Energy-Efficient Topology Management With Interference Cancellation in Cooperative Wireless Ad Hoc Networks

Bingyi Guo, F. Richard Yu, *Senior Member, IEEE*, Shengming Jiang, *Senior Member, IEEE*, Xin Ao, *Member, IEEE*, and Victor C. M. Leung, *Fellow, IEEE*

***Abstract*—With recent advances in parallel cooperative transmissions between multiple source-destination pairs, interference cancellation (IC) can be achieved to improve the capacity performance of wireless networks. However, from energy efficiency perspective, user cooperation may not be always appealing, since the increased data rate of one user comes at the price of the energy consumed by another user. In this paper, we study the potential benefits/drawbacks of cooperative communications on network-level issues, such as the capacity and the energy efficiency. We show that, in terms of network energy efficiency, cooperative communications do not always outperform non-cooperative communications, and cooperative communications should be dynamically applied in topology control to optimize the overall network energy efficiency. Specifically, we propose an energy-efficient topology control scheme by jointly considering the capacity and energy consumption of non-cooperative and cooperative communications. Simulation results are presented to show the effectiveness of the proposed scheme.**

***Index Terms*—Energy efficiency, topology control, interference cancellation, wireless networks.**

I. Introduction

WITH the increasing demand in the use of wireless applications, more users need to share the same spectrum, which motivates cooperative communications as effective ways to improve information transmission quality on the unreliable wireless channel. Different from point-to-point transmission, cooperative relay communications [1], [2] exploit user diversity by decoding the combined signals of direct source-destination signals and relayed signals from assistant relays. This cooperative diversity gain can help to achieve higher capacity [3].

Manuscript received May 29, 2013; revised April 14, 2014; accepted May 10, 2014. Date of publication August 13, 2014; date of current version September 5, 2014. The associate editor coordinating the review of this paper and approving it for publication was C. S. Hong.

B. Guo is with the School of Electronic and Information Engineering, South China University of Technology, Guangzhou 510640, China (e-mail: gbyindeed@gmail.com).

F. R. Yu is with the Department of Systems and Computer Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada (e-mail: richard_yu@carleton.ca).

S. Jiang is with the College of Information and Engineering, Shanghai Maritime University, Shanghai 201306, China (e-mail: smjiang@shmtu.edu.cn).

X. Ao is with the School of Computer, Dongguan University of Technology, Dongguan 523808, China (e-mail: xinxin.ao@gmail.com).

V. C. M. Leung is with the Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, BC V6T 1Z4, Canada (e-mail: vleung@ece.ubc.ca).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TNSM.2014.2346155

In traditional cooperative communications, the main focus is to improve the capacity performance of single source-destination pair through single or multiple relays. Recently, with development of parallel cooperative transmissions between multiple source-destination pairs, interference cancellation (IC) [4], [5] has been proposed to further improve the capacity performance. Different from the traditional approaches of separating concurrent transmissions, multiple source-destination pairs can now transmit simultaneously by canceling the cross-user interference among them. In IC cooperative communications, relays cooperatively amplify and rotate the received combined signals from multiple-sources in such a way that only the desired signals are left at destinations. In other words, with the help of multiple cooperative relays and advanced signal processing technologies, cross-user interference is canceled out.

On the other hand, rising energy costs and increasingly rigid environmental standards have led to an emerging trend of addressing *energy efficiency* issue of wireless communication systems [6], [7]. Therefore, in addition to capacity, energy efficiency is also an important factor in network design [8]. When energy efficiency is used as a design criterion, user cooperation may not be always appealing. The reason is that the increased data rate of one user comes at the price of the energy consumed by another user acting as a relay [9], [10].

Most existing works on cooperative communications are focused on link-level physical layer issues [11], [12]. Consequently, the potential benefits/drawbacks of cooperative communications on network-level issues, such as the capacity and the energy efficiency, are largely ignored. In addition, most existing works on network-level issues are based on the assumption of complex networks with simple links, where the network attempts to manage a maze of point-to-point non-cooperative links. However, cooperative communications, especially IC cooperative communications with multiple source-destination pairs, can handle more complex cooperative links, which enable simple networks with complex links.

Therefore, there is a strong motivation to study network-level upper layer issues in cooperative wireless ad hoc networks (WANETs), which can establish a dynamic network without a fixed infrastructure. Particularly, topology control [13]–[15], which can control where to deploy links and how the links work, needs to be carefully studied in cooperative WANETs.

A capacity-optimized topology control scheme for wireless networks with cooperative communications is proposed in our previous work [16], [17], which discussed a cooperation manner selection issue in topology control for WANETs with cooperative communications to improve network capacity. However, IC cooperative communications with multiple source-destination pairs are not considered in [16]. In this paper, we continue to study the topology control problem in WANETs with cooperative communications, particularly IC cooperative communications with multiple source-destination pairs. As energy efficiency is used as a design criterion, we show that, in terms of the overall network energy efficiency, cooperative communications do not always outperform non-cooperative communications in WANETs. Depending on network conditions, cooperative communications, particularly IC cooperative communications with multiple source-destination pairs, should be dynamically applied in topology control of WANETs to optimize the overall network energy efficiency. Specifically, we propose an energy-efficient topology control scheme by jointly considering the capacity and energy consumption. Taking into account energy efficiency, each node can choose the best transmission pattern (i.e., single-hop, two-hop, decode-and-forward relay, and IC-based transmissions) for each out-going link to form an optimal network topology. Simulation results show the effectiveness of the proposed scheme.

The rest of the paper is organized as follows: the system model and formulation of topology control problem are presented in Section II. Section III introduces the energy-efficient topology control scheme in detail. Simulation results are presented and discussed in Section IV. Finally, this paper is concluded in Section V with future work.

II. System Model and Topology Control Formulation

In this section, we describe the system model with four different transmission patterns adopted in this paper and formulate the topology control as an optimization problem based on the system model.

A. System Model

We model an arbitrary wireless network as a directed graph $G(\mathcal{N}, \mathcal{E})$, where the set $\mathcal{N}$ includes all the nodes in the network and $\mathcal{E}$ is the edge set representing the wireless links. For a pair of nodes $A, B \in \mathcal{N}$, a directional edge $e = (A, B)$ is a member of $\mathcal{E}$ if signals from node A can be decoded at B. To interpret the transmission between a source S_i and a destination D_i, a definition for transmission pattern is introduced as follows.

Definition 1 (Transmission Pattern): The transmission pattern of the link ξ from source S_i to destination D_i, denoted as $g(\xi)$, refers to the set of the relay nodes $\mathcal{R}$ and the way these nodes work $H(\mathcal{R})$. Formally, we have $g(\xi) = (\mathcal{R}, H(\mathcal{R}))$.

In this paper, we will study the following four transmission patterns as shown in Fig. 1.

1) Direct transmission (DT): Direct transmission is a single-hop transmission. S_i transmits directly to D_i using one slot and no relay node is involved. Therefore, $\mathcal{R} = \emptyset$, $H(\mathcal{R}) = DT$.

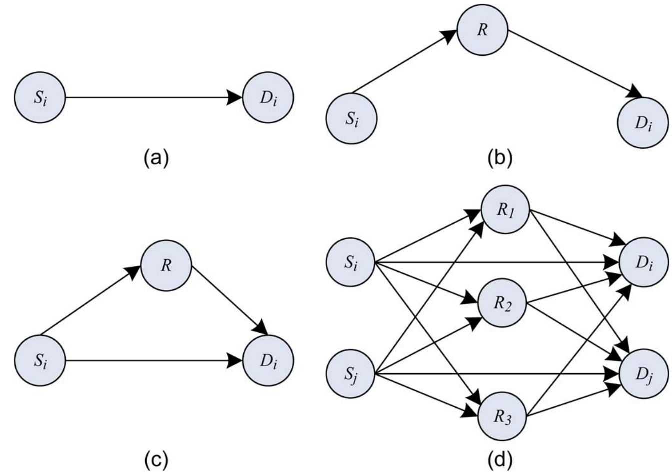


Fig. 1. Different transmission patterns.

2) Two-hop transmission (TT): Two-hop transmission is one type of multi-hop transmissions and used here as a representative. In two-hop transmission, S_i transmits a packet to intermediate node R as a relay in the first slot, which decodes the packet and forwards it to D_i in the second slot. The destination decodes the signals only from the relay. Therefore, $\mathcal{R} = \{R\}$, $H(\mathcal{R}) = TT$.

3) Decode-and-forward relay transmission (DF): We adopt the decode-and-forward relay transmission as the cooperative relay transmission pattern. S_i transmits signals to intermediate node R as a relay in the first slot, which decodes the received signals and forwards them to D_i in the second slot. The combined signals received from the source S_i and from the relay R are decoded at D_i jointly. Therefore, $\mathcal{R} = \{R\}$, $H(\mathcal{R}) = DF$.

4) IC cooperative transmission (IC-based): There is a cooperative transmission pair (S_j, D_j) and three assisting relays R_1, R_2, R_3. In the transmission, S_i and S_j broadcast their packets to the three relays concurrently in the fist slot. In the second slot, each relay scales the observed signals and forwards them to the destination concurrently. Therefore, we have $\mathcal{R} = \{R_1, R_2, R_3\}$, $H(\mathcal{R}) = IC$.

According to [4], to enable IC at relays, the number of relay nodes should be more than the number of source nodes. For K pairs of users, at least $K(K-1)+1$ relays are required to nullify cross-user interference [18]. For simplicity, we consider the case of $K = 2$ in this paper. Therefore, the IC-based cooperative transmission considered above involves two pairs of users with three relays, named as (2, 3, 2) IC-based transmission pattern in this paper.

It should be noted that our study can be extended to embrace other transmission patterns. However, for ease of presentation, we only focus on the above four patterns in this paper. Please note that no transmission pattern is deemed to be better than others, and the performance of them will be discussed in the following sections.

B. Topology Control Formulation

As presented above, a network topology can be modelled as a graph $G(\mathcal{N}, \mathcal{E})$, including all its nodes $\mathcal{N}$ and link connections $\mathcal{E}$ among them. Essentially, network topology control is to determine transmission links and the way they work to form a *good* topology, which can achieve the supposed global network performance $f(G)$ while preserving some global graph properties (e.g., connectivity). Therefore, the general topology control problem can be expressed as:

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

To optimize the objective f, topology control is mainly operated by re-configuring transmission power, antenna direction, channel assignment, transmission pattern, etc. In this paper, to make the topology control problem tractable, we only consider the transmission pattern for each link as the controllable parameter to optimize whole network performance. Re-configuring other parameters for topology control will be our future work. Furthermore, if the network connectivity is not guaranteed, the network can be considered dead or disconnected and the network life time ends. Therefore, the network connectivity should be considered as a constraint when studying the network performance. The connectivity is guaranteed without partitioning the network when all the neighbor connections are preserved. In this paper, link connectivity is not changed because we only select the transmission pattern without destroying the original connectivity, therefore the network connectivity is guaranteed via a hop-by-hop manner. Hence, the specific topology control problem in this paper can be formulated as a link transmission pattern selection problem

$$G^*(\mathcal{E}) = \arg\max f\left(g(\mathcal{E})\right) \tag{2}$$

where $\mathcal{E}$ denotes the links connected to the underlying node, $g(\mathcal{E})$ is the transmission pattern function and f is an objective selected to optimize network performance.

The objective function is important to topology control problems. They may be energy consumption, network capacity, or QoS provisioning under some constraints [19]. In this paper, we consider energy efficiency as the objective function, which will be introduced in detail in the next section.

III. Energy-Efficient Topology Control With Interference Cancellation

Based on the topology control formulation in the previous section, we will detail the design of energy-efficient topology control scheme with interference cancellation (EEIC) in this section. Network energy efficiency is used as the objective function, which involves capacity and energy consumption including the required power for the transmission and the energy consumption of the circuitry. The network connectivity is formulated as a constraint in the optimization problem. Then, we propose an algorithm to find the optimal transmission patterns to optimize the total network energy efficiency. Before addressing EEIC, we introduce the definition of energy efficiency to be used in this paper.

A. Objective Function

Definition 2 (Energy Efficiency): Energy efficiency refers to the achievable information transmission per Joule energy consumption with bit per Joule as the unit. Given a transmission link ξ with transmission pattern $g(\xi)$, the total power consumption of the transmission is $P_{g(\xi)}$, and $C_{g(\xi)}$ is the achievable throughput in the transmission. Energy efficiency, $E_{g(\xi)}$, is expressed as:

$$E_{g(\xi)} = \frac{C_{g(\xi)}}{P_{g(\xi)}}. \tag{3}$$

We assume that medium access control (MAC) mechanisms, such as RTS/CTS signaling mechanism in 802.11 MAC and the RTS/CTS/HTS signaling mechanism in CoopMAC [20], can handle the interference among links. In other words, a link should not share access with other links with equal access time. Whenever a link obtains the access to a channel, other potential interfering links are blocked by the mechanisms in the MAC layer. Hence, the channel is exclusively occupied by the active link and any other potential interfering links will be in the silent state. Therefore, for all the transmission pairs in a network, the objective function in (2) can be set as follows to optimize the total network energy efficiency

$$f(g(\mathcal{E})) = \sum_{\xi\in\mathcal{E}} E_{g(\xi)} = \sum_{\xi\in\mathcal{E}} \frac{C_{g(\xi)}}{P_{g(\xi)}}. \tag{4}$$

Obviously, the topology with larger $f(g(\mathcal{E}))$ has better energy efficiency performance. Therefore, the topology control formulation (2) is equivalent to

$$G^*(\mathcal{E}) = \arg\max f\left(g(\mathcal{E})\right) \tag{5}$$

where $f(g(\mathcal{E})) = \sum_{\xi\in\mathcal{E}} E_{g(\xi)}$.

In transmissions, node i can independently determine its best transmission pattern for each outgoing link $\mathcal{E}_i$. In this sense, for the objective function, we get $\max\sum((C_{g(\mathcal{E}_i)})/P_{g(\mathcal{E}_i)}) = \sum\max(C_{g(\mathcal{E}_i)}/P_{g(\mathcal{E}_i)})$. Therefore, the topology control problem can be divided into multiple independent and parallel sub-problems

$$G^*(\mathcal{E}_i) = \arg\max f\left(g(\mathcal{E}_i)\right), \quad \forall\, \mathcal{E}_i \subset \mathcal{E} \tag{6}$$

where $f(g(\mathcal{E}_i)) = C_{g(\mathcal{E}_i)}/P_{g(\mathcal{E}_i)}$.

The link energy efficiency varies for different transmission patterns. To resolve the specific topology control problem, a detailed energy efficiency expression of different transmission patterns is required, which will be derived in the following.

B. Energy Efficiency for Different Transmission Patterns

For the DT, TT, and DF patterns that involve no more than three nodes, let γ_0, γ_1, and γ_2 denote the received Signal-to-Noise Ratios (*SNRs*) from the source to the destination, from the source to the relay, and from the relay to the destination, respectively. Please note that all of the SNRs in this paper are deterministic. The details of energy consumption and link capacity as well as energy efficiency of four transmission patterns are shown as follows.

1) Direct Transmission: For a transmission between source node i and destination node j, the path loss can be expressed as

$$l_{ij} = \frac{G\lambda^2}{(4\pi)^2 d_{ij}^{\alpha} M_l N_f} \tag{7}$$

where d_{ij} is the distance in meters between these two nodes, α is the path loss factor, G is the total gain of the transmit and receive antennas, λ is the wavelength, M_l is the link margin and N_f is the noise figure at the receiver.

We assume that $P_{PA,DT}$ is the power amplifier consumption for the transmission link $i-j$. Therefore, in the transmission between i and j, the SNR at the receiver is The SNR at the receiver is

$$SNR = \frac{(|h_{ij}|)^2 l_{ij} P_{PA,DT}}{N} \tag{8}$$

where $N = N_0 B$ is the noise power spectral density, B is the system bandwidth in Hertz and h_{ij} is the channel gain over link $i-j$.

In the DT transmission between source node S and destination node D, an outage occurs when the SNR at the receiver falls below a threshold θ. The outage probability of the DT transmission is given by [21], [22]

$$\mathcal{O}_{DT} = \mathcal{O}(SNR_{DT} < \theta) = \frac{N\theta}{P_{PA,DT} l_{SD}}. \tag{9}$$

Fixing the outage probability at a packet loss limit $\mathcal{O}^*$, such that $\mathcal{O} \leq \mathcal{O}^*$, and substituting it in (9) lead to the optimal transmit power for direct transmission:

$$P^*_{PA,DT} = \frac{N\theta}{l_{SD}\mathcal{O}^*}. \tag{10}$$

The total power consumption takes into account the required power for the transmission, which is dependent on the distance between the nodes and the power consumption of the circuitry. Therefore, the total power consumption is constructed by $P_{PA,H(\mathcal{R})}$, P_{TX}, and P_{RX}, where $P_{PA,H(\mathcal{R})}$ is the power amplifier consumption for the transmission and P_{TX} and P_{RX} are the power consumption of the internal circuitry for transmitting and receiving, respectively. In DT transmission, only two nodes are involved in the direct transmission and the total power consumption is

$$P_{DT} = P_{PA,DT} + P_{TX} + P_{RX}. \tag{11}$$

With the outage probability requirement $\mathcal{O}^*$ and the transmission bandwidth B, the achievable link capacity under Rayleigh fading channel is given by [23]

$$C_{DT} = B \log_2\left(1 + \frac{1.5\gamma_0\mathcal{O}^*}{0.2 - \mathcal{O}^*}\right). \tag{12}$$

In DT transmission, energy efficiency is effective when packets arrive at the destination and are decoded without outage. Otherwise, energy efficiency is null because the achievable throughput is zero. Therefore, energy efficiency of the DT transmission is

$$E_{DT} = (1 - \mathcal{O}_{DT}) \cdot \frac{C_{DT}}{P_{PA,DT} + P_{TX} + P_{RX}}. \tag{13}$$

2) Two-Hop Transmission: In a two-hop transmission, the relay has the ability to detect if the packet was received correctly or not, and only in the case of the packet being correctly received the relay will forward the packet to the destination. Otherwise, the packet is considered lost. To discuss the transmission clearly, we define the outage probability for link between nodes i and j, which is

$$p_{ij,MH} = \mathcal{O}(SNR_{ij,MH} < \theta) \simeq \frac{N\theta}{P_{PA,MH} l_{ij}}. \tag{14}$$

The overall outage probability for the two-hop transmission is given by the combination of the outages in the S-R and R-D links:

$$\begin{aligned}\mathcal{O}_{TT} =& \mathcal{O}(SNR_{SR,TT} < \theta) \\ &+ \mathcal{O}\{(SNR_{SR,TT} \geq \theta) \cap (SNR_{RD,TT} < \theta)\} \\ =& p_{SR,TT} + (1 - p_{SR,TT}) p_{RD,TT}.\end{aligned} \tag{15}$$

We obtain the optimal transmit power $P^*_{PA,TT}$ required in the two-hop transmission by replacing $\mathcal{O}_{TT}$ with the target outage probability $\mathcal{O}^*$ in (15):

$$\mathcal{O}^*(P^*_{PA,TT})^2 - (k_1 + k_2)P^*_{PA,TT} + k_1 k_2 = 0 \tag{16}$$

where $k_1 = N\theta/l_{SR}$ and $k_2 = N\theta/l_{RD}$.

The achievable link capacity equals to the minimum of the two hops, i.e.,

$$C_{TT} = \frac{1}{2}\min\{C_{SR}, C_{RD}\} \tag{17}$$

where $C_{SR} = B\log_2(1 + (1.5\mathcal{O}^*\gamma_1/(0.2 - \mathcal{O}^*)))$, and $C_{RD} = B\log_2(1 + (1.5\mathcal{O}^*\gamma_2/(0.2 - \mathcal{O}^*)))$.

In TT transmission, three nodes are involved in the data transmission and the total power consumption is

$$P_{TT} = 2P_{PA,TT} + 2P_{TX} + 2P_{RX}. \tag{18}$$

In this transmission, energy efficiency is effective when messages are transmitted successfully to the destination via the relay. Therefore, the energy efficiency in the two-hop transmission is

$$E_{TT} = \frac{(1 - p_{SR,TT}) \cdot (1 - p_{RD,TT}) \cdot C_{TT}}{2P_{PA,TT} + 2P_{TX} + 2P_{RX}}. \tag{19}$$

3) Decode-and-Forward Relay Transmission: In this cooperative transmission, the corresponding outage probabilities can be easily determined based on (14), with the proper notations (e.g., the transmit power required by the cooperative transmission). The overall outage probability for the cooperative relay transmission, is given by the combination of the outages in the S-D, S-R and R-D links:

$$\mathcal{O}_{DF} = p_{SD,DF}\left[p_{SR,DF} + (1 - p_{SR,DF}) p_{RD,DF}\right]. \tag{20}$$

To find the optimal transmit power required by the cooperative scheme, we replace $\mathcal{O}_{DF}$ by $\mathcal{O}^*$ in (20), and then obtain $P^*_{PA,DF}$ from

$$\mathcal{O}^*(P^*_{PA,DF})^3 - (k_1 + k_2)k_3 P^*_{PA,DF} + k_1 k_2 k_3 = 0 \tag{21}$$

where $k_3 = (N\theta)/l_{SD}$.

This study uses the fixed decode-and-forward relaying scheme with only one relay, which is selected proactively before transmissions. In the DF relaying, the relay node decodes and re-encodes the signal from the source, and then forwards it to the destination. The two signals from the source and the relay are decoded by maximal rate combining (MRC) at the destination. Thus, the SNR of the combined signals equals to $\gamma_0 + \gamma_2$, and the achievable link capacity can be expressed as [24]

$$C_{DF} = \frac{1}{2}\min\{C_{SR}, C_{MRC}\} \tag{22}$$

where $C_{SR} = B\log_2(1 + ((1.5\mathcal{O}^*\gamma_1)/(0.2 - \mathcal{O}^*)))$, and $C_{MRC} = B\log_2(1 + ((1.5\mathcal{O}^*(\gamma_0+\gamma_2))/(0.2 - \mathcal{O}^*)))$.

In DF transmission, three nodes are involved in the data transmission and the total power consumption is

$$P_{DF,DF} = 2P_{PA,DF} + 2P_{TX} + 3P_{RX}. \tag{23}$$

However, the information transmission through relay may fail but the destination receives the signal from the source correctly. The throughput of this case is

$$C_{SD,DF} = B\log_2\left(1 + \frac{1.5\mathcal{O}^*\gamma_0}{0.2 - \mathcal{O}^*}\right). \tag{24}$$

The total power consumption of this case is

$$P_{SD,DF} = P_{PA,DF} + P_{TX} + 2P_{RX}. \tag{25}$$

Another case is that the destination only receives the information from the relay and cannot decode the information from the source. In this case, the transmission degrades to a two-hop transmission and the throughput equals to that of TT transmission, denoted $C_{TT,DF}$ here. The total power consumption of this case equals to $P_{DF,DF}$.

In DF transmission pattern, energy efficiency is effective when messages are transmitted successfully to the destination directly or via the cooperative relay. Therefore, the energy efficiency in DF relay transmission is

$$\begin{aligned} E_{DF} = & p_{SR,DF} \cdot \frac{C_{SD,DF}\cdot(1 - p_{SD,DF})}{P_{PA,DF} + P_{TX} + 2P_{RX}} \\ & + (1 - p_{SR,DF})\cdot(1 - p_{RD,DF}) \\ & \cdot \frac{C_{DF}\cdot(1 - p_{SD,DF}) + C_{TT,DF}\cdot p_{SD,DF}}{2P_{PA,DF} + 2P_{TX} + 3P_{RX}}. \end{aligned} \tag{26}$$

4) IC-Based Relay Transmission: In the (2,3,2) IC-based relay transmission, two S-D pairs can transmit concurrently. From one pair perspective, the overall outage probability of one transmission is given by the combination of the outages in S-D, S-R, and R-D links:

$$\mathcal{O}_{IC} = p_{SD,IC}\left[p_{SR,IC} + (1 - p_{SR,IC})p_{RD,IC}\right]. \tag{27}$$

Note that R is a relay set including three relays R_1, R_2, and R_3 in our transmission model. Therefore, the expression of $p_{SR,IC}$ and $p_{RD,IC}$ is

$$p_{SR,IC} = p_{SR_1,IC}p_{SR_2,IC}p_{SR_3,IC} \tag{28}$$

and

$$p_{RD,IC} = p_{R_1D,IC}p_{R_2D,IC}p_{R_3D,IC}. \tag{29}$$

To find the optimal transmit power required by this transmission pattern, we replace $\mathcal{O}_{IC}$ by $\mathcal{O}^*$ in (27), and then obtain $P^*_{PA,IC}$ from

$$\begin{aligned} \mathcal{O}^*(P^*_{PA,IC})^7 - (t_0t_1t_2t_3 + t_0t_4t_5t_6)(P^*_{PA,IC})^3 \\ + t_0t_1t_2t_3t_4t_5t_6 = 0 \end{aligned} \tag{30}$$

where $t_0 = (N\theta)/l_{SD}$, $t_1 = (N\theta)/l_{SR_1}$, $t_2 = (N\theta)/l_{SR_2}$, $t_3 = (N\theta)/l_{SR_3}$, $t_4 = (N\theta)/l_{R_1D}$, $t_5 = (N\theta)/l_{R_2D}$, and $t_6 = (N\theta)/l_{R_3D}$.

Let the *SNRs* at D_1 and D_2 be γ_{D1} and γ_{D2}, respectively. Then, the total capacity of the IC-based transmission pattern is [24]

$$C_{IC} = \frac{1}{2}(C_{S_1D_1} + C_{S_2D_2}) \tag{31}$$

where $C_{S_1D_1} = B\log_2(1 + ((1.5\mathcal{O}^*\gamma_{D1})/(0.2 - \mathcal{O}^*)))$, and $C_{S_2D_2} = B\log_2((1 + (1.5\mathcal{O}^*\gamma_{D2})/(0.2 - \mathcal{O}^*)))$.

All the nodes in (2, 3, 2) are involved in the data transmission and the total power consumption is

$$P_{IC,IC} = 5P_{PA,IC} + 5P_{TX} + 5P_{RX}. \tag{32}$$

However, the destination may decode the signal from the source directly when relays fail to forward the messages. In this case, the throughput is

$$C_{SD,IC} = B\log_2\left(1 + \frac{1.5\mathcal{O}^*\gamma_0}{0.2 - \mathcal{O}^*}\right). \tag{33}$$

The total power consumption of this case is

$$P_{SD,IC} = 2P_{PA,IC} + 2P_{TX} + 5P_{RX}. \tag{34}$$

Another case is that the destination only receives the information from the relay and cannot decode the information from the source. In this case, the transmission degrades to a two-hop transmission and the throughput equals to that of TT transmission via relays, denoted $C_{TT,IC}$ here. The total power consumption of this case equals to $P_{IC,IC}$.

In IC-based transmission pattern, messages are transmitted to the destination directly or via the cooperative relays. The energy efficiency of the IC-based transmission is

$$\begin{aligned} E_{IC} = & p_{SR,IC} \cdot \frac{C_{SD,IC}\cdot(1 - p_{SD,IC})}{2P_{PA,IC} + 2P_{TX} + 5P_{RX}} \\ & + (1 - p_{SR,IC})\cdot(1 - p_{RD,IC}) \\ & \cdot \frac{C_{IC}\cdot(1 - p_{SD,IC}) + C_{TT,IC}\cdot p_{SD,IC}}{5P_{PA,IC} + 5P_{TX} + 5P_{RX}}. \end{aligned} \tag{35}$$

From the discussion above, we can derive the analytical expression of energy efficiency in different transmission patterns. To further directly relate the expected link energy efficiency with the transmission pattern, i.e., the relay nodes $\mathcal{R}$ and the relay function $h(\mathcal{R})$, we need to find a detailed expression of $g(\mathcal{E}_i)$ which can jointly capture characteristics of the four transmission patterns considered in this paper. Toward this, we define a six-parameter profile to represent the detail of each selected transmission pattern as follows. Let each node firstly sort its neighbors based on arbitrary criteria and then assign them a unique ID from $[1, m]$, where m is the number of neighbors for the underlying node. Hence, its neighbor set can be represented by $\mathcal{N}_N = \{1, 2, \ldots, m\}$ and its out-going link set can be denoted by $\mathcal{E}_N = \{\mathcal{E}_1, \mathcal{E}_2, \ldots, \mathcal{E}_m\}$. Correspondingly, for each out-going link $\mathcal{E}_i (i \in [1, m])$, the six-parameter profile used to capture the detail of each selected transmission pattern is defined as

$$g(\mathcal{E}_i) = (r_{i1}, r_{i2}, r_{i3}, r_{i4}, r_{i5}, r_{i6}) \tag{36}$$

where r_{i1} is used to identify the selected transmission pattern as well as the relay for the TT and DF transmission patterns and $r_{ik}(k = 2 \cdots 6)$ are used to represent the selected assisting source, destination and three relays in IC-based transmission. The range for r_{i1} is set to $R_{i1} = \{0, 1, \ldots, m, m+1, \ldots, 2m, 2m+1\} \setminus \{i, m+i\}$ and the range for $r_{ik}(k = 2 \cdots 6)$ is set to $R_{i2} = \{0, 1, \ldots, m\} \setminus \{i\}$. Therefore, the expression of transmission pattern function $g(\mathcal{E}_i)$ is

$$\begin{cases} r_{i1} = 0 \rightarrow DT \text{ with node } i \text{ as the destination,} \\ r_{i1} \in [1, m] \setminus \{i\} \rightarrow TT \\ \text{with node } i \text{ as the destination, } r_{i1} \text{ as the relay,} \\ r_{i1} \in [m+1, 2m] \setminus \{i, m+i\} \rightarrow DF \\ \text{with node } i \text{ as the destination, } r_{i1} \text{ as the relay,} \\ r_{i1} = 2m+1 \rightarrow IC \\ \text{with node } i \text{ as the destination, } (r_{i2}, r_{i3}) \text{ as} \\ \text{cooperative transmission pair,} \\ \text{and } r_{i4}, r_{i5}, r_{i6} \text{ as assistant relays.} \end{cases}$$

Note that, when r_{i1} is smaller than $2m + 1$, IC-based transmission pattern is not used, and the transmission pattern function is only related to the variable r_{i1}. Therefore, we can set $r_{ik}(k = 2 \cdots 6)$ to an arbitrary value for compressing solution space (set to -1 for simplicity). When r_{i1} equals to $2m + 1$, IC-based transmission pattern is selected. Furthermore, according to the basic requirement of IC transmission model, when m is smaller than 6, IC-based transmission pattern is not available and therefore we can force r_{i1} to be smaller than $2m + 1$. To illustrate such relations, we propose the following constraints to the definition (36) as

$$\begin{cases} r_{i1} < 2m+1, & m < 6 \\ r_{ik} \neq r_{ij}, & \forall\, k \neq j \;\&\; r_{i1} = 2m+1 \\ r_{ik} = -1, & \forall\, k \geq 2 \;\&\; r_{i1} < 2m+1. \end{cases} \tag{37}$$

Based on the above discussions, we are now able to give the detailed analytical expression of the link energy efficiency for transmission pattern $g(\mathcal{E}_i)$

$$f\left(g(\mathcal{E}_i)\right) = \begin{cases} E_{DT}, & r_{i1} = 0 \\ E_{TT}, & 0 < r_{i1} \leq m \\ E_{DF}, & m < r_{i1} \leq 2m \\ E_{IC}, & r_{i1} = 2m+1. \end{cases} \tag{38}$$

C. The Algorithm

For a transmission from the source node to the destination node, the energy efficiency of possible candidate transmission patterns should be evaluated and the transmission pattern with optimal energy efficiency is exhaustively searched according to (6). When $m < 6$, the source can choose DT, TT or DF as the transmission pattern, and it is easy to use the traversal method due to the small computation space. When $m \geq 6$, the source node has chances to use IC as the transmission pattern. Only the nodes in neighbor sets of the source and the destination can be chosen as relays. In practical networks, the solution space is usually small. Therefore, it is practical to use a brute force search approach to find out the optimal transmission pattern. The detail of the algorithm of EEIC operated for a transmission from node i to destination j is shown in Algorithm 1.

Algorithm 1 EEIC Algorithm

Initialization:
source node i and its neighbor set and destination node j
set $k \in R_{i1} - \{2m+1\}$, $K_n (n = 2 \cdots 6) \in R_{i2}$
$E_{temp} = 0$
Computing the optimal:
if $m < 6$ **then**
  for all $k \in R_{i1} - \{2m+1\}$ **do**
    $g(\mathcal{E}_i) = (k, -1, -1, -1, -1, -1)$
    if $f(g(\mathcal{E}_i)) > E_{temp}$ **then**
      $r_{i1} = k$
      $E_{temp} = f(g(\mathcal{E}_i))$
    end if
  end for
end if
if $m \geq 6$ **then**
  for all $K_2, K_3, K_4, K_5, K_6 \in R_{i2}$ **do**
    $g(\mathcal{E}_i) = (2m+1, K_2, K_3, K_4, K_5, K_6)$
    if $f(g(\mathcal{E}_i)) > E_{temp}$ **then**
      $r_{i1} = 2m+1$
      $r_{in} = K_n, (n = 2 \cdots 6)$
      $E_{temp} = f(g(\mathcal{E}_i))$
    end if
  end for
end if
Output:
The optimal transmission pattern $g(\mathcal{E}_i)$ and the best energy efficiency $f(g(\mathcal{E}_i)) = E_{temp}$.

IV. Simulation Results and Discussions

In this section, we evaluate the performance of the proposed energy-efficient topology control scheme with interference cancellation algorithm via computer simulations. We consider a grid topology and a random topology, as shown in Fig. 2, in our simulations. In the grid topology, 36 wireless nodes are placed in a 6×6 grid. The inter-node distance will be changed in the simulations. In the random topology, nodes are randomly deployed in a 300 m $\times$ 300 m square area. The number of nodes in this area will be changed. In addition, the path loss factor will also be changed in both topologies in the simulations.

Besides energy efficiency, network lifetime is used as another performance metric to evaluate the effects of transmission

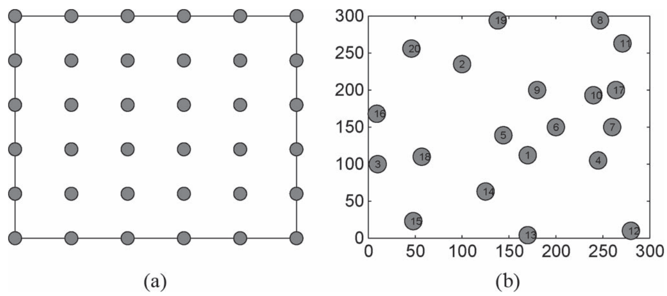


Fig. 2. Two simulation scenarios. (a) Grid topology: 36 nodes are placed in a 6×6 grid. (b) Random topology: nodes are randomly deployed in a 300 m $\times$ 300 m square area.

pattern selection on network performance. The definition of network lifetime depends on network applications. A common definition used in the literature for network lifetime is determined by the moment that the number of dead nodes reaches a threshold beyond which the network can no longer achieve the targeted performance [25]. In this paper, we define the network lifetime as the moment that the remaining alive wireless nodes cannot guarantee the connectivity of the network, because we have the network connectivity constraint in (1) of our formulation.

We compare the energy efficiency and network lifetime of the proposed EEIC scheme to those of three existing schemes: COIC [24], COCO [16] and LLISE [26]. In COIC, the authors study the impacts of cooperative communications on topology control in WANETS and propose a distributed cooperative topology control scheme with opportunistic IC to improve network capacity by jointly considering both upper layer network capacity and physical layer cooperative communications with interference cancellation. In COCO, capacity is used as the only criterion for topology control in wireless networks without considering IC-based cooperative communications. LLISE considers the direct and two-hop transmissions without cooperative communications. All these schemes aim to improve network capacity without considering energy efficiency.

We assume that the channel fading follows Raleigh distribution. $M_l = 40$ dB and $N_f = 10$ dB are used in (7), the total antenna gain is $G = 5$ dBi, the carrier frequency is $f_c = 2.5$ GHz, and $N_0 = -174$ dBm. According to the power consumption values in [27], we consider the power consumption of circuity for transmitting and receiving as $P_{TX} = 97.9$ mW and $P_{RX} = 112.2$ mW, respectively. Moreover, we assume a bandwidth of $B = 10$ kHz and a maximum packet loss rate of $\mathcal{O}^* = 10^{-3}$.

A. Energy Efficiency of Different Transmission Patterns in a Single Link

Before we study the whole network energy efficiency, we first evaluate the energy efficiency of different transmission patterns in a single link. We take the link from node 1 to node 7 in Fig. 2(b) as an example. The energy efficiency of link (1, 7) using DT, TT, DF and IC-based transmission patterns is shown in Fig. 3. From this figure, we can see that cooperative communications do not always outperform traditional non-cooperative communications. Non-cooperative DT transmission can outperform cooperative IC-based and DF transmissions when the

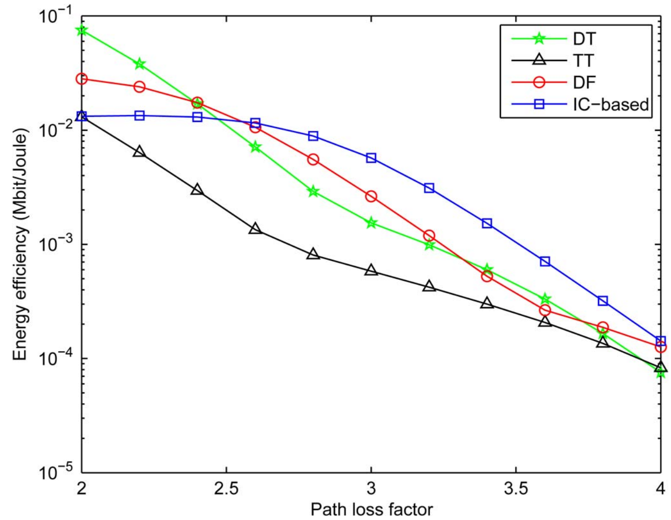


Fig. 3. The energy efficiency performance of link (1, 7) using DT, TT, DF, and IC-based transmission patterns vs. path loss factor.

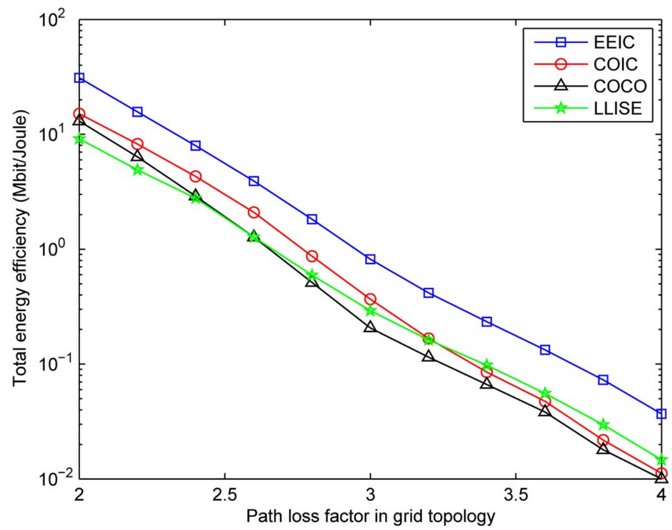


Fig. 4. Energy efficiency vs. path loss factor in the grid topology.

path loss factor is smaller than 2.4. This is because, although cooperative communications can increase data rate, more nodes are involved in the transmission, which will consume more energy. Therefore, from energy efficiency perspective, cooperative communications may not always appealing, especially when the SNR is high.

B. Network Performance in the Grid Topology Scenario

We then study the network performance in the grid topology scenario, as shown in Fig. 2(a). To evaluate the energy efficiency performance under different path loss factors, we increase the path loss factor α from 2 to 4 with a step of 0.2, and the inter-node distance is set to 80 m. The results are depicted in Fig. 4. From the figure, we can see that, the energy efficiency of EEIC, COIC, COCO, and LLISE decreases with the increase of the path loss factor, which means the network has less achievable throughput per Joule energy consumption. The reason is that, with the increase of the path loss factor, all the schemes need to increase the transmit power to keep the

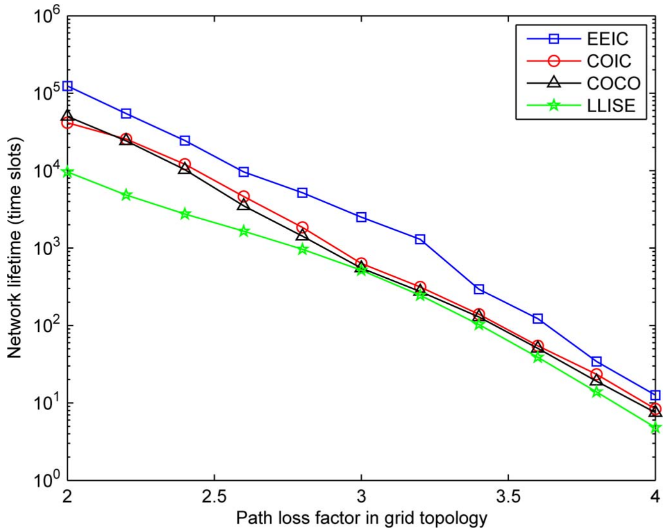


Fig. 5. Network lifetime vs. path loss factor in the grid topology.

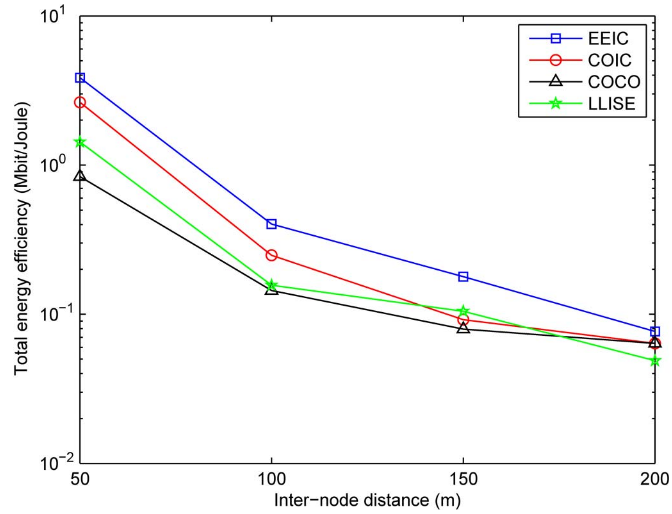


Fig. 6. Energy efficiency vs. inter-node distance in the grid topology.

target packet loss rate. On the other hand, the achievable capacity can be reduced due to the high packet loss rate caused by the reduced SNR. Both aspects contribute to the performance degradation of energy efficiency. Nevertheless, EEIC performs best among all the topology control schemes thanks to the energy-efficient transmission selection with IC. In spite of the adoption of IC, COIC has worse energy efficiency performance than EEIC. This is because COIC uses network capacity as the only optimization objective, and the transmission pattern with high capacity may have low energy efficiency. COCO performs worse than COIC because it does not benefit from the high energy efficiency brought by IC-based transmission pattern in this simulation scenario. As far as LLISE is concerned, with the increase of path loss factor, it performs worse than COCO and COIC in the beginning, better than COCO but still worse than COIC in the middle, then outperforms COCO and COIC when the path loss factor is high. The reason is that, compared to cooperative communications, traditional non-cooperative communications may have better energy efficiency performance in some transmission scenarios and worse performance in other scenarios, as also shown in Section IV-A.

To further study the performance of topology control schemes under different path loss factors, we investigate the network lifetime performance, as shown in Fig. 5. From this figure, we can observe that the network lifetime with different topology control schemes decreases with the increase of the path loss factor. The reason is that, with the increase of the path loss factor, the network energy efficiency decreases, and the network needs more energy to finish the required transmissions. Therefore, the network lives shorter. In comparison, EEIC has longer lifetime than COIC, COCO, and LLISE, because it focuses on energy efficiency optimization, and consumes less energy to achieve the same throughput transmissions due to its high energy efficiency. The lifetime performance of COIC is generally better than COCO. The reason is that, with higher energy efficiency, it consumes less energy to achieve the same throughput transmissions. LLISE performs worst in terms of network lifetime. This is because, without cooperative communication, more pairs are involved in data transmissions, and more energy is consumed, which contributes to the shorter network lifetime.

To show the impact of network density, we increase the inter-node distance from 50 m to 200 m with a step of 50 m when the path loss factor is 3, and the results are depicted in Fig. 6. As shown in Fig. 6, the energy efficiency values of EEIC as well as COIC, COCO and LLISE decrease with the increase of inter-node distance. This performance degradation is mainly attributed to more transmission power to keep the target packet loss and less transmission pairs for the increased inter-node distance. EEIC performs best among the topology control schemes thanks to the energy-efficient transmission selection with IC. COIC has worse energy efficiency performance than EEIC because COIC uses network capacity as optimization objective. COCO performs worse than COIC but close to COIC with the increase of inter-node distance, because COIC has less chances to have IC-based transmission pattern when the network gets sparser. Finally, COIC and COCO have the same performance when the inter-node distance is larger than 200 m because COIC degrades to COCO due to the constraints of IC transmission. For LLISE, with the increase of inter-node distance, it performs better than COCO but worse than COIC when inter-node distance is small than 150 m, outperforms COCO and COIC when the distance is around 150 m and performs worse than COIC and COCO when the distance is larger than about 170 m. The reason is that, compared to cooperative communication, traditional non-cooperative communications may have better energy efficiency performance in some transmission scenarios and worse performance in other scenarios.

We investigate the impact of inter-node distance on the network lifetime as shown in Fig. 7. We can see that the network lifetime of different topology control schemes decreases with the increase of inter-node distance. The reason is that, with the increase of inter-node distance, the network needs more power to achieve the required throughput transmissions and therefore lives shorter. EEIC has longer lifetime compared to COIC, COCO, and LLISE, because it focuses on the energy efficiency optimization and consumes less energy with the same throughput transmissions. COIC performs better than COCO

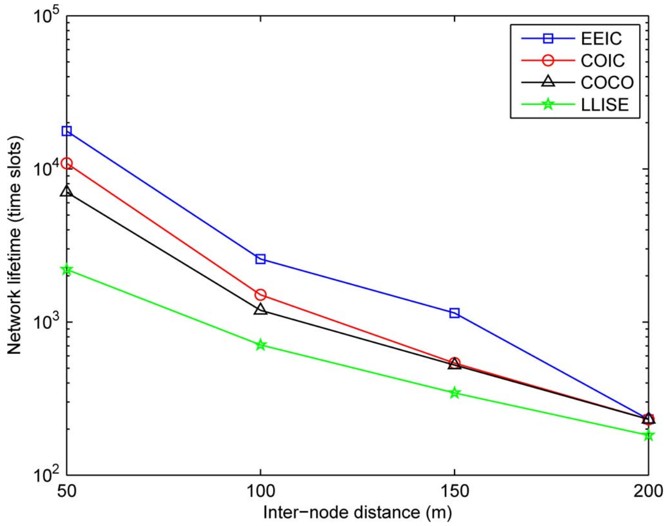


Fig. 7. Network lifetime vs. inter-node distance in the grid topology.

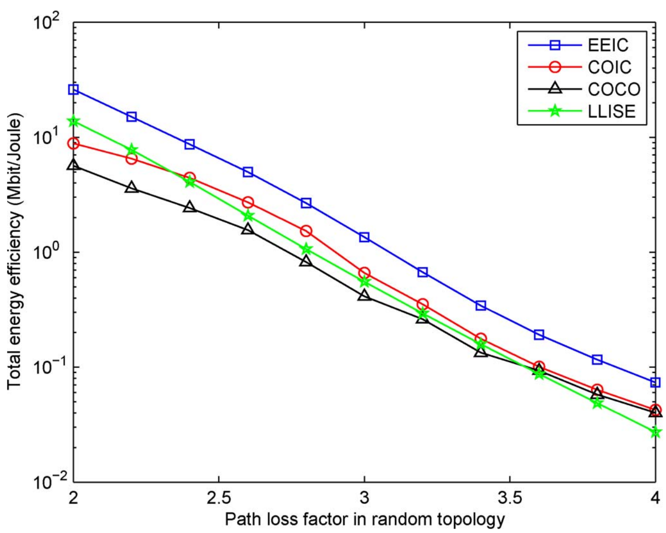


Fig. 8. Energy efficiency vs. path loss factor in the random topology.

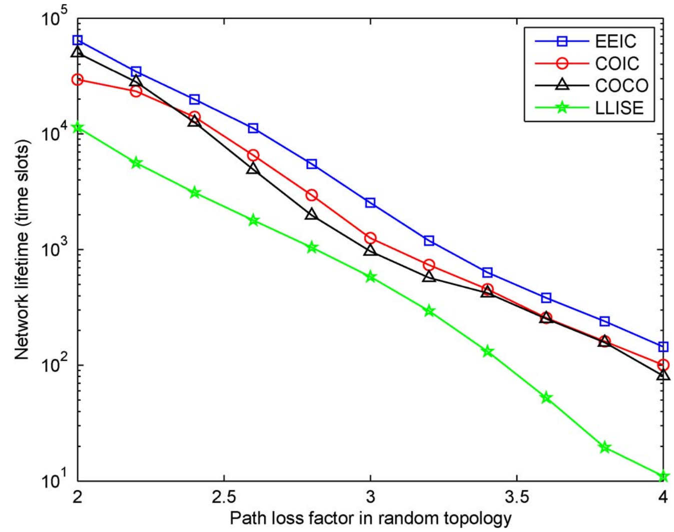


Fig. 9. Network lifetime vs. path loss factor in the random topology.

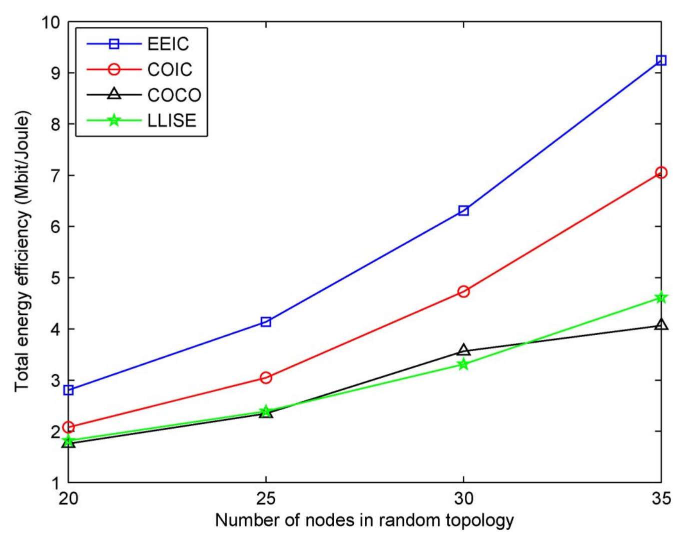


Fig. 10. Energy efficiency vs. node density in the random topology.

because it has higher energy efficiency. LLISE performs worst because of more transmission pairs involved in the required transmissions.

C. Network Performance in the Random Topology Scenario

In this subsection, the performance of different topology control schemes in a random topology is studied. The simulation topology shown in Fig. 2(b) is a 300 m $\times$ 300 m square area where nodes are randomly deployed in the network. We consider two simulation cases using this random topology to evaluate the impact of path loss factor and network density on energy efficiency and network lifetime.

In the first simulation case, we fix the number of nodes as 20 and increase the path loss factor from 2 to 4 with a step of 0.2. The energy efficiency and network lifetime of different topology control schemes are shown in Figs. 8 and 9, respectively. From these two figures, we can observe the similar results as those in the grid topology scenario.

To show the impact of network density in random topology, we fix the path loss factor as 3 and increase the number of nodes from 20 to 35 in the network with a step of 5. The energy efficiency and network lifetime are depicted in Figs. 10 and 11, respectively. From Fig. 10, we can see that the energy efficiency of EEIC, COIC, COCO, and LLISE increases as the network gets denser. The reason is that, with the increase of the node number, there are more transmission pairs in the same area. On the other hand, the network consumes less power to keep the target packet loss due to the shorter distance of the transmission pair. With energy efficiency as the optimization objective, EEIC performs best among the topology control schemes. COIC and COCO perform worse than EEIC because they only consider the capacity optimization, ignoring the energy efficiency. LLISE has the similar performance of COCO when the network nodes are 20 and 25. However, when there are 30 nodes in the network, LLISE performs worse than COCO while outperforms COCO when there is 35 nodes. This is because cooperative communications do not always outperform

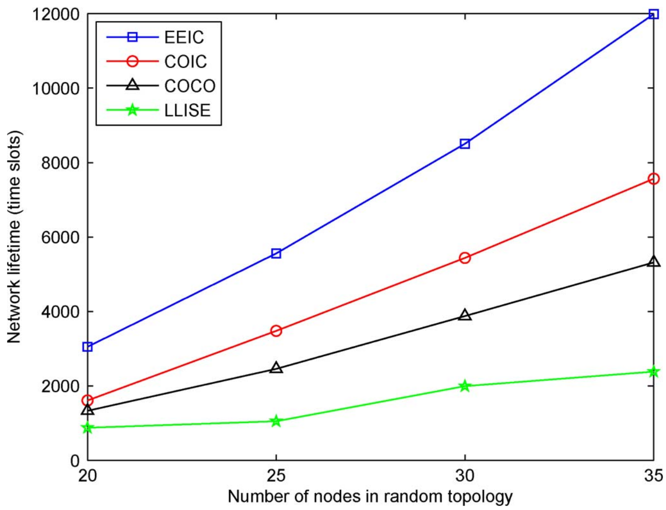


Fig. 11. Network lifetime vs. node density in the random topology.

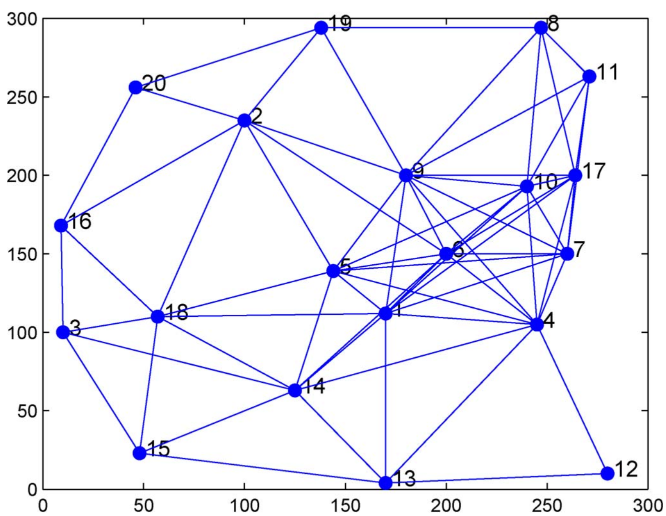


Fig. 12. The original network topology.

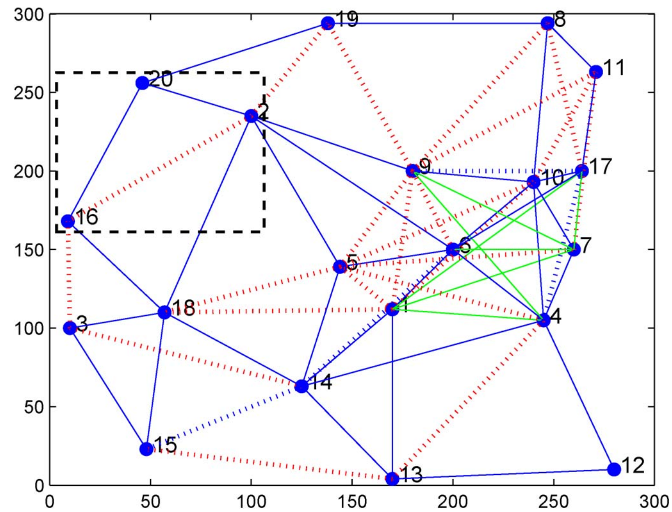


Fig. 13. The topology generated by COIC. (The blue solid lines denote direct transmission. The blue dashed lines denote two-hop transmission. The red dashed lines denote decode-and-forward relay transmission. The green solid lines denote IC-based transmission. Link (2, 16) marked in the rectangle is one example of difference between COIC and EEIC).

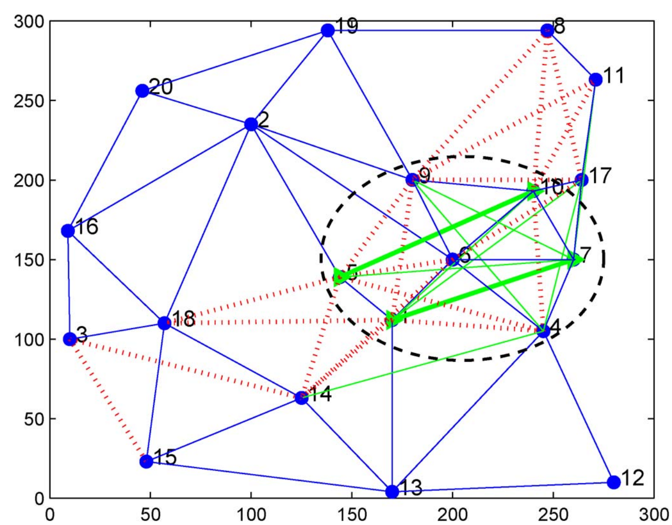


Fig. 14. The topology generated by EEIC. (The blue solid lines denote direct transmission. The red dashed lines denote decode-and-forward relay transmission. The green solid lines denote IC-based transmissions). Link (5, 10) cooperates with link (1, 7) with the help of nodes 4, 6, 9, forming two IC-based parallel transmissions as shown in the black dashed ellipse.

traditional non-cooperative communications and the results are also affected by the randomness of nodes deployment. Fig. 11 shows the network lifetime performance of the topology control schemes in the random topology. From the figure, we can see that, with the increase of nodes number, the network lifetime of different topology control schemes increase. The network needs less power because of the increasing energy efficiency as the network gets denser. This contributes to the increase of lifetime performance. In comparison, EEIC performs better than COIC, COCO, and LLISE.

D. Resulting Topology of the Proposed Scheme in the Random Topology Scenario

The simulations discussed above show the effectiveness of the EEIC in terms of energy efficiency and network lifetime. However, what does the topology generated from EEIC look like? To show the topology visually, we draw the original topology of the network in Fig. 12 and the final topology generated by EEIC in Fig. 14, respectively. In addition, to show the difference between EEIC and COIC, the topology generated by COIC is also drawn in Fig. 13. Note that we optimize the network performance through transmission pattern selection while keeping the original transmission range. In the original topology, all the nodes connect to their neighbors directly with blue solid lines as shown in Fig. 12. In COIC topology control as shown in Fig. 13, only some links select relay-based or IC-based cooperative communication patterns. In EEIC topology control, each node chooses the most energy-efficient transmission pattern to its transmission destination as shown in the Fig. 14. Due to the different optimization objectives, EEIC and COIC may choose different transmission patterns on the same transmission link. For example, for link (2, 16), DF via node 20 is the best choice in COIC as shown in the rectangle in Fig. 13, while DT is the most energy-efficient transmission pattern in EEIC. Note that, there is no two-hop transmission in the final topology generated by EEIC, because this transmission pattern is the worst in terms of energy efficiency. Moreover, the IC-based transmission only happens when the number of neighbor nodes is large enough. For instance, as shown in Fig. 14, link (5, 10) cooperates with link (1, 7) with the help of nodes 4, 6, 9, forming two IC-based parallel transmissions, which is marked in the black dashed ellipse.

V. Conclusion and Future Work

Cooperative communications have significant impacts on the network-level performance, such as network capacity and overall energy consumption. In this paper, we have studied the topology control issues in cooperative wireless ad hoc networks. Four transmission patterns have been considered: single-hop, two-hop, decode-and-forward relay, and IC-based transmissions. We proposed an energy-efficient topology control with interference cancellation (EEIC) to capture the benefits brought by IC-based cooperative communications. With the capacity and energy consumption jointly considered, each node can choose the best transmission pattern to its destination with bits per Joule as the performance metric to construct the most energy-efficient topology. Through computer simulations, we have showed that cooperative communications do not always outperform traditional non-cooperative communications, and the proposed EEIC scheme can achieve better energy efficiency performance by dynamically applying different transmission patterns according to the network conditions.

Future work is in progress to upper layer issues, such as multimedia applications, in the proposed framework. In addition, we assume perfect channel state information is available in the proposed scheme. In realistic networks, perfect channel state information may not be available. It is interesting to design robust and energy-efficient upper layer schemes with imperfect channel state information.

Acknowledgment

We thank the editor and the reviewers for their detailed reviews and constructive comments, which have helped to improve the quality of this paper.

References

[1] L. Cottatellucci, X. Mestre, E. G. Larsson, and A. Ribeiro, “Cooperative communications in wireless networks,” *EURASIP J. Wireless Commun. Netw.*, vol. 2009, p. 768314, Jul. 2009.

[2] A. Nosratinia, T. Hunter, and A. Hedayat, “Cooperative communication in wireless networks,” *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[3] H. Li, N. Jaggi, and B. Sikdar, “Relay scheduling for cooperative communications in sensor networks with energy harvesting,” *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 2918–2928, Sep. 2011.

[4] L. Li, Y. Jing, and H. Jafarkhani, “Interference cancellation at the relay for multi-user wireless cooperative networks,” *IEEE Trans. Wireless Commun.*, vol. 10, no. 3, pp. 930–939, Mar. 2011.

[5] S. Fazeli-Dehkordy, S. Shahbazpanahi, and S. Gazor, “Multiple peer-to-peer communications using a network of relays,” *IEEE Trans. Signal Process.*, vol. 57, no. 8, pp. 3053–3062, Aug. 2009.

[6] F. R. Yu, X. Zhang, and V. C. M. Leung, *Green Communications and Networking*. New York, NY, USA: CRC Press, 2012.

[7] S. Bu, F. R. Yu, Y. Cai, and P. Liu, “When the smart grid meets energy-efficient communications: Green wireless cellular networks powered by the smart grid,” *IEEE Trans. Wireless Commun.*, vol. 11, no. 8, pp. 3014–3024, Aug. 2012.

[8] R. Xie, F. R. Yu, H. Ji, and Y. Li, “Energy-efficient resource allocation for heterogeneous cognitive radio networks with femtocells,” *IEEE Trans. Wireless Commun.*, vol. 11, no. 11, pp. 3910–3920, Nov. 2012.

[9] R. Madan, N. Mehta, A. Molisch, and J. Zhang, “Energy-efficient cooperative relaying over fading channels with simple relay selection,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 8, pp. 3013–3025, Aug. 2008.

[10] O. Amin and L. Lampe, “Opportunistic energy efficient cooperative communication,” *IEEE Wireless Commun. Lett.*, vol. 1, no. 5, pp. 412–415, Oct. 2012.

[11] K. Woradit *et al.*, “Outage behavior of selective relaying schemes,” *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, pp. 3890–3895, Aug. 2009.

[12] H. Ding, J. Ge, D. Benevides da Costa, and Y. Guo, “Outage analysis for multiuser two-way relaying in mixed Rayleigh and Rician fading,” *IEEE Comm. Lett.*, vol. 15, no. 4, pp. 410–412, Apr. 2011.

[13] Y. Zhu, M. Huang, S. Chen, and Y. Wang, “Energy-efficient topology control in cooperative Ad Hoc networks,” *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 8, pp. 1480–1491, Aug. 2012.

[14] M. Cardei, J. Wu, and S. Yang, “Topology control Ad Hoc wireless networks using cooperative communication,” *IEEE Trans. Mobile Comput.*, vol. 5, no. 6, pp. 711–724, Jun. 2006.

[15] Q. Guan, F. R. Yu, S. Jiang, V. Leung, and H. Mehrvar, “Topology control in mobile Ad Hoc networks with cooperative communications,” *IEEE Wireless Comm.*, vol. 19, no. 2, pp. 74–79, Apr. 2012.

[16] Q. Guan, F. Yu, S. Jiang, and V. Leung, “Capacity-optimized topology control for manets with cooperative communications,” *IEEE Trans. Wireless Commun.*, vol. 10, no. 7, pp. 2162–2170, Jul. 2011.

[17] X. Ao, F. R. Yu, S. Jiang, Q. Guan, and V. C. M. Leung, “Distributed cooperative topology control for WANETs with opportunistic interference cancelation,” *IEEE Trans. Veh. Technol.*, vol. 63, no. 2, pp. 789–801, Feb. 2014.

[18] B. Rankov and A. Wittneben, “Spectral efficient protocols for half-duplex fading relay channels,” *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 379–389, Feb. 2007.

[19] X. Jia, D. Li, and D. Du, “Qos topology control in ad hoc wireless networks,” in *Proc. INFOCOM*, 2004, vol. 2, pp. 1264–1272.

[20] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. S. Panwar, “CoopMAC: A cooperative MAC for wireless LANs,” *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 340–354, Feb. 2007.

[21] Z. Wang and G. Giannakis, “A simple and general parameterization quantifying performance in fading channels,” *IEEE Trans. Commun.*, vol. 51, no. 8, pp. 1389–1398, Aug. 2003.

[22] G. de Oliveira Brante, M. Kakitani, and R. Souza, “Energy efficiency analysis of some cooperative and non-cooperative transmission schemes in wireless sensor networks,” *IEEE Trans. Commun.*, vol. 59, no. 10, pp. 2671–2677, Oct. 2011.

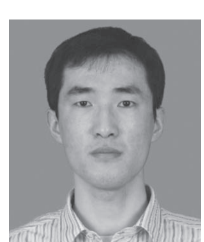
[23] X. Qiu and K. Chawla, “On the performance of adaptive modulation in cellular systems,” *IEEE Trans. Commun.*, vol. 47, no. 6, pp. 884–895, Jun. 1999.

[24] A. Xin, F. Yu, S. Jiang, G. Quansheng, and W. Gang, “Cooperation-aware topology control for wireless Ad Hoc networks with opportunistic interference cancellation,” *IEICE Trans. Commun.*, vol. 95, no. 9, pp. 3047–3051, 2012.

[25] F. R. Yu, H. Tang, P. Mason, and F. Wang, “A hierarchical identity based key management scheme in tactical mobile Ad Hoc networks,” *IEEE Trans. Netw. Serv. Manag.*, vol. 7, no. 4, pp. 258–267, Dec. 2010.

[26] M. Burkhart, P. Von Rickenbach, R. Wattenhofer, and A. Zollinger, “Does topology control reduce interference?” in *Proc. 5th ACM Int. Symp. Mobile Ad Hoc Netw. Comput.*, 2004, pp. 9–19.

[27] S. Cui, A. Goldsmith, and A. Bahai, “Energy-constrained modulation optimization,” *IEEE Trans. Wireless Commun.*, vol. 4, no. 5, pp. 2349–2360, Sep. 2005.



Bingyi Guo received the B.Eng. degree in electronic engineering from China University of Mining and Technology, Xuzhou, China, in 2007. From September 2012 to September 2013, he was a visiting Ph.D. student with the University of British Columbia, Canada. He is currently working toward the Ph.D. degree with the School of Electronic and Information Engineering, South China University of Technology, Guangzhou, China. His research interest is energy efficiency in green communication and networks.

F. Richard Yu (S'00–M'04–SM'08) received the Ph.D. degree in electrical engineering from the University of British Columbia (UBC) in 2003. From 2002 to 2004, he was with Ericsson (in Lund, Sweden), where he worked on the research and development of wireless mobile systems. From 2005 to 2006, he was with a start-up in California, USA, where he worked on the research and development in the areas of advanced wireless communication technologies and new standards. He joined Carleton School of Information Technology and the Department of Systems and Computer Engineering at Carleton University in 2007, where he is currently an Associate Professor. He received the IEEE Outstanding Leadership Award in 2013, Carleton Research Achievement Award in 2012, the Ontario Early Researcher Award (formerly Premiers Research Excellence Award) in 2011, the Excellent Contribution Award at IEEE/IFIP TrustCom 2010, the Leadership Opportunity Fund Award from Canada Foundation of Innovation in 2009 and the Best Paper Awards at IEEE Globecom 2012, IEEE/IFIP TrustCom 2009 and Int'l Conference on Networking 2005. His research interests include cross-layer/cross-system design, security, green IT and QoS provisioning in wireless-based systems.

Dr. Yu is a senior member of the IEEE. He serves on the editorial boards of several journals, including IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, IEEE Communications Surveys and Tutorials, ACM/Springer Wireless Networks, EURASIP Journal on Wireless Communications Networking, Ad Hoc and Sensor Wireless Networks, Wiley Journal on Security and Communication Networks, and International Journal of Wireless Communications and Networking, and a Guest Editor for IEEE Transactions on Emerging Topics in Computing for the special issue on Advances in Mobile Cloud Computing and IEEE Systems Journal for the special issue on Smart Grid Communications Systems. He has served on the Technical Program Committee (TPC) of numerous conferences, as the TPC Co-Chair of IEEE Globecom14, WiVEC14, INFOCOM-MCC14, Globecom13, GreenCom13, CCNC13, INFOCOM-CCSES12, ICC-GCN12, VTC12S, Globecom11, INFOCOM-GCN11, INFOCOM-CWCN10, IEEE IWCMC09, VTC08F and WiN-ITS07, as the Publication Chair of ICST QShine10, and the Co-Chair of ICUMT-CWCN09.

Shengming Jiang (A'96–M'00–SM'07) received the B.Eng. degree from Shanghai Maritime Institute, China, in 1988, and DEA and Dr. degrees respectively from University of Paris VI and University of Versailles Saint-Quentin-En-Yvelines, France, in 1992 and 1995. From 1988 to 1990, he worked in Nanjing Petrol Transportation Company, China. He was a Research Associate in the Department of Electrical & Electronic Engineering and the Computer Science Department, The Hongkong University of Science & Technology, between February1995 and August 1997. He was a member of technical staff in Centre for Wireless Communications, National University of Singapore, between September 1997 and July 2000, and a senior member of technical staff and the leader of the network strategic group between July 2001 and March 2003. He was an Associate Lead Scientist and the leader of End-to-End QoS Laboratory in the Institute for Infocomm Research, Singapore, from October 2003 to September 2004. Between July 2007 and Aug. 2009, he was a Principal Lecturer in the Faculty of Advanced Technology, University of Glamorgan, UK. Currently, he is a Professor in the College of Information and Engineering, Shanghai Maritime University. His major research area is communication networks.

Xin Ao (M'13) received the B.Eng degree from China University of Ming Technology, China, in 2007 and the Ph.D. degree in electrical engineering from South China University of Technology, China, in 2012. He is currently a faculty member in the School of Computer, Dongguan University of Technology, China. From 2011 to 2012, he was a visiting scholar in the University of British Columbia, Vancouver, Canada. He has served as reviewer for IEEE Transaction on Vehicle Technology, Wireless Networks, Wireless Personal Communications, and other International Conferences. He has also served as the Vice Chair of Green Communication and Computing (GCC) Symposium of ChinaCom-2013. His research interests include interference management, topology control, cooperative communication and cross-layer design for wireless networks.

Victor C. M. Leung (S'75–M'89–SM'97–F'03) is a Professor of Electrical and Computer Engineering and holder of the TELUS Mobility Research Chair at the University of British Columbia (UBC). His research is in the areas of wireless networks and mobile systems, where he has co-authored more than 700 technical papers in archival journals and refereed conference proceedings, several of which had won best-paper awards. Dr. Leung is a Fellow of the Royal Society of Canada, the Canadian Academy of Engineering and the Engineering Institute of Canada. He is serving/has served on the editorial boards of IEEE JSAC, Transactions on Computers, Wireless Communications, and Vehicular Technology, Wireless Communications Letters, and several other journals. He has provided leadership to the technical committees and organizing committees of numerous international conferences. Dr. Leung was the recipient of an APEBC Gold Medal, NSERC Postgraduate Scholarships, a 2012 UBC Killam Research Prize, and an IEEE Vancouver Section Centennial Award.