Truthful Topology Control in Wireless Ad Hoc Networks with Selfish Nodes

Jianfeng CAI*, Yunhuai LIU†, Jie LIAN‡, Mo LI†, Udo POOCH* and Lionel NI†

*Texas A&M University, College Station, U.S.A
†Hong Kong University of Science and Technology, Hong Kong
‡University of Waterloo, Canada

Abstract

In Wireless Mobile Ad Hoc Networks (MANETs), energy is a crucial resource. Topology control technology allows network nodes to reduce their transmission power while preserving the network connectivity. A MANET is a non-cooperative system so that only when a node earns its payment, which can cover its cost, the cooperation can be stimulated.

We design a Truthful Topology Control mechanism (TRUECON) for MANETs to induce the selfish, but rational, network nodes to collaborate. Truth-telling is a dominant strategy in TRUECON. A node needs to reveal its true value in order to obtain the maximum expected utility. We prove the overpayment of TRUECON has a bound depending on different radio propagation models.

1. Introduction

Topology control technology let network nodes in a MANET adjust their transmission power in order to reduce their neighbor sets. When every node transmits using its maximum power, the network graph is denoted as $G(V, E)$. The graph derived by topology control is $G'(V, E')$, which is a subgraph of $G(V, E)$, $G'(V, E') \subseteq G(V, E)$. G' must preserve the connectivity of G. In other words, if a pair of nodes u and v is connected in G, they should be connected in G' too.

In G', the node degree is lower than in G. This is desirable in MANETs because the short the edges, the less power a node uses to transmit and the smaller area the radio interference can affect. Furthermore, the wireless network capacity is closely related to the node degree. The network throughput drops quickly as the network size increases [8]. Comparing the power-efficient routing, topology control is a pro-active method to reduce power consumption and radio interference.

Forming a power-efficient network topology without degrading the network connectivity needs the collaborations among all the nodes. The existing topology control algorithms assume that if a network node receives a service request it always follows the pre-defined protocol without any bias. However, this assumption cannot be valid in MANETs anymore.

As a MANET is formed on the fly, there is not a central authority to regulate the behaviors of each node. A node is free to join and leave without notification and permission. Moreover, most of the network nodes are battery-powered and have only a limited energy reserve. Forwarding data packets incurs power consumption at the intermediate nodes without obvious benefit.

If we study the previous scenario from a game-theoretic approach, it is clear that the incentive of a network cannot be ignored. The preference of node v can be represented as a utility function u_v. When v relays n data packets for node u, v consumes its energy to receive the packets and transmit them to its successor on a path. If the energy consumption on one packet is $-\mathcal{E}$, then $u_v = -n \times \mathcal{E}$. u_v is always non-positive because v only drains its own energy during the process. Therefore the best outcome of u_v is 0 while v does not transfer even a single packet for others.

When the incentive of a node is ignored, we cannot expect the network functions well. For example, Wattenhofer et al. [20] prove that having at least on neighbor in a cone of $\frac{5\pi}{6}$ is the tight bound of preserving the network connectivity while reducing the connection degree. So the minimum number of a node's neighbor is 3. If a node u establish such a neighbor set with node v, w, x, each neighbor is critical for u. Without loss of generality, v wants to save its energy and stops forwarding packets for u. u may either suffer from an isolation from the network or have to increase its power to discover another neighbor, which can replace v. In either way, the topology control scheme is defeated by the selfish intention.

Thus, in a MANET the selfish behaviors are inevitable because of the lack of system regulation power and the resource scarcity. Rather than ignore the selfish intention, we design a truthful topology control mechanism, TRUECON, to stimulate cooperation in order to discover a resource-efficient network topology.

The reminder of this paper is organized as follows. Section 2 review the related work in MANET topology control. System model is given in section 3. Section 4 discusses the truthful topology control in MANETs and present the TRUECON algorithm. Section 5 give the simulation results and analysis. Finally, section 6 draws conclusions and points out future work.

2. Related Work

Rodoplu and Meng [19] present a distributed algorithm to reduce the transmission power of each node, while maintaining the minimum energy paths. Li and Halpern improve the algorithm in [12] by proposing SMECN (small minimum-energy communication network) [11] for the wireless sensor networks, such as [23]. They claim SMECN preserve the network connectivity and terminates faster. Both of the algorithms need the aid of some positioning service, such as GPS or localization techniques[15]. In [17], Ramanathan and Rosales-Hain present a spanning tree algorithm to achieve connected static networks.

In [20], Wattenhofer et al. propose Cone-based Topology Control algorithm (CBTC), in which a node only needs to know the direction of its neighbors and the transmission power to reach them. They prove that if in each cone not greater than $\frac{5\pi}{6}$, there is at least one neighbor for a node, the derived network graph preserve the connectivity of the original graph. We base our truthful topology control algorithm on CBTC. However, we prove that our algorithm achieves, in MANETs, a crucial property, which CBTC cannot assure, *truthfulness*.

In [8, 10], the authors theoretically and practically show that while a network size grows, the throughput keeps dropping. Their works validate the importance of topology control technology. If the node degree does not increase as the growth of the network size, we may expect the network throughput not to fall dramatically. In particular, the authors of [3, 14, 13] proposed two topology optimization algorithms in the context of P2P networks.

Cerpa and Estrin design ASCENT [2], an self-configuring topology control protocol for sensor networks. ARCENT adaptively elects a few active nodes for the whole network. The selection of active nodes is based on various parameters, including neighbor threshold and packet loss rate, etc. PAMAS [21] takes advantage of overhearing. If a node overhears the communication of other nodes and knows it cannot transmit any packet for a while, it turns off its radio component to save energy.

Game theory [22] is a method to study the interest conflicts and the behaviors of players based on the strategy interaction. An agent i have a series of strategies to play in order to maximize its utility $u_i(o)$ for every outcome of a game. Mechanism design [16], also called *Inverse Game Theory*, is to design a set of rules of strategies and game outcomes in order to implement an optimal solution in an non-cooperative environment.

There is a family of direct-revelation and strategy-proof mechanisms, VCG mechanisms [7]. They are for problems, in which agents have quasi-linear preferences. According to [6], VCG mechanisms are the only direct-revelation mechanisms, which are allocation-efficient and strategy-proof.

In [4], Eidenbenz et al. propose a truthful routing protocol COMMIT to cope with selfish nodes in MANETs. COMMIT prevent a source node from utilizing strategies and achieve a budget control along power-efficient paths. However it relies on a topology control algorithm to restrict the node degree beforehand. If we cannot trust selfish nodes in routing, can we trust them at other stage? The answer must be **No**. As a result, truthful mechanisms are needed at any time when selfish nodes interact with each other.

3. System Model

A wireless ad hoc network can be interpreted as a graph, $G(V, E)$. Network nodes are represented by a set of vertexes V. The communication range of a node is modeled as a Unit Disk Graph (UDG). If node u is within the communication range of node v, there is an edge (u, v) between them. We assume all nodes are identical and all links are bi-directional. A path from S to D is a series of node identifiers, $\sigma_{S,D} = \{S = \sigma_0, \sigma_1, \ldots, D = \sigma_L\}$. L is the number of hops. $d_{u,v}$ is the Euclidean distance between node u and v.

In MANETs, transferring a packet may cost less power if it is relayed by multiple intermediate nodes rather than is transferred over a single long hop. According to radio propagation models in [18], the received power P_r is inversely proportional to the transmission power P_t and d^α, $\alpha \in [2, 6]$. If P_r is greater than or equal to a threshold P_{rthd}, the packet is received successfully. Otherwise, the receiver cannot interpret the packet. With P_{rthd}, the minimum transmission power, P_{tmin}, used by a sender is $P_{tmin} = \frac{P_{rthd} \times P_t}{P_r}$. Hence, a node can compute the minimum emission power to reach another node as long as the receiver knows the received signal strength and transmission power at the sender side.

Using K to represent all the constants, we have:

$$P_{tmin} = K \times d^\alpha, \ \alpha \in [2, 6] \tag{1}$$

In the free space radio propagation model, α equals 2. And α equals 4 for the two-ray ground reflection model. Receiving packets also incurs power consumption. Comparing to the transmission power, the receiving power is small [5]. To simplify the analysis, we ignore the receiving power intended in this paper as well as the power spent on signaling messages.

In a routing protocol, we demand each node to advertise its transmission power in its packets. The receivers will measure the received signal strength and report the calculated minimum emission power to the sender. Hence the sender can adjust its sending power level accordingly.

Definition A Minimum Transmission Power (MTP) path is a path from its source S to its destination D, along which the total transmission power is not greater than any other path connecting the same pair of nodes.

We do not demand any positioning services in a network. A node does not have to know any geographical information. However, every node needs to be able to detect the direction, from which a packet is received.

Since in the system, a source node needs to pay the forwarding nodes for their services and the power is the overwhelming cost in MANETs, we demand the price of network services should represent the amount of power spent by service providers. One unit payment should be able to buy one unit power. The payment can be authenticated by any seller and receiver. To simplify the analysis in this research, we use the power value as a measurement of payments directly. We assume in a MANET there exists some payment transfer facility, like Sprite [24]. By such a facility, the payment can be delivered to the designated nodes securely.

Li et al. [12] prove $\frac{5\pi}{6}$ is a tight bound for such topology control algorithms that keep the nearest neighbors without the knowledge of their geographical locations. We call a $\frac{5\pi}{6}$ cone a *critical cone* and denote the condition of finding at least one neighbor in each critical cone as *direction constraint*.

4. Truthful Topology Control - Topology Control in Non-Cooperative Environment

We present Truthful topology Control algorithm (TRUECON) based on VCG mechanisms. To the best of our knowledge, this is the first research to consider topology control in a non-cooperative environment.

4.1 TRUECON - a Truthful Topology Control Algorithm

Like CBTC[20], TRUECON needs to know the direction, from which a message is received. The direction information can be obtained by using directional antennas. A node u periodically broadcast *Hello* messages, in which it put its current sending power value P_s. Upon receiving a *Hello* message, a node v_i measures the received signal strength P_{r_i} and calculates the minimum power P_{u,v_i} needed by u to reach it. Node v_i then replies with an *Ack* packet, in which it declares P_{u,v_i} as $\hat{P}_{u,v_i}$. $\hat{P}_{u,v_i}$ may not be equal to P_{u,v_i}. Node u reduces its transmission power to keep in touch with a smallest neighbor set, which is enough to preserve network connectivity for u. Each node in the reduced neighbor set is called a *forwarding neighbor*. Also u decides the price of its forwarding neighbors based on the announced values. Later on, as u receives packets from one forwarding neighbor, it needs to endorse the neighbor's payment.

We define that for node u, each neighbor v_i has a direction to some fixed angle. The direction can be expressed as $dir_u(v_i)$. There is an angle checker function denoted as $Cone_\alpha(N_u)$. It checks whether in the neighbor set N_u there is a gap with degree greater than α between a pair of direction-wise adjacent nodes. If there is such a gap, $Cone_\alpha(N_u)$ returns a TRUE. When a FALSE is returned, there is at least one neighbor in each cone of α around node u.

TRUECON algorithm is shown in figure 1. It is the first distributed topology control algorithm to induce selfish nodes in a MANET to reveal their true costs.

Figure 2 gives an example of running TRUECON algorithm on a network node u. Initially, u broadcasts a *Hello* message using its maximum power P_{max}, and announces P_{max} in the *Hello* message. A neighbor v_i measures the received signal strength P_r and calculates the minimum power P_{u,v_i}, by which u can reach v_i. v_i acknowledges u by sending back an *Ack* message, in which it declares a value $\hat{P}_{u,v_i}$ based on P_{u,v_i}. $\hat{P}_{u,v_i}$ may not equal P_{u,v_i}.

Upon receiving each *Ack*, u adds the neighbor into set N_u. Without loss of generality, u have $N_u = \{v_1, v_2, v_3, v_4, v_5, v_6\}$ before it runs line 6 of TRUECON.

At line 6, u sorts the nodes in N_u by their claimed power value $\hat{P}_{min}$. This value reflects the distance from u to each of its neighbors. If each neighbor declares its value correctly, then after the sort we have $N_u = \{v_2, v_3, v_1, v_4, v_5, v_6\}$.

At line 7-9, u checks whether the direction constraint is satisfied. In the example, when v_1 is added into M_u, $\angle v_1uv_2 = \angle v_1uv_3 = \frac{5\pi}{6}$ and $\angle v_2uv_3 = \frac{\pi}{3}$. Thus, after line 9, M_u contains the closest nodes $\{v_2, v_3, v_1\}$, which make function $Cone_\alpha(M_u)$ return a FALSE. At this point, TRUECON finds the same neighbor set as CBTC finds so that TRUECON inherits the connectivity characteristics of CBTC.

Though we have discovered the nearest neighbor set, which assure the connectivity of a network graph, we need

```
TRUECON(α)
 1. N_u = M_u = φ
 2. broadcast Hello with full power
 3. receive Acks and record the neighbors into N_u
 4. if (N_u == φ)
 5.  return
 6. sort N_u by P̂_{u,v_i} in increasing order, ∀v_i ∈ N_u
 7. while(Cone_α(M_u) AND N_u ≠ φ)
 8.   v_i = DEQUEUE(N_u)
 9.   M_u = M_u ∪ {v_i}
10. if (N_u == φ)
11.  return
12. mark nodes in M_u and set the payment as ∞
13. while(( ∃v_k ∈ M_u, w_{v_k} is ∞) AND (N_u ≠ φ))
14.   v_j = DEQUEUE(N_u)
15.   if((∃v_l ∈ M_u) AND (notCone_α((M_u − {v_l}) ∪ v_j)))
16.       w_{v_l} = P̂_{u,v_j} // w_{v_l} is the payment of v_l
17. if (∃v_m ∈ M_u, v_m is marked, w_{v_m} = ∞)
18.    w_{v_m} = P_max
19. P_u = max(P̂_{u,v_k}), ∀v_k ∈ M_u, v_k is marked
```

Figure 1. TRUECON algorithm running on node u

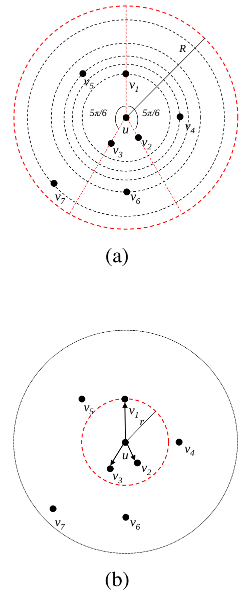

Figure 2. Example of running TRUECON algorithm on node u

to decide the payment of each node in order to stimulate their collaborations. Line 12 to 16 of TRUECON algorithm implement a VCG mechanism in the context of MANET topology control. M_u increments by one node every time. Without loss of generality, v_j is the claimed closest neighbor among all the node left in N_u. After adding v_j, if there exist a node v_k in M_u and v_k could be excluded so that $Cone_\alpha(M_u - \{v_k\} \cup v_j)$ is a FALSE, then payoff for v_k is equal to v_j's claimed power value P_{u,v_j}. Since v_k is already in M_u and the algorithm processes nodes in a non-decreasing order, $P_{u,v_k} \leq P_{u,v_j}$.

When node v_4 is entered into M_u, it can replace the v_2. Then v_4's claimed power value decides v_2's payment w_{v_2}. In the same way, v_5 determines v_1's payment w_{v_1} and v_6 determines v_3's payoff w_{v_3}. After processing v_6, the algorithm reaches the last line. Node u adjusts its transmission power to be the maximum claimed power value of nodes in M_u. If every node reports correctly, then at the end of TRUECON, u sets its power P_u as P_{u,v_1}.

In TRUECON, after a node's payment is set, it is not changed between two rounds of *Hello* messages. To reduce the radio interference caused by sending *Hello*s, we can lower the transmission power of *Hello* messages to the power TRUECON decides. In a MANET, network nodes can move around. Therefore, between two consecutive rounds of *Hello*-*Ack* exchange, the nearest neighbor set may change. Then the transmission powers of *Hello* messages and data packets need to change accordingly.

It is observed that in the example of Fig. 2, every neighbor in M_u has a payment decided before the algorithm ends. However in some cases, the algorithm may stop before each critical neighbor finds a substitute and sets its payoff. Then the payment for those neighbors would be equal to the maximum power P_{max}.

After running TRUECON, if node u receives packets from one of its forwarding neighbor, say v_i, u needs to sign on the payment w_{v_i}. In TRUECON, we let the source node pay the price along the path. The monetary transfers are critical to generate cooperative incentives of rational nodes.

4.2 Analysis of TRUECON algorithm

4.2.1 TRUECON preserves the network connectivity

We denote the network graph, in which each node transmits using its full power P_{max}, as G_R. After running TRUECON, a network node reduce its transmission power to P', $P' \leq P$. The derived network graph is denoted as G_r then.

Theorem 4.1 *If in G_r for each cone not greater than $\frac{5\pi}{6}$ there is a neighbor node, G_r preserves the connectivity of G_R. Node u and v are connected in G_r if and only if they are connected in G_R.*

Proof The connectivity of TRUECON follows CBTC. Since CBTC preserves the network connectivity, TRUECON preserves the network connectivity too.

4.2.2 TRUECON is truthful

In addition to a topology control algorithm, TRUECON is a truthful mechanism as well. The selection function of the mechanism chooses an outcome to minimize the nominal transmission power of a network node, as long as the direction constraint is satisfied.

By definition, TRUECON is a direct-revelation mechanism because it lets each participant announce its private type, which is the minimum transmission power in this case. The payment is decided based on the declared values. Without loss of generality, we let node u run TRUECON. The result neighbor set of u is Nei_u, $Nei_u = \{v_1, v_2, \ldots, v_n\}$. The utility function of a neighbor $v_i, (1 \leq i \leq n)$ is $u(v_i)$.

When v_i receives a *Hello* message from u, it measures the received signal and estimates the minimum power u can use to reach it. The calculated power value is also what it needs to send packets to u. This power is the cost for v_i to forward packets to u and only v_i knows its value. The declared value $\hat{P}_{u,v_i}$ in *Ack* is not necessary to be equal to P_{u,v_i}. Node u needs to decide v_i's payment w_{v_i} based on v_i's and others' announcements. Hence, $u(v_i) = -P_{v_i}(o, P_{v_i,u}) + t_{v_i}(\hat{P})$, where the first part is v_i's cost function representing the power it needs to consume and should be a non-positive value. The second part is the payment function of v_i.

We observe $u(v_i)$ is a quasi-linear function. By [16, 6], VCG mechanisms are the only allocation-efficient and strategy-proof mechanism for all direct-revelation mechanisms, in which agents have quasi-linear utility functions. If TRUECON implements a VCG mechanism, we can guarantee the efficiency and truthfulness of TRUECON.

The selection rule of TRUECON is $k : P_{v_1} \times P_{v_2} \times \ldots \times P_{v_n} \rightarrow \mathcal{K}$ and the payment rule is $t_i : P_{v_1} \times P_{v_2} \times \ldots \times P_{v_n} \rightarrow \mathbb{R}$, for each neighbor v_i. Node v_i reports the power value $\hat{P}_{v_i,u}$ with its strategies s_{v_i}, then $\hat{P}_{v_i,u} = s_{v_i}(P_{v_i,u})$. $\hat{P}_{-v_i,u}$ denotes the reported value of all the neighbor nodes except i.

The selection rule of TRUECON, with a direction constraint, computes $k^* = arg \min_{k \in \mathcal{K}} \sum_i P_{v_i}(k, \hat{P}_{v_i,u}), v_i \in Nei_u$. k^* is the choice that minimize the total reported power over the minimal satisfactory neighbor set.

The payment rule in TRUECON mechanism is defined as $t_{v_i}(\hat{P}) = h_{v_i}(\hat{P}_{-v_i,u}) - \sum_{j \neq i} P_{v_j}(k^*, \hat{P}_{v_j,u})$, where $h_{v_i}(\hat{P}_{-v_i,u})$ is a function over all the neighbor nodes except v_i. With $h(.)$, t_{v_i} picks v_i's first substitute, which has a greater declared power and keeps the direction constraint satisfied without v_i. Function t_{v_i} guarantees the Individual Rationality (IC) because if a node participates the mechanism and reports correctly, its expected utility is always non-negative. In another word, a participant is always overpaid. As we prove later, the overpayment has an upper bound against the total cost.

By substitution, we have

$$u_{v_i}(\hat{P}_{v_i}) = -P_{v_i}(k^*(\hat{P}), P_{v_i,u}) + t_{v_i}(\hat{P}) \tag{2}$$

$$= \begin{cases} -P_{v_i,u} - \sum_{j \neq i} P_{v_j}(k^*(\hat{P}), \hat{P}_{v_j,u}) \\ +h_{v_i}(\hat{P}_{-v_i,u}), \quad v_i \in Nei_u \\ 0, \quad otherwise \end{cases} \tag{3}$$

The first two terms are the negative part of the utility function because the power value represents the cost of each node while serving others. We can ignore the h_i function, as it has nothing to do with v_i. If v_i wants to maximize its utility, it must minimize the absolute value of the negative part. Hence, v_i want to find a strategy to solve:

$$\min_{s_{v_i} \in S_{v_i}} \left[P_{v_i}(k, P_{v_i,u}) + \sum_{j \neq i} P_{v_j}(k, \hat{P}_{v_j,u}) \right] \tag{4}$$

If (4) is solved by a single strategy $\bar{s}_{v_i}$, v_i can secure its maximum expected utility no matter what strategies other nodes play. v_i can affect the mechanism outcome, $k^*(\hat{P}_{v_i,u}, \hat{P}_{-v_i,u})$, by reporting $P_{v_i,u}$ as different values. However, only when $\hat{P}_{v_i} = P_{v_i}$, the mechanism, with the direction constraint, explicitly solve:

$$\min_{k \in K} \sum_i (\hat{P}) \tag{5}$$

$$= \min_{k \in K} \left[P_{v_i}(k, P_{v_i,u}) + \sum_{j \neq i} P_{v_j}(k, \hat{P}_{v_j,u}) \right] \tag{6}$$

Since the neighbor's direction is detected by the node running TRUECON, the neighbors' strategies have no influence on the direction constraint. As a result, Truth-revelation is the *dominant strategy* of v_i, whatever the reported $\hat{P}_{-v_i,u}$. Then we prove the following theorem.

Theorem 4.2 *TRUECON mechanism is strategy-proof.*

In TRUECON, no node can obtain a higher expected utility by cheating as long as there is another node to be able to replace it. Please note that we assume there is no collusion among all network nodes. Everyone is on its own when deciding what strategy to play.

4.3 Routing with TRUECON

Each node runs TRUECON locally and adjusts its transmission power accordingly. In this section, we discuss the design of DSR-TRUECON, a Dynamic Source Routing protocol (DSR) [9] with TRUECON enhancement.

4.3.1 DSR-TRUECON — the DSR enhanced with TRUECON

DSR is a reactive routing protocol. When a source node S wants to communicate to a multi-hop-away destination node D, S initiates a route discovery process by broadcasting a Route Request packet (RREQ). S adds its ID into an address list in the request packet. The RREQ has a unique ID so that each receiver can identify it. Upon receiving a RREQ, a network node checks whether it is the destination. If it is not and does not know a path to D, it inserts its ID into the address list and broadcasts it again. While the RREQ finally reaches D, D replies with a Route Reply packet (RREP) containing all the accumulated route information. The RREP is sent back to S by reversing the path. After S receives the RREP from D, data packets will be transferred along the discovered path.

```
DSR-TRUECON()
  while (true)
   if (received a Route Request message)
     if (this is the destination)
       sum up the total cost and save RREQ
       reset time T_r
     else if (this RREQ is seen previously)
       sum up the total cost
       if (the new RREQ has a lower cost)
         set last node' cost and append my ID
         broadcast the RREQ
       else
         disregard this message
   else if (receive a Route Reply message)
     set and sign on predecessor's payment
     send the RREP to the predecessor
   else if (timer T_r is expired)
     generate a Route Reply message
     copy the smallest cost route into the RREP
     set and sign on predecessor's payment
     send the RREP to the predecessor
```

Figure 3. DSR-TRUECON algorithm for processing Route Request and Route Reply

TRUECON requires some adaptations of DSR in order to discover a cost efficient route while keeping the incentive-compatible property. Each node can run TRUECON and adjusts its transmission power based on TRUECON's result. In DSR-TRUECON, the source node needs to pay the bill of sending packet along the entire route. Since the source node needs the forwarding service to fulfill its own functions, it is reasonable to charge it as a service consumer.

Fig. 3 presents the DSR-TRUECON algorithm of processing Route Request and Route Reply packets. It is shown that DSR-TRUECON implements a distributed Bellman-Ford algorithm to find a shortest path for a single source in a weighted graph. We use a two-pass scheme to discover the power-efficient path and transfer the payment information.

By the design of DSR-TRUECON, the routing protocol always finds a most power-efficient path. Each node broadcasts a RREQ at least once. In the worst case, a node needs to transmit a RREQ for every other node if an incoming RREQ always reveals a more power-efficient path than the previous RREQs. Therefore, the message complexity of DSR-TRUE is $O(n^2)$, where n is the number of network nodes.

4.3.2 Overpayment of DSR-TRUECON

In DSR-TRUECON, the price of a MTP path is higher than the total cost and not necessary to be the cheapest for the same source and destination.

Definition *Overpayment* (OP) is the ratio of the total payment against the total cost along a path.

Then, $OP_{S,D} = \frac{\sum_{i=1}^{l-1} w_{v_i}}{\sum_{i=0}^{l-1} P_{v_i}}$, where w_{v_i} is the payment to node v_i and P_{v_i} is the transmission power of node v_i, ($v_0 = S$). On a l-hop path, there are $l-1$ nodes transmitting data packets, including the source S and there are $l-2$ nodes earning payment.

The overpayment of DSR-TRUECON could be very high when a forwarding node is paid at the maximum rate and very close to its successor on a route. Network nodes may not be happy if they pay too much for a MTP path and become financially broke fast. We revise TRUECON to pay a forwarding neighbor by whatever is smaller between the pre-decided payment and the cost to reach its predecessor from its successor along a path. Except the payment function, the outcome function of the mechanism remains the same. We call the revised algorithm TRUECON-ECO, since it assures the economy of the outcome. We prove that the overpayment can be bounded for the source node.

Lemma 4.3 *TRUECON-ECO is strategy-proof.*

Proof Due to the space limitation, we omit the proof.

We denote the DSR routing protocol with TRUECON-ECO integration as DSR-TRUECON-ECO.

Theorem 4.4 *In DSR-TRUECON-ECO, the upper bound of the overpayment along a MTP path is* 2^α.

In the scenario of Fig. 4, a, b, c form a triangle, we have

$$d_{a,c} < d_{a,b} + d_{b,c} \tag{7}$$

We let $\bar{b}$ be the projection of b on segment (a, b). The source node a is two-hop away from the destination node c. The payment to the forwarding node b is the same as the transmission power on edge (a, c). The cost of this route equals to the sum of the transmission power on (a, b) and (b, c). By (1), we have

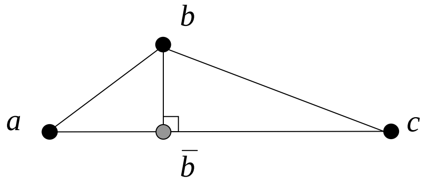

Figure 4. $\{c, b, a\}$ is of a part of a minimum transmission power path from node S to node D.

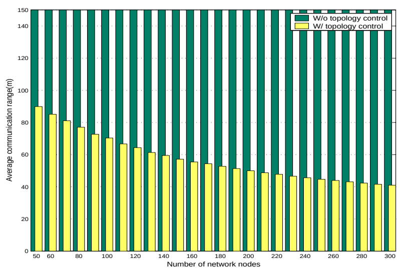

Figure 5. Average communication range

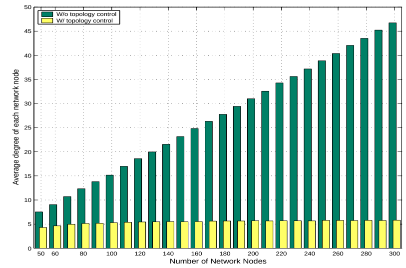

Figure 6. Average node degree

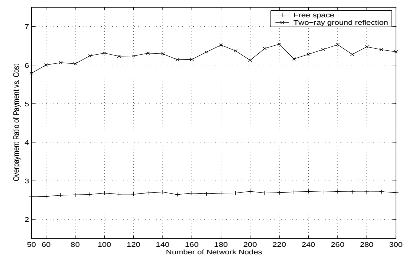

Figure 7. Overpayment of $\alpha = 2$ models

$$OP_{a,c} < \frac{d_{a,c}^{\alpha}}{d_{a,\bar{b}}^{\alpha} + d_{\bar{b},c}^{\alpha}} \tag{8}$$

$$\leq \frac{d_{a,c}^{\alpha}}{(\frac{1}{2}d_{a,c})^{\alpha} + (\frac{1}{2}d_{a,c})^{\alpha}} \tag{9}$$

$$= 2^{\alpha-1} \tag{10}$$

Since $\alpha \in [2, 6]$, $OP_{a,c}$ varies between 2 and 32.

The overpayment has a significant impact on the usability of a mechanism. If a mechanism cannot restrain its overpayment, a node may run of money quickly and cannot afford any form of communication. Then the performance of the whole network degrades. In TRUECON-ECO, even though a source node does not know how much the total cost of a path is, it knows it cannot pay more than 2^{α} times of the total cost. An bound of the overpayment is also important for deciding how much start funding needs to be deposited for every node in a network.

5. Simulation of TRUECON

We simulate TRUECON in MANETs using ns-2 [1] to evaluate the system performance. As a reference, we also simulate MANETs, in which every node transmits using the maximum power.

In our experiments, network nodes are distributed uniformly, except a source node and a destination node, into a $600m \times 600m$ area. Each node has a transmission range of $150m$ and is stationary throughout the experiments.

After TRUECON terminates at each node, a source node starts a route discovery to find a path from to a destination node. This pair of nodes is intentionally placed on different sides of a network such that a path between them always has multiple hops. The total cost, sum of transmission power, along the path is compared with that in the original graph, in which each node communicates using the maximum power.

We investigate the result data with several metrics, which are average communication range, average node degree and overpayment on the path.The total number of network nodes varies from 50 to 300. Fig 5 - **??** present the simulation results. Each point on the graphs represents an average value of 100 runs.

Fig. 5 shows the average communication range of each node at different node densities. As the node density rises, the communication range decreases. In the sparse network graphs, the average Euclidean distance between different nodes is farther than that in the dense graph. So in sparse network, a node is expected to have a smaller neighbor set at the maximum transmission power and need to keep a longer communication range in order to maintain the connectivity. While there are many nodes in network, each node holds a larger neighbor set at the maximum transmission power. It can drop off many nodes without degrading the network connectivity.

Fig. 6 plots the average degree at different node density. Without the topology control mechanism, the node degree increases linearly as the node density increases. The higher connection degree the higher the probability of packet collisions. Using TRUECON topology control mechanism, the node degree almost stays as a constant value.

Fig 7 shows the simulation results in term of the overpayment. The two curves in Fig. 7 show the average values of the overpayment along a path with the free space model and the two-ray ground reflection model respectively. The experimental data conforms to the theoretical bounds.

6. Conclusion and Future Work

We study the topology control problem of MANETs in a non-cooperative environment. Due to the limited energy reserve of a network node, saving energy is critical to maintain the usability of a MANET. Topology control algorithms allow network nodes to reduce their transmission power while keeping the same network connectivity as they use the maximum power. However, there is no guarantee on the collaboration among network nodes in MANETs. Forwarding packets for others only incurs energy consumption on intermediate nodes without any obvious benefit. Limited critical resource possession gives an intention to every node to act selfishly.

We propose a truthful topology control mechanism (TRUECON) to attack the selfish intention. TRUECON is a direct-revelation mechanism, in which every node has a quasi-linear utility function. TRUECON belongs to the VCG mechanism family. The truthfulness is proved in this research.

TRUECON can be integrated with ad hoc routing protocols. We revise DSR routing protocol to find a minimum transmission path over the TRUECON-induced network graph. Though the payment along a path must be higher than the actual cost in order to give an incentive to the forwarding nodes, we prove a general upper bound of the overpayment. We simulate TRUECON in various scenarios and the experimental data complies with our analysis.

TRUECON has its limit in sparse networks, because it is hardly to find a replacement for every forwarding neighbor. The impact of node mobility needs to be investigated in future work.

References

[1] ns2 notes and documentations. http://www.isi.edu/vint/nsnam/.

[2] A. Cerpa and D. Estrin. Ascent: Adaptive self-configuring sensor networks topologies. *IEEE Transactions on Mobile Computing Special Issue on Mission-Oriented Sensor Networks*, 3(3), July 2004.

[3] C.Wang, L.Xiao, Y. Liu, and P. Zheng. Distributed caching and adaptive search in multilayer p2p networks. In *Proceedings of ICDCS*, 2004.

[4] S. Eidenbenz, G. Resta, and P. Santi. Commit: A sender-centric truthful and energy-efficient routing protocol for ad hoc networks with selfish nodes. In *Proceedings of WMAN 05*, 2005.

[5] L. M. Feeney and M. Nilsson. Investigating the energy consumption of a wireless network interface in an ad hoc networking environment. In *Proc. of IEEE INFOCOM*, 2001.

[6] J. R. Green and J.-J. Laffont. Characterization of satisfactory mechanisms for the revelation of preferences for public goods. *Econometrica*, 45, 1977.

[7] T. Groves. Incentives in teams. *Econometrica*, 41:617–631, 1973.

[8] P. Gupta and P. R. Kumar. The capacity of wireless networks. *IEEE Transactions on Information Theory*, 46(2):388–404, March 2000.

[9] D. Johnson, D. Maltz, Y. Hu, and J. Jetcheva. The dynamic source routing protocol for mobile ad hoc networks. IEEE internet draft, March 2001.

[10] J. Li, C. Blake, D. S. J. D. Couto, H. I. Lee, and R. Morris. Capacity of ad hoc wireless networks. In *Proceedings of MobiCom*, 2001.

[11] L. Li and J. Y. Halpern. Minimum-energy mobile wireless networks revisited. In *Proceedings of ICC*, 2001.

[12] L. Li, J. Y. Halpern, V. Bahl, Y.-M. Wang, and R. Wattenhofer. Analysis of a cone-based distributed topology control algorithms for wireless multi-hop networks. In *Proceedings of ACM PODC*, 2001.

[13] X. Liu, L. Xiao, A. Kreling, and Y. Liu. Optimizing overlay topology by reducing cut vertices. In *Proceedings of ACM NOSSDAV*, 2006.

[14] Y. Liu, X. Liu, L. Xiao, L. M. Ni, and X. Zhang. Location-aware topology matching in p2p systems. In *Proceedings of IEEE INFOCOM*, 2004.

[15] L. M. Ni, Y. Liu, Y. C. Lau, and A. Patil. Landmarc: Indoor location sensing using active rfid. *Wireless Networks*, 2004.

[16] D. C. Parkes. *Iterative Combinatorial Auctions: Achieving Economic and Computational Efficiency*. PhD thesis, University of Pennsylvania, May 2001.

[17] R. Ramanathan and R. Rosales-Hain. Topology control of multihop wireless networks using transmit power adjustment. In *Proceedings of IEEE INFOCOM*, 2000.

[18] T. S. Rappaport. *Wireless Communication: Principles and Practice*. Prentice Hall, 1996.

[19] V. Rodoplu and T. H. Meng. Minimum energy mobile wireless networks. In *Proc. of IEEE ICC'98*, volume 3, pages 1633–639, Atlanta, GA, June 1998.

[20] V. B. Roger Wattenhofer, Li (Erran) Li and Y.-M. Wang. Distributed topology control for power efficient operation in multihop wireless ad hoc networks. In *Proceedings of IEEE INFOCOM*, 2001.

[21] S. Singh and C. S. Raghavendra. Pamas: Power aware multi-access protocol with signalling for ad hoc networks. *ACM Computer Communication Review*, 28(3), July 1998.

[22] L. Thomas. *Games, theory and applications*. Ellis Horwood Limited, England, 1984.

[23] W. Xue, Q. Luo, L. Chen, and Y. Liu. Contour map matching for event detection in sensor networks. In *Proceedings of ACM Sigmod*, 2006.

[24] S. Zhong, Y. R. Yang, and J. Chen. Sprite: A simple, cheat-proof, credit-based system for mobile ad hoc networks. In *Proceedings of INFOCOM*, 2003.