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Location-free topology control protocol in wireless ad hoc networks

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Topology control emphasizes the proper adjustment of the transmission power of each node in wireless mobile ad hoc networks. It not only saves power but also increases the system throughput by increasing the spatial reuse of communication channels. However, there is a hidden terminal problem at the medium access control (MAC) layer if we merely address the topology control issue at the network layer. This paper proposes a distributed protocol that deals with topology control at the network layer and at the same time overcomes the hidden terminal problem at the MAC layer. Each node in the networks determines its power for data transmission and control packets transmission according to the received beacon messages from its neighbors. The proposed protocol works without location information and use little control packet overhead to prevent potential collisions due to hidden terminals. Simulations show that our protocol significantly decreases the total power consumption in the networks and has a better network throughput compared to other protocols.

1. Introduction

Mobile ad hoc networks (MANETs) have once again become a popular research topic. MANETs essentially are a collection of wireless nodes or devices, without the support of a centralized infrastructure, in which nodes cooperate to form a connected network by peer-to-peer multi-hop fashion. Due to the mobile manner of wireless nodes, the construction of an ad hoc network, called topology, is usually temporary or changes dynamically. In a MANET, besides the distribution of wireless nodes, the topology is mainly decided by how nodes communicate or link to each other, in other words, their transmission power or radius. Conventionally, in a MANET, the transmission radii of nodes are fixed; that is to say, it is defined that all nodes use the maximum power to transmit packets [19].

However, it has been proven that the overall performance of end-to-end delay, channel utilization, as well as the lifetime of a MANET is enhanced if the transmission power of the nodes is properly adjusted to a lower level [4,5,12,16,22]. The primary objective of topology control is to design an energy efficient protocol that optimizes the transmission power of each node, while the resulting topology remains the property of connectivity. Generally speaking, higher network throughput can be achieved after controlling the network topology because of the following two benefits that are obtained. First, the interference is reduced by varying the transmission radii of nodes to a nearer scope [5]. Second, more data transmissions are able to be carried out simultaneously in the neighborhood of a node, which in turn increases spatial channel reuse [4,12] and reduces interference [3]. On the contrary, if a network has a bad topology, there may be many adverse effects, such as low capacity, high end-to-end packet delay [18], and weak robustness to node failures [11].

In the literature there are many papers addressing topology control. Based on their principal framework they can be classified into centralized controlling and distributed computing methods. The centralized topology control methods [7,9,18], such as the minimum spanning tree (MST) based algorithm [18], assume that a central entity (e.g. sink or access point) knows the locations of each node, and is capable of determining the optimum transmission power for all nodes through the collected global information. Although this centralized method is simple, it is not realistic. One reason is the drawback of scalability. Moreover, such a central entity is against the nature of ad hoc networks which normally lack an infrastructure. On the other hand, the distributed counterparts [2,10,18,20,22] have the advantage of scalability and adaptation to mobility of nodes, in which each node makes its own local decision on the level of suitable transmission power, based on the information gathered from nearby neighbors. However, the primary challenges of the distributed approach are the guaranty of network connectivity and total power efficiency when one node sends messages to a node far-away in the network.

Until now, most proposed approaches for topology control held the assumption that each node knows its own location information by means of a global positioning system (GPS), triangulation-based positioning protocols and other positioning methods.

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However, acquisition of location information will introduce computation delay, extra message overhead and energy consumption at each node. The authors in [24] presented the XTC algorithm, which is one of the few topology control protocols that are location-free.

Although many efforts have targeted the topology control issue, most papers [6,9,18,22] focused on the network layer and failed to consider the interference or collision problems that may occur at the medium access control (MAC) layer. The potential collision, which is the well-known hidden terminal problem, occurs when each node does not have the same transmission power in the resulting topology after power control. Unfortunately, this problem cannot be overcome by using the standard RTS/CTS control packets mechanism, since the power of the control packets is the same as that of the data packets. Several MAC layer power control protocols have been proposed to solve the hidden terminal problem [25]. In those protocols, each node transmits control packets using the common maximum power to avoid the hidden terminal problem. However, the corresponding cost is the reduction in spatial channel reuse. This is due to the fact that a node restrains all nodes in its neighborhood from transmitting when it is communicating period, even though the transmissions of the neighboring nodes do not interfere with the proper reception of its message.

In this paper, we propose a distributed protocol, named *location-free topology control* (LFTC) protocol, to deal with the topology control issue at the network layer and the hidden terminal problem at the MAC layer. The proposed protocol includes two phases. An appropriate transmission power for data packets at each node is decided after they carry out the first phase. In this phase, each node continuously considers which neighbors it can exclude from direct communication to conserve power. A power-efficient topology of a MANET, in which each node only needs to broadcast a "*hello*" message once, is attained quickly and easily. In the second phase, each node evaluates its reasonable transmission power for the control packets. A node initially judges whether or not it is a potential interfering node, that is, if it will result in interfering or colliding with the ongoing communication neighbors once it starts to transmit. If a node finds that it is a potential interferer to others, it actively notifies those affected neighbors to increase the transmission power for their control packets. This will effectively avoid the hidden terminal problem. The LFTC protocol is not only simple but it also has a low message exchange overhead. Moreover, the protocol does not require the assumption of knowing the node location information which is needed in most of the proposed protocols. In addition, the LFTC allows multiple communications to be carried out concurrently in the neighborhood. Finally, the proposed protocol preserves the connectivity property.

The rest of this paper is organized as follows. Section 2 provides a review of related studies. Section 3 describes our protocol. Section 4 presents the simulation results, and finally in Section 5 we conclude our paper.

2. Related works

In MANETs, controlling the topology of the network by changing the transmission power can optimize performance metrics such as network lifetime and throughput. The topology control problem can be defined as follows: Let V denote the set of wireless nodes and $G = (V, E)$ denote the graph on V that contains all edges (connected links) if all nodes use the maximum transmission power P_{max}. E is the edges set, in which an edge (u, v) between node u and node v exists if nodes u and v can directly communicate using the power P_{max}. Running topology control protocol will yield a subgraph $G' = (V, E')$ of G. In G', nodes have shorter edges and fewer degrees than that in G.

Previous works on topology control generally can be classified into the centralized approach and the distributed approach. In this paper, we focus on the distributed approach. In the distributed approach [2,10,18,20,22], each node is capable of determining its own optimal transmission power by exchanging messages with its one-hop neighbors and by keeping the connectivity property in the resulting topology. The cone-base topology control algorithm [22] is a distributed algorithm in which each node makes local decisions about its level of transmission power. The basic idea in this paper is that a node increases its transmission power until it finds a neighbor node in every cone of degree α. When $\alpha < 5\pi/6$, the algorithm has been proven to preserve the network connectivity. It should be noted that this protocol is based on the directional information, instead of the exact location information. Furthermore, the algorithm is optimized in [23] to reduce the power consumption by removing some of the edges at each node.

Two other approaches for topology control are related to *computational geometry*: the *relative neighborhood graph* (RNG) and *Gabriel graph* (GG) [2,21,24]. Let $d(u, v)$ denote the Euclidean distance between two nodes u and v. Then the definition of RNG is given as follows: edge (or link) between nodes u and v exists if and only if there is no node w such that $d(u, w) < d(u, v)$ and $d(v, w) < d(u, v)$. This means that there is no node in the intersection area (the boundary is excluded) of two circles centered at nodes u and v if and only if there is an edge between them. Similar to the RNG, the GG has an edge between nodes u and v if and only if there is no any node w such that $d^2(u, w) + d^2(v, w) \leqslant d^2(u, v)$. That is, there is no node in the inside of the circle (the boundary is included) where nodes u and v are the two ends of the diameter of the circle. Both RNG and GG are connected graphs, and the algorithms based on them can be implemented by the local knowledge.

The topology control algorithms mentioned previously need either location information or directional information. The XTC topology control algorithm [24] works without either information. The algorithm consists of three steps. In the first step, each node broadcasts once at maximum power and then ranks all its neighbors according to its link quality to them (from high to low). Here the link quality reflects a more general notion. It could be the Euclidean distance, signal attenuation or packet arrival rate, which allows the algorithm to run more practicable in different situations. Each node transmits its ranking results to neighboring nodes during the second step. In the final step, each node examines all of its neighbors in the order of their ranking and decides which one need to be linked directly. The XTC algorithm features the basic properties of topology control such as symmetry and connectivity while running faster than many other algorithms.

In wireless ad hoc network without a topology control mechanism, all nodes transmit their packets with maximum power. The link relation between any pair of nodes is symmetric. Such a symmetric wireless network will encounter the hidden terminal problem, which refers to the collision of packets at a receiver due to the simultaneous transmission of those nodes that are within the transmission range of the receiver, but are not within the transmission range of the transmitter. For example, let's consider Fig. 1(a). If both nodes A and C transmit to node B at the same time, then their packets collide at node B. This is because nodes A and C are not aware of each other. In IEEE 802.11 standard [15] uses the RTS/CTS to solve the hidden terminal problem. When nodes attempt to transmit or receive data packets, they broadcast the control packets RTS/CRS to prevent all other potential interfering nodes from starting their own transmission. Any node that hears the RTS/CTS packets defers its transmission until the ongoing communication is over.

It is evident that an asymmetric communication may occur in the wireless network after topology control. Asymmetric communication is when one node, say u, has higher transmission power

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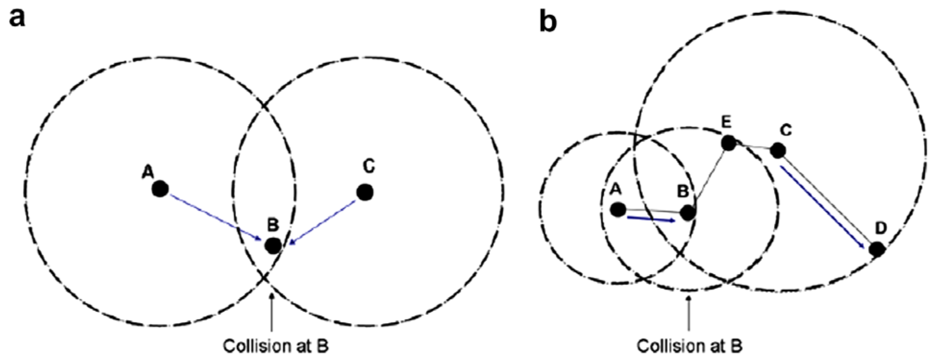

Fig. 1. Hidden terminal problem (a) symmetric case (without RTS/CTS mechanism) and (b) asymmetric case (with RTS/CTS mechanism).

to directly link to another node, say v, however, node v's transmission power is not high enough to directly link to u. Then the network with the asymmetric communication will encounter the hidden terminal problem, no matter the standard RTS/CTS mechanism is implemented or not. For example, an asymmetric communication topology is shown in Fig. 1(b). If node A intends to transmit data packets to B, it first sends a RTS packet at a determined power (the dotted circle centered at A). Node B replies a CTS at its determined power (the dotted circle centered at B) to ensure all its one-hop neighbors (e.g., A and E) can overhear. Then, node A starts to transmit the data packets to B. Nodes C and D, who are outside the reserved floors of nodes A and B, do not receive the RTS/CTS message exchanged nodes A and B. As C uses its determined power (the dotted circle centered at C) to send packets to the direct linking neighbor D, it causes a collision at node B. The hidden terminal problem is due to the asymmetric communication between nodes B and C. Some previous works [1,3,14] consider to minimize the signal interference by reducing the edge coverage which is the number of nodes affected by communications over a certain link. The resulting topology is connected or is a spanner for Euclidean length. However, the hidden terminal problem cannot be solved by these schemes because the resulting topology is also an asymmetric communication topology.

So, it is evident that the previous topology control protocols do not solve the hidden terminal problem for asymmetric communication topology. A number of MAC layer protocols have been proposed in [12,13,25] to address the problem. The solutions behind them are similar to the 802.11 scheme in which nodes still use the maximum power to send RTS/CTS control packets or collision avoidance information (CAI) messages [9] prior to transmitting data packets to notify all possible interfering neighbors. This approach solves the hidden terminal problem, but at the cost of reducing spatial channels reuse. The situation is illustrated in Fig. 2, where nodes A and B first use the common maximum power to send RTS and CTS packets, respectively. The reserved scope (union area covered by the two dotted circles) constructed by A and B will block the transmission between nodes C and D. Actually, both transmissions (A to B and C to D) can take place simultaneously without affecting to each other if nodes A and C use the adjusted power (the solid circles centered at A and C). Consequently, the network throughput is negatively impacted by the use of the maximum power control packets approach. Thus, there is a need for a cross-layer solution to consider not only the topology control problem at the network layer, but also the hidden terminal problem at the MAC layer.

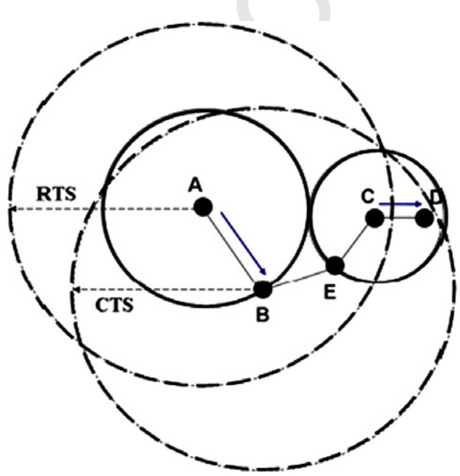

Fig. 2. The problem if RTS/CTS are sent at maximum power.

3. Location-free topology control (lftc) protocol

In this section, we will present a protocol that constructs a power-efficient network topology and at the same time avoids any potential collision due to the hidden terminal problem. The protocol environmental assumptions are described as follows. In the network, nodes are deployed in a two-dimensional area, where each node has limited battery power and similar capabilities (processing/communication). Each node has a unique *ID* and can communicate to other nodes through an omni-directional antenna. None of the nodes are aware of their exact coordinates and relative distance to their neighbors in the area. However, the signal from other nodes can be received accurately and the received signal power can be measured exactly, with the help of a radio interface in each node.

The initial topology is $G = (V, E)$ before topology control is applied. In other words, there is at least one path between any pair of nodes in G. The minimum power for node u to communicate directly with node v is denoted asP_{uv}. Here, we take the model presented in [25] for node u to determine power P_{uv} when u receives a message from v, and v's maximum transmission power $P_{\max}$ is known to u. Suppose that u receives the message with power P_{r}, and $P_{\min}$ denotes a node's smallest possible receiving power. Thus, $P_{uv} = P_{\max}.\ P_{\min}/P_{\mathrm{r}}$. This presented model is based on the following equation:

$$P_{\mathrm{r}} = P_{\mathrm{t}}\left(\frac{\lambda}{4\pi d}\right)^{n} g_{\mathrm{t}} g_{\mathrm{r}}$$

where, P_{t} and P_{r} denote the signal power at the transmitting and receiving antenna, respectively, λ denotes the carrier wavelength, d denotes the distance between the sender and the receiver, n denotes the path loss coefficient, and g_{t} and g_{r} denote the antenna gains at the sender and receiver, respectively. The energy cost for u sending one packet to v is denoted by $C(P_{uv})$ which can be obtained according to powerP_{uv}. The transmission medium is symmetric in our environmental assumptions, therefore, $P_{uv} = P_{vu}$ and $C(P_{uv}) = C(P_{vu})$. The common maximum transmission power of each node is denoted by $P_{\max}$. All nodes in the network are capable of changing their transmission power below the value of $P_{\max}$. In addition, we assume that there is an underlying MAC layer for solving the packet contention problem.

Our protocol consists of two phases: the first phase is the *link determination phase*, and the second one is *interference announcement phase*. In the *link determination phase*, each node, say u, independently selects a set of its next-hop nodes from all of its neighbors according to a power-efficient strategy. These chosen next-hop nodes would belong to the *direct communication set* of node u, denotes DCS(u). The data packet transmission power of a node u, $P_{\text{data}}(u)$, is the minimum power that node u can communicate with all members in DCS(u) and is determined at the end of *link determination phase*. In the *interference announcement phase*, some nodes will actively inform their neighbors in advance if they consider themselves as potential interferers who can affect the ongoing communications of their neighbors. Finally, an appropriate RTS/CTS control packet transmission power of a node u, $P_{\text{control}}(u)$, is decided after it performs the *interference announcement phase*.

3.1. Link determination phase

In the first phase, each node independently decides its *direct communication set* (DCS) whenever it receives a "*hello*" message from a neighbor. The intuition behind our approach is that a node u will directly communicate with its neighboring node v if there is no *common neighbor* node i (denoted by CN_i) of u and v such that messages sent from u to v via i ($u \to i \to v$) have a lower total energy than the energy required from u directly to v ($u \to v$). Each node will randomly broadcast a "*hello*" message once using maximum power $P_{\max}$ at any time during the first phase. When a node u hears a "*hello*" message from a neighbor v, it immediately computes for P_{uv} and $C(P_{uv})$ since the transmission power of a "*hello*" message is a constant, $P_{\max}$. Every "*hello*" message contains the sender *ID* and a specific data structure of the sender which is referred to as the *vicinity table*.

There are four fields in the *vicinity table*, as shown in Fig. 3. The first field, *neighbor_ID*, records the node's *ID* if a node, say u, overhears the "*hello*" message sent from a node v. The field of *direct_comm_cost* stores the $C(P_{uv})$ which is the required cost when u directly communicates with v. The *min_comm_cost* records the minimum communication energy cost from node u to node v. The value in this field gets dynamically updated whenever node u learns of a less-energy path for it to communicate with node v. Note that the communicating path between nodes can be direct (one-hop) or indirect (multi-hop). The last field *link_type* indicates whether or not the neighbor v belongs to the DCS (u). If marked as "*d*", node v is a next-hop node of node u (u can directly link to v); otherwise, v is an indirectly communicating neighbor of u and is marked as "*i*" in the *link_type* field.

The content in the *vicinity table* in each node is empty at the beginning. Upon overhearing a "*hello*" message from any node, a receiver inserts a new record and updates the fields of its table according to the collected information in the "*hello*" message. Assuming that a node u hears a "*hello*" message sent from node v, it will insert a record of v into its *vicinity table* and act as follows.

If there is no CN between nodes u and v, node u records node v as one of its next-hop neighbors ($v \in$ DCS(u)). The *link_type* of v in u's *vicinity table* (written as $link\_type_u(v)$ for the sake of simplicity) is marked as "*d*". Obviously, the value in *min_comm_cost* of v in u's *vicinity table* (written as $min\_comm\_cost_u(v)$) is the same as the value of *direct_comm_cost* of v (written as $direct\_comm\_cost_u(v) = C(P_{uv})$), which represents the temporary minimum energy consumption of the communication cost from u to v by direct transmission.

According to the role of CN taking part in the communication from u to v, we classify all CNs of u and v into three types. The first is the relay CN. It represents that if node u takes such CN as its relay to communicate with v, it achieves better power-efficiency than if it transmits directly to v. The second is called the benefited CN. If node u has a benefited CN, say node i, in its *vicinity table*, then that means that the original minimum communication energy cost from u to i ($min\_comm\_cost_u(i)$) can be further reduced through node v. The rest of the CNs which do not belong to the above two types are called the irrelevant CNs. An irrelevant CN will not affect the communication model of node u with its neighbors.

If there are some CNs between nodes u and v, node u will check the type of each CN i and update the *vicinity table* accordingly. If the summation of $min\_comm\_cost_u(i)$ in u's table and $min\_comm\_cost_v(i)$ in v's table is smaller than the $direct\_comm\_cost_u(v)$, then node i is a relay CN and node u has a power-efficient path to node v via node i. For example, in Fig. 4, i_1 is a relay CN of u and v, where the number on each link represents the transmission cost of the link. In this case, node u excludes v from its next-hop neighbors ($v \notin$ DCS(u)) by marking the $link\_type_u(v)$ as "*i*". Thus, the minimum communication cost from u to v ($min\_comm\_cost_u(v)$) is replaced by the summation of $min\_comm\_cost_u(i)$ and $min\_comm\_cost_v(i)$. If node i is not a relay CN, node u computes the summation of $min\_comm\_cost_u(v)$ and $min\_comm\_cost_v(i)$, which is equal to the minimum communication cost from u to i via v ($u \to \cdots \to v \to \cdots \to i$). If the summation is smaller than the $min\_comm\_cost_u(i)$, node i is a benefited CN, i.e., i_2 in Fig. 4, and node u has a power-efficient path to node i via node v. Therefore, the $min\_comm\_cost_u(i)$ is updated to the summation of $min\_comm\_cost_u(v)$ and $min\_comm\_cost_v(i)$ and node i does not belong to u's next-hop nodes ($j \notin$ DCS(u)). If the CNs does not belong to the above-mentioned types, they are called the irrelevant CNs, i.e., i_3 in Fig. 4. The irrelevant CNs will not have any effect on the communication cost of node u with its neighbors.

For example, assuming nodes D and E have received the "*hello*" messages from some of their neighbors and established their *vicinity tables* as shown in Fig. 5(a). Then, in Fig. 5(b), node E broadcasts a "*hello*" message at $P_{\max}$ including the information of its *vicinity table*. Once D receives the "*hello*" message from E, it computes the $C(P_{DE})$ and puts the value into $direct\_comm\_cost_D(E)$. Assume that the value of $C(P_{DE})$ is equal to 8. There exist two CNs, A and B between nodes D and E. Since the summation of $min\_comm\_cost_D(A)$ in D's table and $min\_comm\_cost_E(A)$ in E's table is smaller than the $direct\_comm\_cost_D(E)$, node A is a relay CN and node D has a power-efficient path to node E via node A. The *min_comm_cost* of

neighbor_ID	*direct_comm_cost*	*min_comm_cost*	*link_type*
v	*5*	*5*	*d*

Fig. 3. The *vicinity table* of a node u.

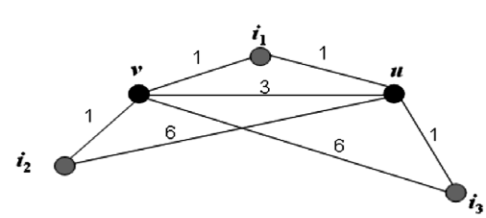

Fig. 4. An example of three types CNs of u and v.

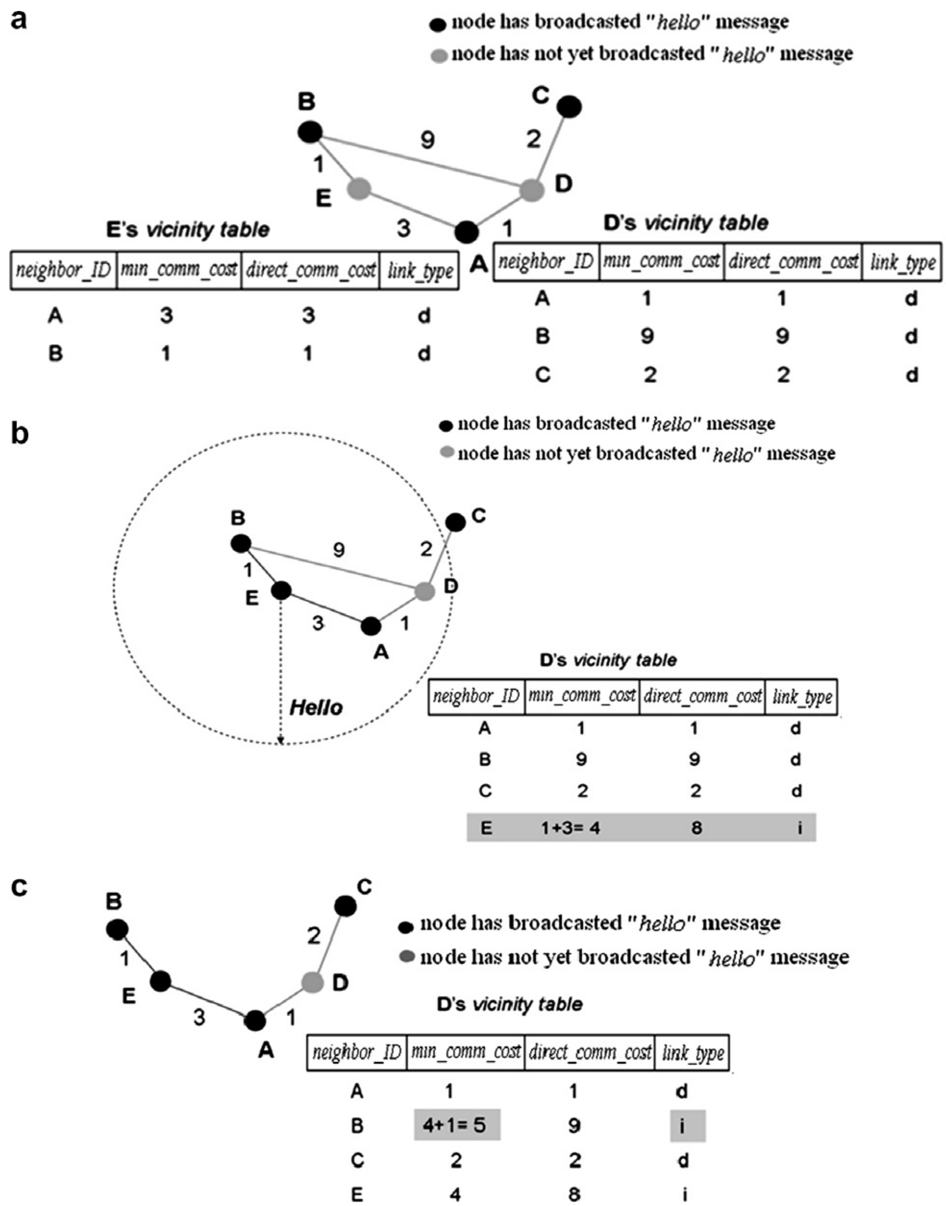

Fig. 5. (a) *Vicinity tables* of nodes *D* and *E*, (b) a record of new neighbor *E* is inserted into *D*'s *vicinity table* with *min_comm_cost* = 4, (c) the *min_comm_cost* from node *D* to node *B* is updated to 5.

node *D* to node *E* is equal to 4 as shown in Fig. 5(b). Fig. 5(c) illustrates that the communication power consumption from *D* to *B* can be further reduced after the $min\_comm\_cost_D(E)$ is determined. The $min\_comm\_cost_D(B)$ is updated to 5 and node *B* becomes the benefited CN. Accordingly, the field $link\_type_D(B)$ is changed to "*i*".

After a node *u* received the "*hello*" messages from all its neighbors, it can determine the DCS(u) and $P_{data}(u)$ from its *vicinity table*. Node *u* determines node *v* as its next-hop neighbor if the $link\_type_u(v)$ is marked as "*d*". The determined transmission power of node *u*, $P_{data}(u)$, is the value required to directly communicate to the farthest node in the DCS(u). Since some indirect node *v* of node *u* with $link\_type_u(v)$ = "*i*" may be located in node *u*'s determined transmission radius $P_{data}(u)$, *u* will update the value of $link\_type_u(v)$ in its *vicinity table* to "*d*". It must be noted that the edges (links) constructed in the resulting topology are bi-directional. If nodes *u* and *v* in the resulting topology have an edge between them, then the power-efficient way to communicate with each other is through the direct link. However, having no edge between two nodes does not always mean that the transmission power of one node cannot reach to the other node, because sometimes an asymmetric link exists between them, for example, node *B* and node *C* as shown in Fig. 1(b).

Theorem 1. *Let G = (V,E) be the undirected graph generated by having each node use P_{max} to communicate. Let G′ = (V, E′) be the undirected graph constructed based on the link determination phase in our protocol. If G is connected, G′ is connected also.*

Proof. Assume any two nodes *u* and *v* in *G* has a route $R_{u,v}$ from *u* to *v* with *n* hops. We prove that *u* and *v* also have a route $R'_{u,v}$ in *G′* by induction. For the base case, any two neighboring nodes *u* andv in *G*, i.e., *n* = 1, node *v* is a direct or indirect neighboring node of *u* in *G′*. If *v* is a direct neighboring node of *u*, *u* can communicate with *v* directly. Otherwise,*u* has a power-efficient path to *v* via a relay common node *x*. That is, *u* has a route to *v* and $R'_{u,v} = R'_{u,x} \cup R'_{x,v}$. For the inductive step, if any two nodes *u* and *v* has a *k*-hop ($1 \leqslant k < n$) route in *G*, there exists a route R'_{uv} in *G′*. Assume the distance between any two nodes *u* andv in *G* is *n*-hop. There exists a

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route $p = (u \to \omega_1 \to \cdots \to \omega_{n-1} \to v)$ in G from u to v. By the inductive hypothesis, there exist a route $R'_{u,x}$ in G' and a route $R'_{x,v}$ in G', where $x = \omega_{n-1}$. Therefore, we have a route $R'_{u,v} = R'_{u,x} \cup R'_{x,v}$. □

A summary algorithm of link determination phase is presented as follows:

Link determination phase

Each node broadcasts a "*hello*" message with its *vicinity table*.
If a node u receives the "*hello*" message from its neighbor v;
  If u has a power-efficient path to node v via node i /* i is a relay CN */
    Insert (v, *direct_comm_cost*$_u(v)$, *min_comm_cost*$_u(i)$ + *min_comm_cost*$_v(i)$, ***i***) into u's *vicinity table*;
  Else
    Insert (v, $C(P_{uv})$, $C(P_{uv})$, ***d***) into u's *vicinity table*;
  end If
If u has a power-efficient path to node i via node v /* i is a benefited CN */
  Update the record of i in its *vicinity table* with (i, *direct_comm_cost*$_u(i)$, *min_comm_cost*$_u(v)$ + *min_comm_cost*$_v(i)$, ***i***);
end If
If node u received the "*hello*" messages from all its neighbors in the link determination phase it will adjust the transmission power $P_{data}(u)$ such that u can directly communicate with all of its neighbors in its *direct communication set* DCS(u).

3.2. Interference announcement phase

After all the nodes have broadcast the "*hello*" messages once and the optimal data transmission power at each node has been determined, each node starts to execute the *interference announcement phase*. This phase avoids data collision resulting from the hidden terminal problem when nodes use the power determined by the previous phase to transmit the data packets. The prevention mechanism proposed here is similar to the 802.11 protocol which takes advantage of the RTS/CTS control packets. However, the difference is that in our method each node can determine a more appropriate power $P_{control}$, to transmit the control packet. As we know, using excessive control packet power has the adverse effect of preventing data transmissions in the neighborhood, resulting in a low system throughput.

In the beginning, the control power of each node u, denoted by $P_{control}(u)$, is set to the same value as its determined data transmission power $P_{data}(u)$. In the meantime, u has to judge if it will cause interference with an ongoing transmission in its indirect neighbors in the future. It is not necessary for node u to consider that it will interfere with the data transmission of its direct link neighbors, because the RTS/CTS packets sent by these neighbors before sending their data can be overheard by u. However, it probably causes a hidden terminal problem since node u does not receive the control packet in advance from the indirect nodes, and starts its transmission. This case is shown in Fig. 1(b), where the interferer, node C, causes a collision with its indirect neighbor B. To determine whether it is a potential interferer to the indirect linking neighbors or not, node u needs only to observe its resulting *vicinity table* formed in the first phase. If it finds that any node $v \notin \mathrm{DCS}(u)$ and v is located in the transmission range of $P_{control}(u)$ ($P_{uv} \leqslant P_{control}(u)$), node u realizes that it is a potential interferer to node v.

If a node u is aware that it is a potential interferer to some indirect linking neighbor v, it will notify the interfered node v in advance. The notification performed by u is to broadcast an "*Inform*" message including the information of its *ID* and $P_{data}(u)$. It is not necessary for node u to use P_{max} to inform all of its neighbors. Instead, the transmission power of the "*Inform*" message should be just high enough to reach to the farthest interfered node. When a node v overhears an "*Inform*" message from a node u, node v will check whether the sender u is its direct neighbor or an indirect one. If the "*Inform*" message is sent from the direct neighbor $u \in \mathrm{DCS}(v)$, v just ignores the message. Otherwise, if $u \notin \mathrm{DCS}(v)$, then v compares its current $P_{control}(v)$ to P_{vu}. If $P_{control}(v) < P_{vu}$, then $P_{control}(v)$ is set to P_{vu} in order to ensure that the RTS/CTS control packets sent out by v can be correctly heard by node u.

An example for the *interference announcement phase* is illustrated in Fig. 6. Fig. 6(a) shows that a node A realizes its future transmission (the range of its data transmission power is indicated by a solid circle) may affect the ongoing transmissions of nodes C and D. Therefore, it broadcasts an "*Inform*" message to notify them in advance (the range of the "*Inform*" message is indicated by dashed circle). In Fig. 6(b), assuming that node D received "*Inform*" messages from nodes A and node C, it recognizes that A and C are its interferers. Therefore, D will magnify the RTS/CTS control packet transmission power, $P_{control}(D)$ (the range is represented by a dashed circle) to prevent all potential interferers such as A and C from starting their transmissions.

A summary algorithm of interference announcement phase is presented as follows:

Interference announcement phase

Set $P_{control}(u) = P_{data}(u)$;
If u is a potential interferer to the indirect linking neighbors v
  u will broadcast an "*Inform*" message to inform the interfered nodes;
End if
If node u overhears an "*Inform*" message from node v
  If v is not a direct neighbor of u
    If $P_{control}(u) < P_{uv}$
      Set $P_{control}(u) = P_{vu}$ to ensure u's RTS/CTS control packets can be correctly heard by v;
      If u is a potential interferer to an indirect linking neighbor i
        u will broadcast an "*Inform*" message to inform the interfered node i;
      End if
    End if
  End if
End if

After performing the *link determination* and *interference phases* each node can determine its suitable transmission powers of data packet and RTS/CTS control packet to enhance the spatial channel reuse. The transmission power of control packet, $P_{control}$, can be larger than the data packet transmission power, P_{data}, in our protocol. Each node u can transmit the RTS/CTS control packet to notify its potential interferers. Thus, our protocol can avoid the potential collision of the hidden terminal problem. However, larger control power has less spatial channel reuse. An example is shown in Fig. 6(b). Assume nodes G and D are indirect neighbors of each other. When node D communicates with its neighbor B, node G will receive the RTS/CTS control packet from node D. The RTS/CTS packets will defer node G's transmission until the communication between nodes B and D is over. Therefore, it results in a low system throughput.

Here, we propose a scheme to improve the system throughput. When a node u receives the RTS/CTS control packet from a node v, u needs to check if both nodes are indirect neighbors with each other. If $u \in \mathrm{DCS}(v)$ or $v \in \mathrm{DCS}(u)$, node u will be restrained from communicating with its neighbors. Otherwise, when node u wants to communicate with one of its neighbors, it needs to check whether or not the RTS/CTS control packet $P_{control}(u)$ will interfere with the ongoing transmission of node v. If $P_{control}(u) \geqslant P_{uv}$, node u will use the $P_{data}(u)$ to transmit the RTS/CTS control packet. Since the transmission range of the $P_{data}(u)$ is smaller than $P_{control}(u)$, the ongoing transmission of node u may affect its neighbors. If $P_{control}(u) < P_{uv}$, node $u$will transmit the RTS/CTS control packet with $P_{control}(u)$. Therefore, in Fig. 6(b) node G can use $P_{data}(G)$ to transmit the RTS/CTS control packet when it wants to communicate with node H. The RTS/CTS control packet will not affect the communica-

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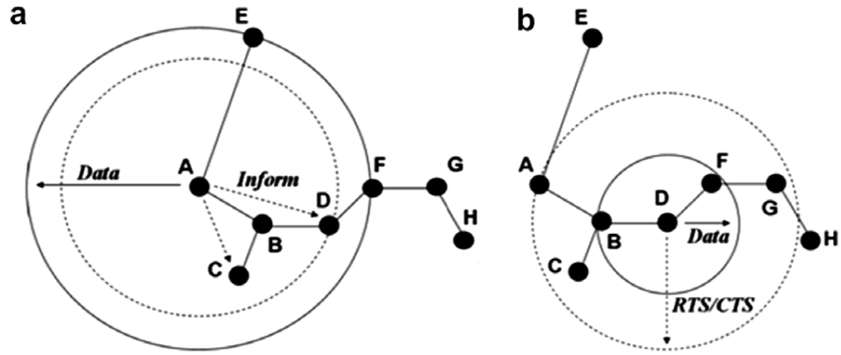

Fig. 6. (a) *A* broadcasts an "*Inform*" message to the interfered neighbors *C* and *D* and (b) *D* broadcasts a control packet to inform nodes *A* and *C* prior to data transmission.

tion between nodes *D* and *B*. The transmissions of nodes *G* to *H* and *B* to *D* can be executed simultaneously.

4. Simulation results

In this section, we use GloMoSim [26] to evaluate the performance of the proposed LFTC protocol. Nodes are randomly distributed in a square region of 1000 m × 1000 m. A two-ray path loss model for terrestrial communication is used in GloMoSim, which has been shown to be close to reality [27]. A transmission from node u to node v takes power $p(u, v) = td(u, v)^n$ for some constant t at node u, where $n \geqslant 2$ is the path-loss exponent of outdoor radio propagation models, and $d(u, v)$ is the distance between u and v. At the same time, the SNR threshold based signal reception model, the IEEE 802.11 PHY DSSS (direct sequence spread spectrum) and MAC DCF (distributed coordination function) are also used in GloMoSim. The parameters for the physical layer models are set to be: SNRT (SNR threshold) = 5 dB, CST (carrier sense threshold) = −54 dBm, RXT (receiving threshold) = −45 dBm, 914 MHz radio frequency and 24.5 dBW transmit power. The raw transmission bandwidth is assumed to be 2 Mbps and the maximum communication range of each node is up to 190 m.

For comparison purposes, we take the CSMA/CA MAC protocol with the RTS/CTS mechanism. The AODV routing protocol [17] is used and slightly modified to find the minimum energy consumption paths instead of the shortest paths between two end-nodes. The XTC topology control algorithm [24] is chosen as our comparison candidate since it has the same advantage as our protocol which works without the aid of either directional or location information. Since the XTC algorithm only decides on one power, the transmission power for the data and the RTS/CTS control packets at each node is assumed to be the same in our simulation.

Before proceeding to compare and analyze the results of the XTC algorithm and our proposed LFTC protocol, we want to fully understand the characteristics of the resulting topology of both protocols. Fig. 7(a) shows the original network topology of 100 nodes, wherein the nodes use the maximum power to communicate with others. Figs. 6(c) and 7(b) represent the resulting topologies generated by the XTC algorithm and our LFTC protocol, respectively. Based on the average degree of the nodes in these topologies, we will discuss their pros and cons. Nodes with large degree means they have large number of neighbors. So, a large degree implies an increase of interference and collision, as well as unnecessary energy waste, such as the topology shown in Fig. 7(a). Nodes with small degree means they have small number of neighbors by reduce their transmission power. So, a small degree tends to increase the overall network power consumption because longer paths have to be taken from end to end. Note that the topology of our protocol has a higher average degree than the one in the XTC. This is because each node in our protocol considers the best power-efficient links to all neighboring nodes, while the nodes in the XTC only allow a minimum number of links to connect to the closer neighbors.

Several metrics for performance evaluation are listed as follows:

Hop counts in the least-cost path: The hop count not only affects the total energy consumption between two nodes, but it also reflects another important metric: the delay time of one successful transmission from end to end.

Energy cost of the least-cost path: For any pair of nodes in the resulting topology we use the modified AODV protocol to find out the route which has the minimum total power consumption among all paths between them. For the sake of simplicity, we called this route the least-cost path. The energy cost in the least-cost path is the summation of transmission power of all transmitting nodes which participate in the data dissemination along the path.

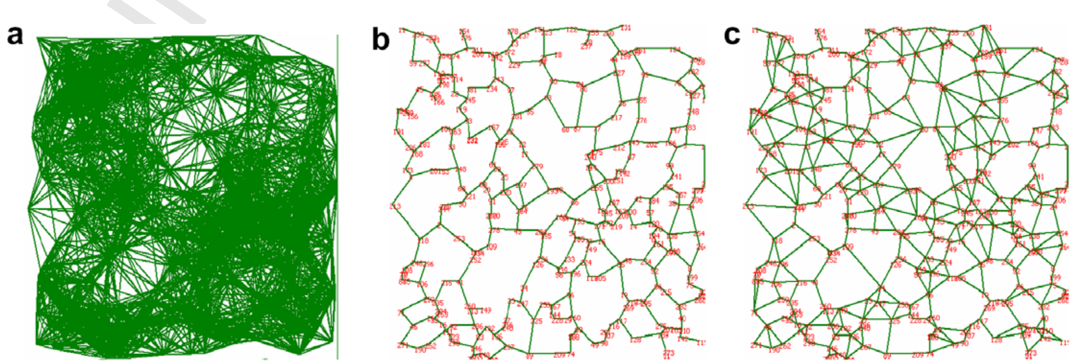

Fig. 7. Network topologies of 100 nodes constructed by (a) without topology control, (b) XTC protocol and (c) LFTC protocol.

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Throughput: The throughput is evaluated by the total amount of successful received data (in bytes per second) by the network. The metric also reflects the channel utilization when nodes disseminate data packets.

Collision rate: The collision rate is defined as the ratio of collisions to total transmissions. It has a significant impact on network performance parameters such as throughput and delay. A higher collision rate incurs more data retransmissions and, in turn, leads to inefficient use of energy and channel bandwidth.

The following two figures show the impact of network density on the hop counts and that of the energy cost on the least-cost path. The number of ad hoc nodes varies from 50 to 300 in the 1000 m × 1000 m region. Fig. 8 compares the average hop count in our protocol with the one in the XTC approach. While the hop count in both protocols increase as the network density becomes denser, the hop count in our protocol is obviously less than that in XTC. It is worth noting that the difference of the average hop count of the two algorithms grows from about 1 hop in 50-nodes network environment to around 4 hops in a 300-nodes environment. This shows that the denser the network size, the better the performance of the resulting topology generated by our protocol if one node sends packets to another node. This is because fewer hop counts means less time delay in the multi-hop wireless transmission.

Fig. 9 shows the average energy cost of the least-cost paths between all node pairs in the network. It is evident that our protocol has similar simulation results to that performed by the XTC algorithm. Since the nodes in our protocol have slightly higher average degrees than those of the XTC, it implies that the decided data transmission power of nodes in our protocol could be slightly more than that in the XTC. However, our protocol has the benefit of having fewer hop counts in the least-cost path. Overall, the LFTC performs just as well as the XTC algorithm with regards to the average energy cost in the least-cost path.

The prevention mechanism of collision avoidance (*interference announcement phase*) is integrated into the topology control algorithm (*link determination phase*) and becomes the LFTC protocol. Next, we compare the ratio of collision of the LFTC with the XTC in the environment where 100 nodes are deployed in a 1000 m × 1000 m region. Note that in the XTC, it is assumed that nodes use their determined power to transmit both the data and the control packets. In Fig. 10, the *x*-axis represents the number of end-to-end paths (or number of source nodes) in which data packets are disseminating simultaneously. The *y*-axis is the ratio of total collisions of data packets. In the simulation, source nodes are randomly chosen and send a data packet once. The retransmission mechanism is not implemented when collisions occur. Our protocol has close to a 95% successful data receiving ratio no matter how many concurrent data transmission paths exist in the network. On the contrary, the collision ratio in the XTC increases smoothly in the beginning as the number of paths increase, but then increases sharply as the number of paths continue to increase. When there are 50 concurrent transmission paths in the network, the ratio of collisions in the XTC reaches 75%, which means only 1/4th of the total transmitted data packets can be received successfully. This proves that our protocol effectively avoids the problem of collision and enhances the overall performance.

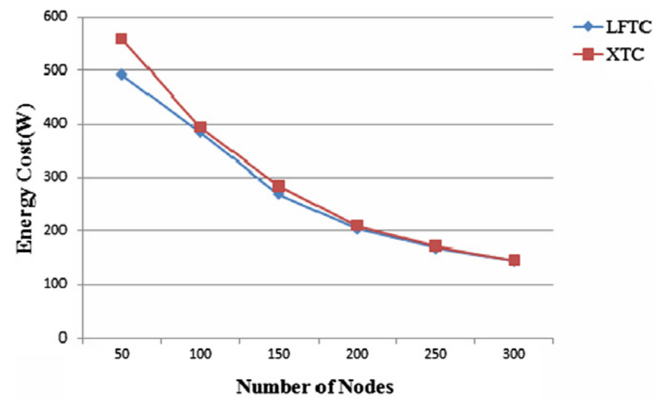

Fig. 9. Average energy cost of the least-cost paths between all node pairs in various network densities.

The throughput of the LFTC and the XTC with the 802.11 standard in the 100 nodes network is demonstrated in Fig. 11. In it we vary the number of source nodes which generate data packets. Each data packet is assumed to be 256 bytes. It is evident that the throughput of our LFTC is on average about 1.4 times higher than that of the XTC. The increase of channel utilization is due to the fact that multiple transmissions can proceed simultaneously in the LFTC protocol. However, with the XTC protocol, only one transmission can occur at a time within the communication range of the transmitter and the receiver, since all their neighbors are within the carrier-sense range.

Assume the percentage of transmission power is 100% if a node uses the maximum power $P_{\max}$ to communicate. Fig. 12 illustrates the percentage of the average and highest transmission power of data/control packets for all nodes over different network densities in our LFTC protocol. It is evident that for our protocol the percentage of average transmission power for either data or control packets is less than 80%. When the network is denser, the performance of energy conservation is more prominent. It should be noted that the average RTS/CTS transmission power is only very slightly higher than the average data transmission power. This indicates that

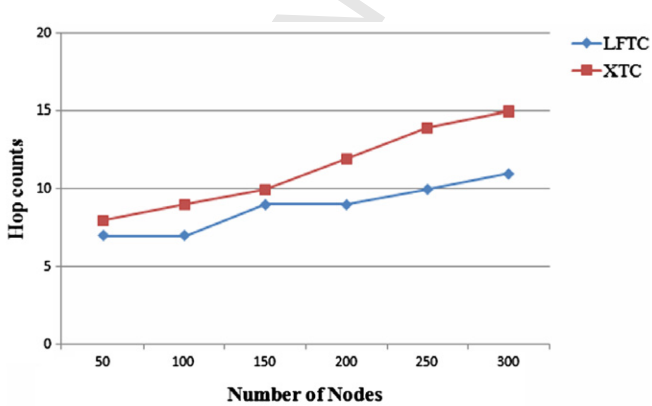

Fig. 8. Average hop counts in various network densities.

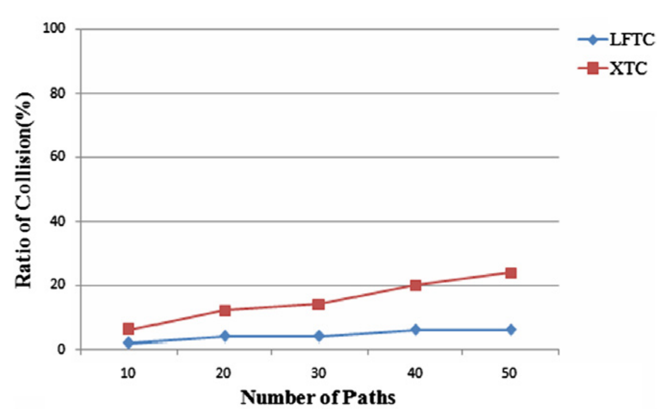

Fig. 10. Ratio of collisions in 100 nodes network.

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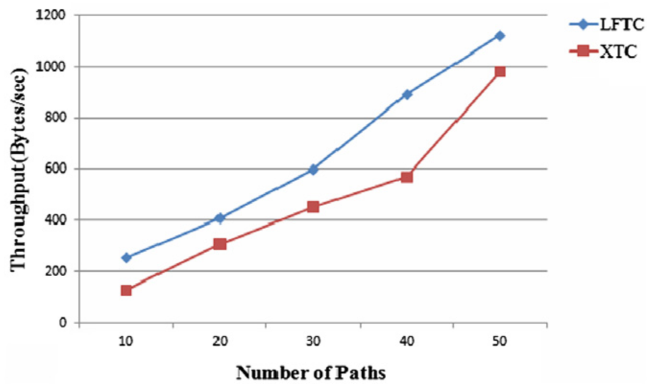

Fig. 11. Throughput performance of LFTC and XTC.

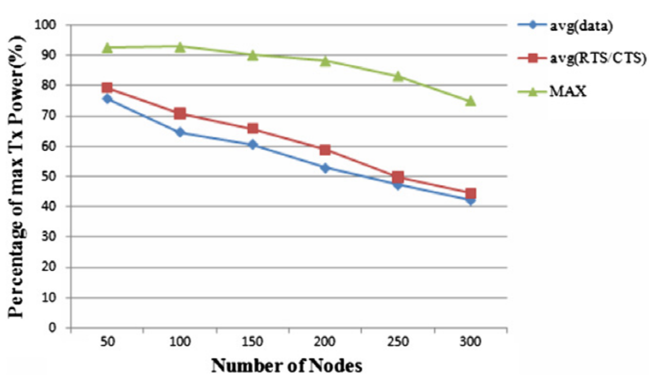

Fig. 12. Percentage of transmission power of data and control packets in the LFTC protocol.

only slightly higher power by the control packets in some nodes is sufficient to block the potential interferers in the neighborhood from beginning their transmissions. Instead of using the maximum power to transmit RTS/CTS control packets, our protocol can significantly reserve considerable energy at most nodes.

Next we analyze the control packet overhead for constructing the different topologies using our approach and the XTC, respectively. In general, at least two broadcasting messages at each node are required to perform the XTC algorithm. In comparison, our protocol only uses one control packet, the "*hello*" message, at each node in the *link determination phase* to achieve the same consequence of topology control. Our protocol provides an additional mechanism where each node can decide locally its optimal control packet transmission power to prevent interference, with only a slight overhead. The extra overhead is the "*Inform*" message broadcast in the second phase. Fig. 13 shows that only 45–70% of nodes in the network participate in the broadcasting action of the "*Inform*" message when the network density is from 50 to 300 nodes. Therefore, the control packet overhead at each node in our protocol are apparently less than 2.

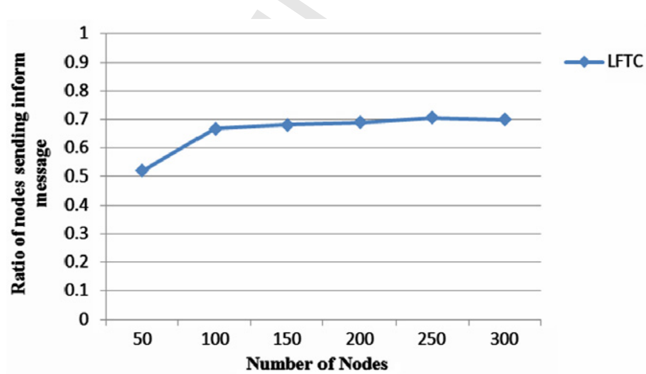

Fig. 13. Ratio of nodes which broadcast "*Inform*" messages.

5. Conclusions

In this paper, we proposed a two-phase LFTC protocol for topology control, providing a mechanism to prevent the hidden terminal problem after the construction of the topology. Our protocol is a location-free protocol. Each node is able to determine two optimal powers: one for data transmission and another one for control packets transmission. To ensure that every transmitted data packet will be received intact without any interference, we used the RTS/CTS mechanism in IEEE 802.11, but with a slight modification. That is, the transmission power of RTS/CTS can be controlled and different from transmission power of data packet. The node does not necessarily use the maximum power to send the RTS/CTS for deferring all of its neighbors' transmissions. Consequently, the network throughput is not negatively impacted by the use of the maximum power control packets approach. Simulation results prove that our LFTC protocol has a smaller hop count, low control packet overhead and a low ratio of collision compared to another location-free protocol, XTC. In addition, our protocol also surpasses the XTC in throughput by about 1.4 times. The percentage of average transmission power of all nodes in our protocol ranges from 77% to 40% of the maximum power when the number of nodes in the network ranges between 50 and 300. Thus, our LFTC protocol has good energy conservation. Our protocol also has higher topology connectivity than that of XTC under nodes mobility.

6. Uncited reference

[8]. Q1

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