Play Alone or Together - Truthful and Efficient Routing in Wireless Ad Hoc Networks With Selfish Nodes

Jianfeng Cai
Department of Computer Science
Texas A&M University
College Station, TX, 77843-3112
j0c1194@cs.tamu.edu

Udo Pooch
Department of Computer Science
Texas A&M University
College Station, TX, 77843-3112
pooch@cs.tamu.edu

Abstract

A wealth of research proposals in ad hoc networks has been seen on the problem of routing along power efficient paths. However they do not take into account the interests of individual nodes. Managed by different profit-oriented entities, network nodes can no longer be assumed to cooperate with each other. Incentive-compatible routing seems to be more realistic to deal with selfish nodes in ad hoc networks.

We propose the Transmission power rEcursive Auction Mechanism (TEAM) routing protocol to prevent the selfish behaviors and stimulate cooperative works from the game theoretic approach. It pays nodes for their services and makes cheating not attractive. Interests of nodes will be best served if they only reveal true information. With some assumptions the truthfulness of TEAM can be proved. We present a theoretical bound of the power efficiency of TEAM protocol. It is also shown that comparing to another truthful routing protocol, Ad hoc-VCG, TEAM reduces the message complexity significantly.

1. INTRODUCTION

Mobile Ad hoc NETworks (MANET) have drawn more and more attention from researchers in both academia and industries. "Communicating anytime and anywhere" is always a fascinating idea for people. Due to the limited energy reserve of mobile devices, such as laptops and PDAs, how to maximize the utilization of the scarce resource in ad hoc context is very important. Many researches [5, 12, 15, 16, 18, 24, 27, 30, 31] have been proposed to deal with the energy efficient routing problem. However, behind these researches is an assumption that every node in networks always does exactly what it is supposed to do. Ironically, when modern mobile technologies bring the communication freedom to people, they also bring the freedom to break rules in this field. Network nodes may be managed by different profit-oriented entities. As a result they follow their own interests, instead of any pre-defined procedures. Protocols without consideration of this new characteristic will fall short while dealing with ad hoc networks, in which nodes intend to be selfish.

For example, an ad hoc network is formed in a technical conference by laptops that belong to different people. The conference may have several ongoing sections distributed in a wide area. There is no guarantee on the delivery of data packets because forwarding packets for others only drains the battery without bringing back any benefit to the relay nodes. Running out battery for helping others' business is not attractive for intermediate nodes.

Based on these observations, we argue that selfish behaviors are inevitable in MANETs run by different entities. Any protocol has no luxury to assume they are completely fulfilled by all nodes in this context. Researchers have tackled the selfishness from two approaches. One is to regard the selfish nodes as a security threat and try to identify and punish them. However, the selfish nodes are different from the malicious nodes, though they may degrade the network performance as the malicious nodes. Selfish nodes are rational, which means they only want to maximize their own benefit and are not interested in attacking others on their own cost. Therefore another approach is to stimulate cooperation by giving payments to service providers.

Game theory [28] seems to be the right tool to deal with interest conflicts. It models the behaviors, strategies in another word, of players and the outcomes of games. In particular, mechanism design (see chapter 2 in [22]) defines the rules and the outcome function of a game. When the social function is implemented as a dominant strategy, which yields a better payoff than any other strategies, the game will get a desirable result.

With an appropriate mechanism, things will be different in ad hoc networks with selfish nodes. Suppose a college student Bob wants to surf on the Internet for course materials while enjoying the sunshine on the lawn outside the main library and any departmental buildings where the wireless Access Points (APs) are installed. His laptop is out of the range of all APs but can communicate with a few of other mobile devices. These devices can help him out if they forward the packets between his laptop and any of the APs. Since forwarding packets always consumes energy, the service request may be refused if the intermediate devices are not compensated in some forms. On the other hands, if the payment is attractive enough, any device in the middle may want to earn the benefit even by lying if it works. A mechanism is designed to assure that every service provider is given incentive to cooperate and only truth is told to earn the payoff. Hence, Bob can lie down on the grass while browsing websites through the PDA of another student, say Alice. Later on, Alice can claim and redeem what she earns from serving others. The school saves money on providing a full wireless coverage on campus. Such a truthful and efficient routing mechanism is the motivation of this research.

We present Transmission power rEcursive Auction Mechanism (TEAM) routing protocol to cope with the selfish intention. TEAM tries to optimize the aggregate transmission power along a route from the source to the destination. We ignore the receiving power here in that it is likely much lower than the transmission power [9], which increases with the exponent of 2 (in the free space model) or 4 (in the two-ray reflection ground model) [23] in the distance between the sender and receiver. We believe when taking the receiving power into account the theoretical analysis of TEAM is still true.

TEAM works inside game theoretic settings. Each node plays a set of strategies to maximize its own profit. In order to achieve this goal, cheating may happen. Forwarding nodes can earn payoffs by providing services. The amount of the payoffs is decided according to their contributions and is enough to cover the cost incurred by serving others. The outcome generated by TEAM makes that cheating is not an appealing choice anymore. Only when a node tells the truth, can its interests be best served. Nodes volunteer to participate the routing as long as their energy reserve allows. Wealth can be spent to pursue better Quality-of-Service (QoS). For instance, a rich node can bid more for a crucial resource than poor nodes. However how to redeem the fortune is out of the range of this paper and is worth further research works.

TEAM works in two phases. First, it runs an AODV-like [7] protocol to quickly find a route from the source to the destination. The routers chosen at this stage share the payment from the source node. The price of each communication session is flat for the source node. We try to minimize the hop number at this stage because energy efficient path will be established recursively in the second phase. Then we call for auctions within each hop along the route. Each intermediate node, which overhears the routing messages, can bid to redirect the path by advertising the aggregate transmission power if the path goes through it. Only the best offer wins the auction and the payoff of the winner is decided according to the power improvement after the redirection. Auctions will be held iteratively along the newly redirected path until no better path is found. If in the first auction, no node can offer a better path than a direct path from the sender to the receiver within one hop, the sender will send packets directly to its successor on the route. Obviously, TEAM may not find the most power efficient path every time, but it reduces the energy consumption along a route with the consideration of the incentives of individual nodes.

We prove that with some assumptions TEAM is a truthful protocol and its performance can be bounded theoretically. The simulation results show the power efficiency of TEAM paths is very close to the Minimum Transmission Power (MTP) path. Comparing to another truthful routing protocol, Ad-hoc VCG [3], TEAM has a significantly lower message overhead. TEAM is an approximation algorithm for energy conserving problems with a truthful characteristic.

The remainder of this paper is organized as follows: Section 2 reviews related work. An introduction to the system model used in this paper is given in section 3. Section 4 presents the TEAM protocol design. Section 5 proves the truthfulness of TEAM. Efficiency analysis can be found in section 6. Section 7 gives simulation results. And Section 8 concludes.

2. RELATED WORK

PARO [12] reduces the aggregate transmission power by taking advantage of multi-hop transmission. It allows a route to be redirected by intermediate nodes. Since the nodes in ad hoc networks have the intention to be selfish, they may not volunteer to redirect a path all the time. SPAN [5] elects coordinators to form a forwarding backbone. Non-coordinators can enter the doze state to save energy. SPAN does not use adaptive emission power, thus every node keeps a uniform power level as long as it is on. This may cost more energy than necessary and cause more radio interference. In [30], the cone-base distributed topology control algorithm reduces the degree of the nodes in a wireless ad hoc network. Thus the radio interference is decreased and the energy is saved. GAF [31] divides an area into virtual grids. Nodes in the same grid are the equivalent routers and shift in three states: active, sleeping and discovering to forward network traffic in turn. [15] gives a survey of energy conservation technologies across the protocol stack of wireless networks. Li, et al. [17] study the relationship between the transmission range and the connectivity of resulted graphs. They show that (K+1)-connected graph can be achieved with certain probability when the emission radius and the node number satisfy some conditions.

[8] calls protocols, which ignore the fact that a node is willing to save the energy for its own usage, compulsory protocols. In real world, a protocol may not have the authority to force all nodes to do what they are supposed to do. In contrast, individual nodes in ad hoc networks are able to manipulate a protocol. Marti, et al. [19] show that even a small portion of misbehaving nodes can degrade the network performance dramatically. [21, 32] attack the security routing by establishing countermeasure mechanisms against malicious nodes. However, selfish nodes are different from malicious nodes because they are rational.

Economic concepts have already been introduced into distributed system research area [10]. In [4, 8, 26], the collaborations between different nodes are no longer taken for granted. Instead, some mechanisms are designed to stimulate the cooperative works. In [4], network services are traded on each hop toward the destination.

Game theory [28] gives us methods to model cooperative and non-cooperative works between different parties. A player has its own preference, which is represented by a utility function, and is private information. A player has incentive to maximize its utility while playing a game. In the game theoretic setting, the network nodes act as the players in a game. Selfish nodes are common in ad hoc networks since energy is a scarce resource and nodes are managed by different authorities. The cooperation of nodes is the basis of network services. So the support for the network functions should not come for free. As the service providers get compensation in some form for their cost, the intention of cooperating with others is stimulated.

Due to the characteristics of wireless propagation [23], multi-hop transmission may save the total transmission power. We allow an intermediate node to redirect the route if this redirection can decrease the aggregate transmission power. We measure the transmission power reduction and use it as a gauge of the payoff. The more power saved by the redirection, the more payoff a node earns.

Viewing and solving problems in distributed systems from the approach of mechanism design theories is a recent trend [11, 25]. [6, 13, 29] are the three seminal papers of the famous VCG mechanism, named after Vickrey, Clarke and Groves, generally the second best sealed bid auction. Nisan and Ronen [20] discusses mechanism design and its applications from the algorithmic aspect. Ad hoc-VCG [3] is a work close to our research. It implements the generalized VCG in ad hoc networks in order to achieve the cost-efficiency and truthfulness. It pays intermediate nodes a premium, which covers the incurred cost. Its overpayment has a theoretical bound. However the message overhead of Ad hoc-VCG is high, $O(n^3)$, in that it exhausts each possible path to find the most energy efficient one. TEAM tries to improve the power efficiency along a path while keeping the message complexity significantly low, $O(n + L \times n)$. L is the number of hops.

3. SYSTEM MODEL

An wireless ad hoc network can be interpreted as a weighted graph, $G(V, E, W)$. In the graph network nodes are represented by a set of vertices, $V = \{V_0, V_1, \dots, V_{n-1}\}$. If a node V_i is within the communication range of another node V_j, there is an edge, (V_i, V_j) between them. We assume each node is identical and the link between a pair of nodes is bi-directional. The weight W_{V_i,V_j} on edge (V_i, V_j) is the transmission power, P_{V_i,V_j}, consumed by the sender.

We denote a source node as S, which generates and sends out packets and a destination node as D, which is the intended receiver of the packets sent by S. A path from S to D is a series of node identification numbers, $\sigma_{S,D} = \{S = \sigma_0, \sigma_1, \dots, D = \sigma_L\}$. L is length of the path, which is the number of hops. $d_{i,i+1}$ is the Euclidean distance between V_i and V_{i+1}. We try to find an energy efficient path from the source to the destination, on which each node cooperates to forward packets and earns its payoff.

From the wireless propagation models [23], we know the signal strength, P_r, at the receiver end is related to the distance, d, and the emission power, P_t, at the sender end.

$$P_r = \frac{P_t K}{d^\alpha} \tag{1}$$

K is a constant and α is 2 for the free space model, 4 for the two-ray ground reflection model. To simplify the analysis without loss of generality, we use the free space propagation model in this paper.

We assume nodes use omnidirectional antennas to communicate. When a sender sends out a packet, others within a certain range will correctly receive it, if the received signal strength is above a threshold P_{thd}. Thus, if the transmission power is known to the receiver, a minimum power level, $P_{t_{min}}$, used by the sender to reach the receiver can be estimated at the receiver end.

$$P_{t_{min}} = \frac{P_t P_{thd}}{P_r} \tag{2}$$

In TEAM 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. However, in the real environment due to the irregularity of the radio propagation range, the ideal minimum sending power may not exist. In a real-world implementation, this can be realized as different emission power levels at sender side. The sender can choose a transmission power level based on the feedback from a receiver to achieve better channel quality while saving energy. To simplify the analysis, we still use the minimum transmission power in this paper.

So the weight of a path from S to D can be expressed as

$$W_{S,D} = \sum_{i=0}^{L-1} P_{\sigma_i,\sigma_{i+1}} = \frac{P_{thd}}{K} \sum_{i=0}^{L-1} d^2_{\sigma_i,\sigma_{i+1}}$$

A Minimum Transmission Power (MTP) path is a path from the source S to the destination D along which the total transmission power P_{MTP} is not larger than any other path.

We assume that a secure payment facility exists in ad hoc networks. Some peer works (e.g. Sprite [33]) provide appropriate evidences for this assumption. If a node promises to forward network packets, its payoff will be determined by TEAM. The payment facility assures that the payoff can be delivered only after a node has really served and it can only take the right amount.

There is also a finance center (FC), like the Credit Clearance Service (CCS) in [33], which has an authority to draw a tax from each node and use it to pay for the public welfare. When a node has a link to the finance center, the debit and credit transactions will be performed. As TEAM has two phases, there are two kinds of payers for each phase. A source node is usually expected to pay the cost of the communication initiated by it. It pays a flat rate to the nodes chosen in phase one so that the less the node number, the more each node can earn. A source is assumed to be truthful because it needs the network service to fulfill its own tasks. The auction winners in phase two will be paid by the finance center, which uses the public money collected from the whole network. Each auction in phase two finds a better power efficient path therefore paying those forwarding nodes to stimulate cooperation is justified in a whole-network-wide point of view.

The FC can even work off-line while the serving nodes move to it and bring evidences of services to claim their payment. As in the Bob and Alice example we presented previously, the school can implement the finance center because it is easy for it to collect service fees and spend them for good. We also assume there is no collusion among network nodes and the control messages are forwarded by each node for free. Every node can be given a certain amount of initial funding to pay the tax and the communication fees.

4. TEAM PROTOCOL DESIGN

The intuition of TEAM is that it may not find the most energy efficient path, a MTP path, but through a truthful mechanism it can find an alternative, which approximates the MTP path. We divide the route discovery into two phases. First, TEAM run an AODV-like protocol to find a minimum-hop route from the source S to the destination D. Initially, S broadcast a route request RREQ into the network. Each node receiving the RREQ checks whether it is the destination. If it is not, it forwards the request by broadcasting it again. After the destination node receives the RREQ, a route reply message RREP is created and sent out along the backward path. Each node on the route records the destination node and next hop toward it. As soon as the source receives the RREP, a minimum-hop path is established and the phase two starts.

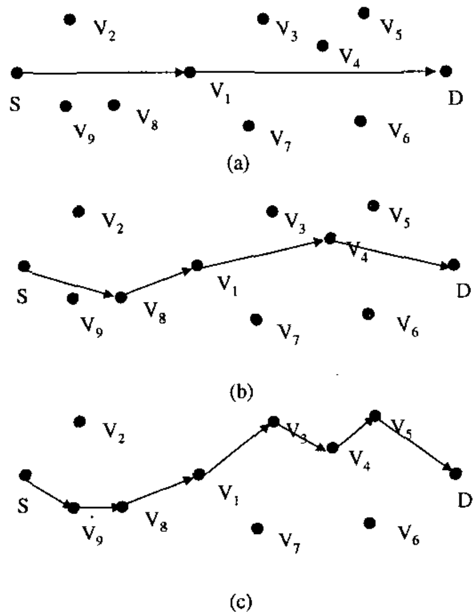

Figure 1. Route discovery: establish a path through recursive auctions.

Since the energy efficiency along a route is improved in phase two, the longer each hop in phase one, the bigger improving space we have in phase two. The RREQs need to be broadcast with maximum power by each intermediate node. To induce nodes to broadcast in this way, TEAM makes the price of each communication session flat at M, which is the amount a source needs to pay. All the nodes, chosen in phase one, share the payment. Thus, each node will receive $\frac{M}{L-1}$ equally, while L is the hop count of the path. Only when L decreases, can intermediate nodes increase their payoffs. The value of M is set depending on the diameter of a network. We just assume this value is decided beforehand in a way to make it attractive enough for any forwarding nodes and affordable for any source nodes.

In phase two, TEAM calls for auctions within each hop on the current path. The nodes picked in phase one have known their payoffs that will not change no matter what the phase two turns out. Thus these nodes will act correctly in the phase two. Intermediate nodes, which are overhearing the routing messages and within the communication range of both the upstream and downstream nodes, V_i and V_{i+1}, bid to redirect the path as long as the redirections can reduce the power consumption. Each of those nodes uses one-hop broadcast messages, as the hello messages, to announce the total transmission power spent along the redirected path that goes through it. The cost incurred by the route redirection is compensated by a flat-rate participation bonus from the finance center. The cost is a function of the transmission power and residual energy. Since each node has a maximum emission power level, and its participation is voluntary, the cost cannot be arbitrarily high. The finance center draws taxes from each node to pay for the public affairs. This is reasonable because the network-wide energy saving is beneficial for each node. The best offer, or the minimum transmission power redirected path, will win the auction. The two end nodes of the hop update their routing tables according to the auction result. The winner receives a payoff, Pf, in addition to the participation bonus, for its service. Pf is equal to the power saved by the redirection. Then,

$$Pf = P_{V_i,V_{i+1}} - P^{Redirect}_{V_i,V_{i+1}} = P_{V_i,V_{i+1}} - (P_{V_i,V_j} + P_{V_j,V_{i+1}})$$

V_j is the winner of an auction.

After a redirection ends, another round of auctions starts within the newly redirected hops as long as a power improvement can be achieved. Please note that in a real-world application, the auction stop condition may be modified in order to take the receiving energy consumption into account. But in following sections we just keep ignoring it to simplify the analysis. Since the new auctions do not change the payoff of redirectors selected previously, these nodes have no intention to misbehave from now on.

TEAM does not establish the final path at once. Intermediate nodes are put into the cooperative situation one by one through each auction. The advantage of recursive auctions is that we can prevent cheating in each round. As a node is picked by the protocol, it secures its payoff by working correctly. Afterwards, it does not need to lie anymore. This mechanism stimulates cooperation in an environment where the selfish behavior is almost for sure.

5. TRUTHFULNESS ANALYSIS

As we mentioned above, a sender includes the transmission power in its packets. A receiver calculates and reports the minimum power needed by the sender to reach it. As an overhearing node, V_j, competes to be the redirector within a hop, it needs to report to upstream node, V_i, the minimum power $P_{V_i,Vj}$ and listen to the downstream node, V_{i+1}, to get the minimum power $P_{V_j,Vi+1}$. Since the payoff for a redirector is tied with the saved transmission power, V_j cannot lie without decreasing its earnings.

First, V_j tells the true value of the power used by V_i. It is because if it gives a higher value, it may not be selected as a redirector so that it cannot earn the payoff. If it is still chosen, its payoff is reduced due to the higher reported power. If it sends a lower power value, the communication may fail, which causes it to lose the payoff. Therefore, V_j always tell the truth to the upstream node V_i.

Second, V_j always announces its transmission power correctly. If it exaggerates its emission power value, the downstream V_{i+1} will reply with a higher value. That may cause V_j to lose the competition with others. Suppose it is still selected then it has to accept a lower payoff than it could earn. To prevent a false decreased emission power value, we let V_{i+1} do a handshake with V_j with the calculated minimum power. If it fails, then V_{i+1} informs V_i. V_j will be kicked out because it does not announce correctly. As a result, if an intermediate node V_j wants to be the redirector, it has to act truthfully.

When the winner secures its payment, it does not have the intention to cheat. Thereafter, it will stay as a truth-teller.

Theorem 5.1 *TEAM protocol is truthful.*

6. EFFICIENCY ANALYSIS

Intuitively, TEAM can save power along a multi-hop path. In this section we show that if the source S and the destination D can communicate directly in one hop, the total power of a TEAM path can be bounded within $\lceil \frac{L}{2} \rceil P_{MTP}$, where L is the hop number of the MTP path.

From the protocol design, we know if an intermediate node, V_j, wants to be a redirector, the path passing through it must consume less power than the direct transmission from the upstream node, V_i, to the downstream node, V_{i+1}. We use the free space radio propagation model in our analysis [23]. Consequently the first redirector must be in a cir-

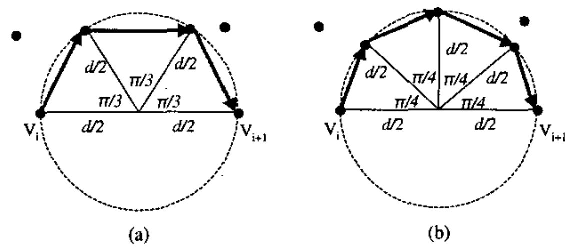

Figure 2. There is no redirector in the circle with the diameter d. However there exist a MTP path. (a)L=3 (b)L=4

cle area with the diameter $d_{V_i, V_{i+1}}$, which is the distance from V_i to V_{i+1}. If there is no such node inside the circle area, TEAM always prefers to a direct transmission. We study TEAM in two cases. One is that there is no redirector found. The other is that there is at least one redirector chosen by the protocol.

In the first case (see figure 2), if there is a MTP path from V_i to V_{i+1}, different than the direct path, it must circumvent the circle to reach V_{i+1}. If the MTP has length L, the power spent along it cannot be less than the path that $L-1$ nodes are evenly distributed on a half circle from V_i to V_{i+1}. We denote the aggregate transmission power on the MTP path with L hops as P^L_{MTP} and that on the ideal path as P^L_{min}, then we have

$$P^L_{MTP} \geq P^L_{min}$$

$$P^L_{min} = L\frac{P_{thd}}{K}[(\frac{d^2}{2}) - \frac{d^2}{2}cos(\frac{\pi}{L})] = L\frac{P_{thd}}{K}\frac{d^2}{2}[1 - cos(\frac{\pi}{L})]$$

$$P^L_{MTP} \geq L\frac{P_{thd}}{K}\frac{d^2}{2}[1 - cos(\frac{\pi}{L})] \tag{3}$$

As we know,

$$P_{TEAM} = \frac{P_{thd}d^2}{K}$$

By substitution,

$$P_{TEAM} \leq \frac{2}{L(1 - cos(\frac{\pi}{L}))}P^L_{MTP} \tag{4}$$

When
$L = 3$, $P_{TEAM} \leq 1.33 P_{MTP}$
$L = 4$, $P_{TEAM} \leq 1.71 P_{MTP}$
$L = 5$, $P_{TEAM} \leq 2.09 P_{MTP}$
$L = 6$, $P_{TEAM} \leq 2.49 P_{MTP}$
$L = 7$, $P_{TEAM} \leq 2.89 P_{MTP}$
...

Now we study the second case in which at least one redirector is found inside the circle. Because of the design of TEAM and wireless propagation characteristics, the first redirector is always the node nearest to the middle point of a straight line from V_i to V_{i+1}. If it is also the middle point on the MTP path which has a length L, then

$$P_{TEAM} \leq \lceil\frac{L}{2}\rceil P_{MTP} \tag{5}$$

In figure 3, the MTP path from V_i to $V_{i+1}$is $\{V_i, V_i^0, V_i^1, V_i^2, V_{i+1}\}$. V_i^1 is the first redirector selected by TEAM. $d_{V_i V_i^1}$, $d_{V_i^1 V_{i+1}}$ denote the distances from V_i to V_i^1 and from V_i^1 to V_{i+1}. So,

$$P_{TEAM} \leq \frac{P_{thd}}{K}(d^2_{V_i V_i^1} + d^2_{V_i^1 V_{i+1}})$$

Since there are two hops before and after V_i^1, then

$$P_{MTP} \geq \frac{P_{thd}}{K}\frac{d^2_{V_i V_i^1} + d^2_{V_i^1 V_{i+1}}}{2}$$

Thus, we have

$$P_{TEAM} \leq 2P_{MTP} \tag{6}$$

Actually in this simple topology, the two intermediate nodes, V_i^0 and V_i^2, will also be chosen by the TEAM recursively. It is not surprising to see that TEAM finds a path, which is also a MTP path.

Furthermore we prove that the bound (5) is held even when the first redirector is not on the MTP path. For instance, in figure 4, the MTP path is $\{V_i, V_i^0, V_i^1, V_i^2, V_{i+1}\}$. We choose the node in the middle of the path, which is V_i^1 in this topology. Since the V^0_{TEAM} is the winner of the first auction, the 2-hop path passing through it consumes less transmission power than any other 2-hop path from V_i to V_{i+1}. So we have

$$(d_{V_i V^0_{TEAM}})^2 + (d_{V^0_{TEAM} V_{i+1}})^2 \leq (d_{V_i V_i^1})^2 + (d_{V_i^1 V_{i+1}})^2$$

(6) is still true in figure 4. When we substitute V_i with S and V_{i+1} with D, $\lceil\frac{L}{2}\rceil P_{MTP}$ is the bound of the power efficiency of the TEAM path if S can contact D directly. We can expect much better performance of TEAM since it is rarely to see that TEAM just finds a single redirector while the MTP path has multiple hops. With the increase of node density, there are more alternative paths from S to D. TEAM finds an approximately optimal path among those alternatives. Along the TEAM path, every node is willing to forward network packets and earn its payoff.

Inherited from AODV, the message complexity of TEAM is $O(n)$ in phase one. In phase two, TEAM calls for the power auctions recursively. The nodes on the final path are picked one by one, resulting in $O(L \times n)$ messages in a stationary network. L can be the diameter of a graph or, in the worst case, n. Please note that all nodes only need to broadcast the control messages at full power level in phase one. During the auctions, they can reduce their transmission power to a lower level, which is enough to negotiate with neighbors. This is a desirable property because the radio interferences can be reduced and so is the energy consumed on control messages. In Ad hoc-VCG[3], cost efficiency is assured with a high message overhead, $O(n^3)$. Comparing to that, TEAM achieves power efficiency with a significantly lower message overhead.

7. SIMULATION AND RESULTS

We simulate TEAM in ns-2 network simulator [1] with the wireless extension of Monarch project [2]. TEAM runs

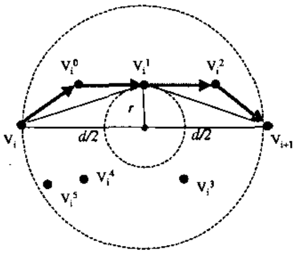

Figure 3. There is a TEAM path in the circle with diameter d. The first redirector is the middle point of the MTP path.

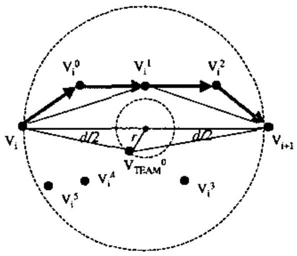

Figure 4. There is a TEAM path in the circle with diameter d. The first redirector is not on the MTP path.

as a routing protocol on the top of IEEE 802.11 MAC layer, which uses Channel Sense Multiple Access with Collision Avoidance(CSMA/CA). Before the data transmission, RTS-CTS are exchanged between the sender and receiver. The data packets are transmitted using dynamic minimum power, while RTS and CTS are always sent with maximum transmission power.

Every node in our simulations has radio with 2Mbps bandwidth and 250-meter communication range. We run TEAM in a 300m × 300m area, in which we vary the node density from 2 to 60. Nodes are stationary and put in the area randomly with a uniform distribution. Because in phase one all nodes broadcast at the maximum power, the distance between a pair of adjacent nodes on a phase one path is usually the same as the maximum communication range. So we always choose a pair of nodes, 250-meter away from each other, as the source and destination. In each topology the source initiates a route discovery by sending out a RREQ. After two phases, a power efficient path is established. The aggregate transmission power is measured. We repeat the experiment 1000 times for each node density.

To evaluate the performance of TEAM, we also imple-

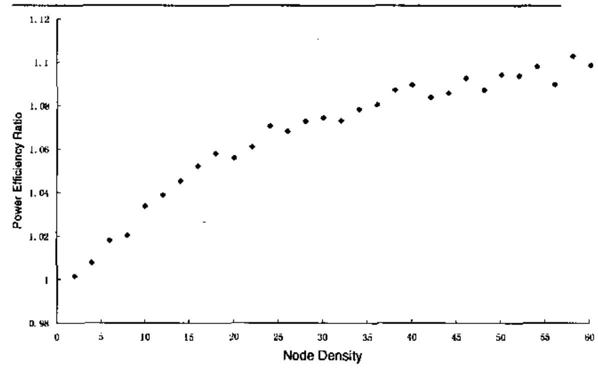

Figure 5. The average ratio of the power on a TEAM path vs. a MTP path at different node densities.

ment the Dijkstra algorithm to find the MTP paths in the same network topologies as TEAM. The power efficiency ratio, which is the aggregate transmission power of a TEAM path over its MTP counterpart, is plotted in figure 5. Table 1 presents the overall experimental results.

It is observed that with the increase of node density, the power efficiency ratio increases. It means that the TEAM paths shift away farther from the MTP paths. This is because the more nodes around, the more alternative paths from the source to the destination. Though TEAM tries to optimize the power efficiency greedily in each round of phase two auctions, the final result may not be the best. However it is shown the performance of TEAM is close to the optimal result since the ratio only increases within a narrow range even when the network topology becomes pretty dense (e.g. 60 nodes within the simulation area).

In the simulation, TEAM can almost find the MTP path for sure when the network is very sparse. Ultimately, the MTP has only one intermediate node that is always picked by TEAM as well.

8. CONCLUSION

In wireless ad hoc networks, cooperation among profit-oriented nodes cannot be taken for granted anymore. Each node is free to follow its own interests. Although researchers have proposed a wealth of energy saving protocols, the selfishness in ad hoc networks has not been noticed until recently.

Selfish nodes are different from malicious nodes. A selfish node is rational and not interested in attacking other nodes. Its objective is to maximize its own profit. Researchers have shown that even a small part of misbehaving nodes can degrade the network performance dramati-

node density	average	max/hops of MTP path	standard deviation
2	1.001481	1.209226 / 3	0.000047
4	1.007567	1.449115 / 3	0.000239
6	1.018049	1.655392 / 5	0.000571
8	1.020374	1.541751 / 6	0.000644
10	1.0337	1.766807 / 5	0.001066
12	1.03882	1.690144 / 8	0.001228
14	1.045251	1.961561 / 6	0.009329
16	1.052269	1.932788 / 7	0.001653
18	1.058064	1.927126 / 8	0.001836
20	1.05592	1.789274 / 8	0.011528
22	1.061113	2.045898 / 10	0.000745
24	1.070623	1.789599 / 10	0.000108
26	1.068386	1.663842 / 11	0.001438
28	1.072929	2.081505 / 11	0.002306
30	1.074406	1.841529 / 11	0.002353
32	1.073218	1.964102 / 9	0.005993
34	1.078408	1.802884 / 18	0.002292
36	1.080445	1.774716 / 10	0.002544
38	1.087305	1.75219 / 12	0.002424
40	1.089756	2.1501 / 10	0.000766
42	1.083883	1.945597 / 10	0.004345
44	1.085873	1.91378 / 10	0.002716
46	1.092842	1.912383 / 13	0.005316
48	1.087426	1.841414 / 11	0.002765
50	1.094422	1.856569 / 13	0.000273
52	1.093925	2.200487 / 16	0.000841
54	1.098169	2.260616 / 15	0.007331
56	1.089928	1.771828 / 16	0.002957
58	1.103075	1.979415 / 16	0.002889
60	1.098718	2.222226 / 18	0.001073

Table 1. The power efficiency ratio of all experiments.

cally. Inducing selfish nodes to cooperate by using payment is a promising approach to tackle the selfishness problem in MANETs. Game theory, in general, mechanism design, in particular, seems to be the appropriate tool to cope with interest conflicts.

In this paper, we present the Transmission power rEcursive Auction Mechanism (TEAM) routing protocol to discover a power efficient path, which approximates the Minimum Transmission Power (MTP) path, in an ad hoc network that consists of selfish nodes. TEAM pays the service providers according to their contributions. Recursive auction routing can induce nodes to cooperate with each other and significantly reduce the message overhead comparing to Ad hoc-VCG. Each node decides whether to participate the routing service voluntarily in TEAM.

We prove that with an underlying secure payment facility, TEAM is truthful. No node can lie without decreasing its payoff. If the source and destination can communicate with each other directly, the performance of TEAM has a theoretical bound.

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