AND FUTURE WORK

In this article, we have introduced physical layer cooperative communications, topology control, and network capacity in MANETs. To improve the network capacity of MANETs with cooperative communications, we have proposed a Capacity-Optimized Cooperative (COCO) topology control scheme that considers both upper layer network capacity and physical layer relay selection in cooperative communications. Simulation results have shown that physical layer cooperative communications techniques have significant impacts on the network capacity, and the proposed topology control scheme can substantially improve the network capacity in MANETs with cooperative communications. Future work is in progress to consider dynamic traffic patterns in the proposed scheme to further improve the performance of MANETs with cooperative communications.

REFERENCES

[1] J. Laneman, D. Tse, and G. Wornell, "Cooperative Diversity in Wireless Networks: Efficient protocols and Outage Behavior," *IEEE Trans. Info. Theory*, vol. 50, no. 12, 2004, pp. 3062–80.

[2] P. H. J. Chong *et al.*, "Technologies in Multihop Cellular Network," *IEEE Commun. Mag.*, vol. 45, Sept. 2007, pp. 64–65.

[3] K. Woradit *et al.*, "Outage Behavior of Selective Relaying Schemes," *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, 2009, pp. 3890–95.

[4] Y. Wei, F. R. Yu, and M. Song, "Distributed Optimal Relay Selection in Wireless Cooperative Networks with Finite-State Markov Channels," *IEEE Trans. Vehic. Tech.*, vol. 59, June 2010, pp. 2149–58.

[5] Q. Guan *et al.*, "Capacity-Optimized Topology Control for MANETs with Cooperative Communications," *IEEE Trans. Wireless Commun.*, vol. 10, July 2011, pp. 2162–70.

[6] P. Santi, "Topology Control in Wireless Ad Hoc and Sensor Networks," *ACM Computing Surveys*, vol. 37, no. 2, 2005, pp. 164–94.

[7] T. Cover and A. E. Gamal, "Capacity Theorems for the Relay Channel," *IEEE Trans. Info. Theory*, vol. 25, Sept. 1979, pp. 572–84.

[8] Q. Guan *et al.*, "Impact of Topology Control on Capacity of Wireless Ad Hoc Networks," *Proc. IEEE ICCS*, Guangzhou, P. R. China, Nov. 2008.

[9] P. Gupta and P. Kumar, "The Capacity of Wireless Networks," *IEEE Trans. Info. Theory*, vol. 46, no. 2, 2000, pp. 388–404.

[10] M. Burkhart *et al.*, "Does Topology Control Reduce Interference?," *Proc. 5th ACM Int'l. Symp. Mobile Ad Hoc Networking and Computing*, Tokyo, Japan, May 2004, pp. 9–19.

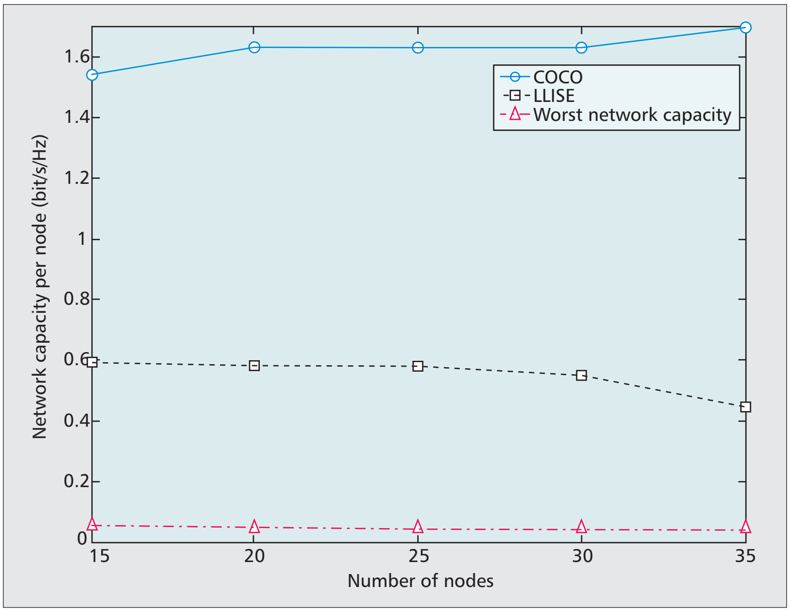


Figure 4. *Network capacity versus different numbers of nodes in the MANET.*

BIOGRAPHIES

QUANSHENG GUAN [S'09] received his B. Eng degree in electronic engineering from Nanjing University of Post & Telecommunications, China, in 2006, and hisPh.D. degree at South China University of Technology, China in 2011. From September 2009 to September 2010, he was a visiting Ph.D. student at the University of British Columbia and Carleton University, Canada, which is supported by China Scholarship Council. He is a faculty member at South China University of Technology since 2011, and a posdoc researcher at the Chinese University of Hong Kong since 2012. He research areas include topology control, routing and cooperative communications for mobile ad hoc networks and cognitive networks.

F. RICHARD YU [S'00, M'04, SM'08] received the Ph.D. degree from the University of British Columbia (UBC) in 2003. From 2002 to 2004, he was with Ericsson in Lund, Sweden. From 2005 to 2006, he was with a start-up in California. He joined Carleton University in 2007, where he is currently an associate professor. He received the Carleton Research Achievement Award in 2012, the Ontario Early Researcher Award in 2011, and a number of other awards. He serves on the editorial boards of several journals and the TPC of numerous conferences.

SHENGMING JIANG received his Bachelor's, Master's, and doctoral degrees in computer science in 1988, 1992, and 1995, respectively. He was a research associate at Hongkong University of Science and Technology between 1995 and 1997, a (senior) member of technical staff in the National University of Singapore between 1997 and 2003, and a principal lecture of the University of Glamorgan, United Kingdom, between 2007 and 2009. Now he is a professor at South China University of Technology.

VICTOR C. M. LEUNG [S'75, M'89, SM'97, F'03] is a professor of electrical and computer engineering and the Telus Mobility Research Chair at the University of British Columbia, where he pursues research on wireless networks and mobile systems. He has contributed more than 500 technical papers and 25 book chapters in these areas. He is a Distinguished Lecturer of the IEEE Communications Society, and serves on the editorial boards of *IEEE Transactions on Computers* and several other journals.

HAMID MEHRVAR received his Ph.D. in electrical and computer engineering from Concordia University, Canada in 2001. He has over 15 years of research and development experience at Nortel and Ciena. He is the primary inventor of five key product patents at Nortel and Ciena. His research interests include wireless networks, data networks and communication protocols. He has also been a part-time professor teaching graduate courses at University of Ottawa for eight