A Truthful Geographic Forwarding Algorithm for Ad-hoc Networks with Selfish Nodes

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Abstract

Geographic routing algorithms for ad-hoc networks exhibit better scalability compared to topology-based routing algorithms. However, geographic routing algorithms assume a cooperative network setting for ad-hoc networks. In this paper, we present ***TGF***, a truthful geographic forwarding algorithm for ad-hoc networks that consist of *selfish* nodes. These selfish nodes forward data packets from other nodes, if they get enough payment to cover their individual forwarding cost. ***TGF*** stimulates node cooperation by using the concept of virtual money and prevents nodes from cheating over their cost. We introduce three auction schemes for forwarding packets to a next hop. In all schemes the next hop node is typically the winner of the auction. We show that ***TGF*** is a *truthful* geographic forwarding algorithm −an algorithm is truthful if it maximizes the utility of nodes only when they bid or claim their true cost. Furthermore, we show the effectiveness of ***TGF*** via extensive simulations under various network scenarios. To the best of our knowledge, ***TGF*** is the first truthful geographic forwarding algorithm for ad-hoc networks.

Keywords: Ad-hoc networks, geographic forwarding, nodes cooperation, selfish nodes, truthfulness

1 Introduction

Geographic routing protocols [21], also known as position-based routing protocols, for mobile ad-hoc networks use position information of nodes in the network for routing and location service. Unlike topology-based routing protocols [13, 18], nodes in geographic routing protocols do not establish or maintain routes in the network. A node forwards packets towards the destination solely based on the position of the destination, its own position, and the position of its neighboring nodes. By using only the local topology information, geographic routing protocols cope with node mobility, and exhibit better scalability than topology-based routing protocols [21].

Geographic routing protocols generally assume a cooperative network setting where nodes help each other for packet forwarding. However, in ad-hoc networks, nodes may have only limited resources like the battery power. As forwarding packets is more energy consuming than receiving, nodes may behave *selfishly.* Selfish nodes may not be willing to help other nodes *freely* at the cost of their own limited resource, especially in networks where nodes belong to different authorities. Since nodes in the network use a limited radio range, communication beyond radio range becomes impossible without the help of intermediate nodes. Thus, selfish behavior poses real threat to the proper functioning of an ad-hoc network.

One way to cope with selfish nodes is to stimulate nodes cooperation by using the virtual money mechanism. In this mechanism, nodes that forward packets for a source-destination pair get payment (and even some bonus) for their forwarding service from the source or the destination. However, nodes utilizing forwarding service want to pay a lowest possible payment to nodes offering the forwarding services. Thus it is desirable to reimburse nodes according to their cost for forwarding packets. To achieve this goal, the source or the destination needs to know the forwarding cost of each intermediate node. However, to maximize their utility (payoff) selfish nodes may not reveal their true cost. This poses the need for designing *truthful* mechanisms. A protocol is *truthful* (or strategy-proof) if it maximizes the nodes' payoff only when they reveal their true cost.

Recent research [2, 7, 10, 25] focused on designing truthful protocols for selfish nodes problem in the context of topology-based routing protocols. Such protocols rely on the discovery and maintenance of routes in the network, which require substantial overhead (in the order of $O(n^3)$ [2, 25] control messages, where n is the number of nodes in the network). On the other hand, geographic forwarding incurs a localized overhead of control messages [21]. Thus, it is desirable that a geographic forwarding algorithm designed to cope with selfish nodes should also be localized in nature. In this paper, we present such an algorithm, viz., the Truthful Geographic Forwarding algorithm (***TGF***) for data forwarding in ad-hoc networks. ***TGF*** introduces three auction-based packet forwarding schemes that *guarantee truthfulness* while inheriting the localized nature of geographic forwarding. We prove that ***TGF*** is truthful, statistically analyze the average progress made per hop for the proposed auction-based packet forwarding schemes, and present results from our extensive simulation study. To the best of our knowledge, ***TGF*** is the first algorithm to address truthfulness in the context of geographic forwarding.

The rest of the paper is organized as follows. Section 2 provides preliminaries and the system model. Section 3 presents the truthful geographic forwarding protocol. Section 4 presents an analysis of ***TGF***. Section 5 presents the performance evaluation through simulations. Section 6 reviews the related work. Section 7 concludes the paper.

2 Preliminaries

2.1 System Model

To model an ad-hoc network we use the well known *Unit Disk Graph* (UDG). In an UDG, nodes are distributed in a two dimensional Euclidean plan. All nodes use a constant radio range assumed to be normalized to 1. Two nodes u, v in an UDG are connected iff the Euclidean distance between them $\overline{uv} \leq 1$. Each node in the network can be selfish but rational. By rational we mean that selfish nodes are not willing to help others freely at the expense of their own resources instead, they make decision consistently with an aim of maximizing their expected payoff[1].

A node pays (virtual money) to intermediate nodes that forward its packets. The payment generally covers packet forwarding cost, and includes some bonus. Each node uses constant power to send packets and it incurs the same cost to send a packet to different neighbors. The value of a node's forwarding cost may vary over time. Since different nodes may incur different cost for packet forwarding, it is desirable to pay nodes according to their cost. However, to maximize their payoff, nodes may not reveal their true cost. We assume a payment mechanism [24] that takes care of accounting and transferring of payment between nodes, while insuring that nodes receive proper payment for their forwarding service.

Each node knows its own position by means of a positioning system like GPS, and reveals its true position. Furthermore, the source node is assumed to know the position of the destination [12, 23]. The network is assumed to be dense enough such that there is more than one path between any two nodes in the network, and avoids dead-ends due to geographic forwarding.

[1]Note that selfish nodes are different from malicious nodes, which intends to harm other nodes or destroy the network.

2.2 Fundamentals of Auction

In ***TGF***, nodes use an auction-based approach to select a next hop for packet forwarding. For the clarity of explanation, we briefly describe the auction schemes next.

An auction is a gathering of persons to bid for an item/good according to certain rules declared a priori. It has been used since prehistory and is still a very common mechanism in today's economics. According to rules and the information known to the bidders, auction can be classified into different types [1]. For example, the bidders can make their bids simultaneously where each bidder puts his bid into a sealed envelop, or sequentially where the auctioneer gives successive bids and the bidders vie for those bids. Auction can also be classified based on how the winner is decided and payed. In the *first-price* scheme, the winner is the one who bids the highest (lowest) price and pays (receives) the same. In the *second-price* scheme the winner is the one who bids the highest (lowest) price but pays (receives) the second-best price quoted by the bidders. Among these auctions schemes, the second-price sealed bid auction is well studied in the economy theory. This auction is also called *Vickrey auction*, named after Richard Vickrey, a Nobel Prize winner in economics. One of the salient features of this auction is that making bids equal to their true valuations is the dominant strategy for the bidders to win the auction. By doing so, bidders will always get non-negative utilities (payoffs).

3 Truthful Geographic Forwarding

3.1 Basic Idea

The truthful geographic forwarding algorithm (***TGF***) is a combination of the greedy forwarding with an auction scheme. Unlike the pure greedy forwarding where the selection of next hop is based on the progress (Euclidean distance) made towards the destination, in ***TGF*** the selection of next hop is based on a combination of bid value (for packet forwarding) along with the progress made by the node towards the destination. To achieve this, nodes exchange periodic hello messages containing their positions and bid values, and establish neighbor tables. The bid value specified by a node in the hello message represents its bid (cost) for which it is willing to forward a packet from its neighbors. This bid value in a hello message is valid for a hello period (typically one or two seconds). By exchanging bid values proactively via hello messages, nodes declare *a priori* the bids (cost) per packet-forwarding without any bias towards any neighboring nodes.

When a node has a packet to forward to the destination, it uses an auction scheme to select a next hop for the destination from its neighbors. As the bid values and the positions of the neighbors are known a priori (because of hello message exchange) selecting a next hop requires a neighbor table look-up and figuring out a neighbor according to the auction scheme. The auction scheme(s) guarantee that ***TGF*** is truthful. Note that the control overhead incurred by ***TGF*** is only due to the hello messages, which are one hop broadcast messages. Thus, the control overhead of ***TGF*** is $O(1)$ per node every t seconds, where t is the hello interval.

3.2 A Hello Protocol

In ***TGF***, nodes resort to *hello* messages to exchange location information so that they can establish and maintain neighbor tables. Neighbor tables help nodes in forwarding control and data packets. The neighbor table consists of multiple entries, each corresponding to a neighbor. A neighbor table entry includes the following fields $<ID_i, Pos_i, Cost_i, TS_i>$, where ID_i is the neighbor node's identity, Pos_i is its last known position, $Cost_i$ is its cost of sending one packet and TS_i is the time of establishing this entry, respectively.

Each node maintains two timers: a hello timer (HT) and a neighbor table flush timer ($NTFT$). Upon the expiration of HT, each node broadcasts a *hello* message. A *hello* message includes the following fields: $<ID, Pos, Cost>$, corresponding to its identity, position and cost of sending a packet, respectively. Upon receiving a *hello* message, neighbors add an entry corresponding to the issuer of the *hello* message into neighbor tables if it is not already present or refresh the entry otherwise. Then the nodes reset the $NTFT$ for this entry. Upon the expiration of $NTFT$, a node check the time-stamp of the entry. If the entry is older than a predetermined period (typically 2 to 3 seconds), then the node deletes it from its neighbor table.

3.3 Packet Forwarding

Generally, geographic routing protocols [21] use greedy forwarding in which a node forwards a packet to a node that is geographically closest to the destination among its neighboring nodes. However, this approach is not suitable in the context of selfish nodes, where nodes are more interested in their cost and payment. To address this issue ***TGF*** takes into account cost of packet forwarding of nodes, and enforces nodes to show their true cost. ***TGF*** uses three forwarding schemes viz., the basic scheme, the restricting bidders scheme and unit price bid scheme.

3.3.1 Basic Forwarding Scheme (BaFS)

Upon receiving a packet destined for a certain node, a node F selects a next hop using the second-price sealed bid auction scheme. All neighboring nodes of F that make progress towards the destination are qualified bidders. From this view the node that is selecting a next hop, i.e., F, is an *auctioneer*. Note that nodes do not bid for each packet. Instead they bid (on a per packet basis) periodically by attaching bids in their periodic *hello* messages. Since the *hello* interval is very short, it is reasonable to assume that nodes' cost will not change during that period.

Let $\mathcal{D}(a, b)$ be the Euclidean distance between node a and node b, and $\mathcal{NB}^a$ be the set of neighboring nodes of a. Then, the qualified bidders $K \in \mathcal{NB}^{\mathcal{F}}$ are nodes that satisfy the condition $\mathcal{D}(K, D) < \mathcal{D}(F, D)$, where D is the destination ID. Denote the set of qualified bidders as $\mathcal{N}$. The winner of the bid is a node $N \in \mathcal{N}$ that seeks the least cost for forwarding packets. The payment to N will be the second least bid among nodes in $\mathcal{N}$. If there are more than one neighboring node seeks the least bid value, the node making the maximum progress towards the destination (i.e., having $min(\mathcal{D}(K, D))$) will be the winner. However, the payment to this node is the same as its bid since the second lowest bid equal the lowest bid. After selecting the next hop node N, F adds the node identity N and its payment Pay^N to the packet header, and forwards the packet to node N. Under the assumption that nodes are selfish but not malicious, a forwarding node N is not supposed to modify its payment Pay^N.

However, to avoid such modifications, two methods can be applied. The first method resorts to the cryptography. Besides items N and Pay^N, F calculates a MAC (Message Authentication Code) over these two items, digitally signs it with its private key, and appends this MAC to the packet. When the destination receives the packet, it can verify the amount of payments. The second method resorts to neighbor monitoring. Neighbor monitoring is a key technology in detection-based methods for selfish nodes problem. Each node works in the promiscuous mode and can overhear packets transmitted by nodes within the radio range. To prevent the modification of payment amount Pay^N, each neighboring node of F saves the overheard packet P sent to N in its buffer. Upon overhearing the instance of packet P sent out from node N, they compare the corresponding header area of two instances of packet P and check if Pay^N is modified or not. We leave such extension as our future work.

3.3.2 Average Plus Forwarding Scheme (A$^+$FS)

In the basic scheme, each node making progress towards the destination is a potential next hop. However, it is possible that the lowest bidder selected using the basic scheme may make the least progress (among the potential next hops) towards the destination. Thus, the basic forwarding scheme can increase the number of hops, resulting in a higher total payment. Hence, it is desirable to reduce the total cost as long as the truthfulness is guaranteed.

If an auctioneer selects only those nodes making *enough* progress towards the destination as qualified bidders, then the average hop count to the destination will be reduced. To achieve this, an auctioneer calculates the average distance ($AvgDst$) over all neighboring nodes that are closer to the destination than the auctioneer. It selects only nodes that make progress more than $AvgDst$ towards the

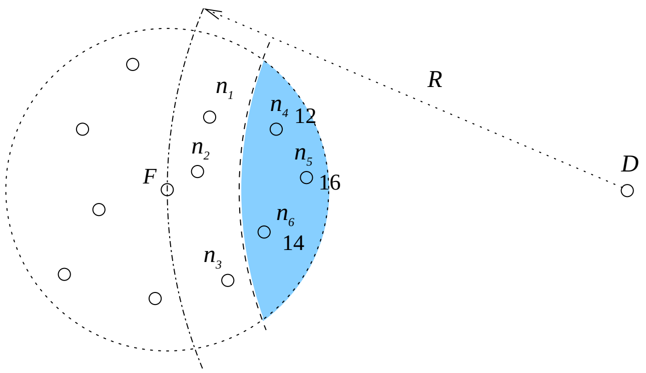


Figure 1: Illustration of average plus forwarding scheme (A^+FS)

destination as the qualified bidders (QB'). The bidder with the lowest bid in QB' will win the auction. Its payment will be the second least bid in QB'. If there are less than two qualified nodes in QB', then the auction fails. In such a case, the auctioneer returns to the BaFS, i.e., sets all nodes making progress towards the destination as the qualified bidder, and selects the lowest bidder as the winner.

Figure 1 illustrates an example of the A^+FS. In the figure, F is the auctioneer and the dotted circle denotes the radio range of F. R denotes the distance from F to the destination D. Nodes $n_k, k \in [1, 6]$ are the neighbors of F that are closer to the destination than F. The dashed line denotes $AvgDst$ of these six nodes. Thus only nodes in the shadowed area, n_4, n_5 and n_6, are the qualified bidders (i.e., belong to QB'). Among these nodes, n_4 has the lowest bid (12) and n_6 has the second lowest bid (14). Thus n_4 will be the winner of the auction and gets payment of 14.

3.3.3 Unit Price Bid

In both the BaFS and A^+FS, bidders quote their bids for sending a packet and the lowest bidder wins the auction. An alternative way for bidding in both schemes is to use the price of unit progress as a criterion. In this case, the bidder asking the least price per unit progress will be the winner. For example, in BaFS the auctioneer F selects all neighboring nodes that make progress towards the destination D as qualified bidders (QB). Based on the bid b_i value and progress ($\mathcal{D}(n_i, D) - \mathcal{D}(F, D)$) of each node $n_i \in QB$, F calculates the unit price of each node n_i as

$$\mu_i = \frac{b_i}{(\mathcal{D}(n_i, D) - \mathcal{D}(F, D))}.$$

The auctioneer F selects the node with the least μ_i, denoted as n_s, as the next hop. The payment to n_s will be made according to the unit price instead of the bid for the packet. The next hop node, n_s, gets the unit payment as the second least unit price among QB, denoted as μ'. Thus, the payment to the node n_s per packet will be $\mu' * (\mathcal{D}(n_s, D) - \mathcal{D}(F, D))$.

4 Analysis of *TGF*

In this section, first we show that truthful bidding is the dominant strategy for each node for BaFS, A^+FS and unit price bid schemes. Second, we present an analysis of progress made per hop for both BaFS and A^+FS schemes.

4.1 Truthfulness of *TGF*

Theorem 1. *In the BaFS, bidding the true cost is the dominant strategy for every qualified bidder.*

Proof. Suppose a bidder i with true cost v_i declares a bid b_i. Let i's utility be u_i. Denote the minimum bid besides b_i as m^{-i}, and the distance between i and the destination D as $\mathcal{D}_i$. According to the auction rule, the utility u_i of a bidder is

$$u_i = \begin{cases} m^{-i} - v_i, & b_i < m^{-i} \\ m^{-i} - v_i, & b_i = m^{-i} \wedge \mathcal{D}_i = \underset{\forall j \in \text{bidders}}{min} \{\mathcal{D}_j\} \\ 0, & b_i > m^{-i} \end{cases}$$

There are two possibilities: Bidder i may over-bid or under-bid its cost v_i.

Case of over-bidding: If the bid is higher than the cost, i.e., $b_i > v_i$, then there are five possibilities.

1) If $b_i < m^{-i}$, then i wins the auction and $u_i = m^{-i} - v_i$. However, i can get the same payoff by bidding its cost v_i.
2) If $v_i < m^{-i} < b_i$, then i loses the auction and gets zero payoff. However, by bidding v_i, it can get a positive payoff.
3) If $m^{-i} < v_i$, then i gets zero payoff, the same as it could have gotten by bidding v_i.
4) If $m^{-i} = b_i$ and $\mathcal{D}_i = \underset{\forall j \in \text{bidders}}{min} \{\mathcal{D}_j\}$, then i gets the same payoff as by bidding v_i.
5) If $m^{-i} = b_i$ and $\mathcal{D}_i \neq \underset{\forall j \in \text{bidders}}{min} \{\mathcal{D}_j\}$, then i loses the auction and gets zero payoff. However, by bidding v_i it can get a positive payoff.

Thus, i has no incentive for over-bidding.

Case of under-bidding: If the bid is lower than the cost, i.e., $b_i < v_i$, then there are five possibilities.

1) If $v_i < m^{-i}$, then i gets payoff $m^{-i} - v_i$, the same as it could have gotten by bidding v_i.
2) If $b_i < m^{-i} < v_i$, then i gets negative payoff as $m^{-i} - v_i < 0$. However, by bidding v_i, i gets zero payment, which is better than a negative payoff.
3) If $b_i > m^{-i}$, then i gets zero payoff, the same as it could have gotten by bidding v_i.

4) If $b_i = m^{-i}$ and $\mathcal{D}_i = \min_{\forall j \in \text{bidders}} \{\mathcal{D}_j\}$, then i gets $m^{-i} - v_i < 0$. However, by bidding v_i, i gets zero payment, which is better than a negative payoff.

5) If $b_i = m^{-i}$ and $\mathcal{D}_i \neq \min_{\forall j \in \text{bidders}} \{\mathcal{D}_j\}$, then i gets zero payoff, the same as it could have gotten by bidding v_i.

Thus, i has no incentive for under-bidding.

In both the cases i's dominant strategy is to bid its cost v_i -hence the theorem. □

Corollary 1. *In the A^+FS, bidding the true cost is the dominant strategy for each node.*

Proof. There are only two possibilities.

1) There is more than one node in QB' (refer to A^+FS algorithm). Only nodes in QB' are qualified bidders. They may over-bid or under-bid their cost. However, from Theorem 1, their dominant strategy is to bid their true cost.

2) There is at most one node in QB'. In this case, the auction for QB' cannot be set up. Thus the auctioneer sets up the auction as in BaFS. From Theorem 1, the dominant strategy is to bid their true cost.

□

Theorem 2. *In the unit price bid scheme along with BaFS, bidding the true cost is the dominant strategy for each bidder.*

Proof. Suppose a bidder i with true cost v_i bids with a value b_i, and let i's utility is u_i. Denote $\mathcal{D}(F, D) - \mathcal{D}(i, D)$ as δ_i, where F is the position of the auctioneer, and the minimum unit bid besides i as t^{-i}. The utility of a node (qualified bidder) i is

$$u_i = \begin{cases} t^{-i}\delta_i - v_i, & \frac{v_i}{\delta_i} < t^{-i} \\ t^{-i}\delta_i - v_i, & \frac{v_i}{\delta_i} < t^{-i} \wedge \mathcal{D}_i = \min_{\forall j \in \text{bidders}} \{\mathcal{D}_j\} \\ 0, & \frac{v_i}{\delta_i} > t^{-i} \end{cases}$$

Bidder i may over-bid or under bid its cost v_i.

Case of over-bidding: The bid is higher than the cost, i.e., $b_i > v_i$, then there are five possibility.

1) If $b_i/\delta_i < t^{-i}$, then i wins the auction and gets the payoff as $t^{-i}\delta_i - v_i$. However, i can get the same payoff by bidding its cost v_i.

2) If $v_i/\delta_i < t^{-i} < b_i/\delta_i$, then i loses the auction it should win and gets zero payoff. By bidding v_i, it can get a positive payoff.

3) If $t^{-i} < v_i/\delta_i$, then i gets zero payoff, the same as by bidding its cost v_i.

4) If $t^{-i} = b_i/\delta_i$ and $\mathcal{D}_i = \min_{\forall j \in \text{bidders}} \{\mathcal{D}_j\}$, then i gets the same payoff as by bidding v_i.

5) If $t^{-i} = b_i/\delta_i$ and $\mathcal{D}_i \neq \min_{\forall j \in \text{bidders}} \{\mathcal{D}_j\}$, then i loses the auction it should win and gets zero payoff. By bidding v_i, it can get a positive payoff.

Thus, i has no incentive for over-bidding.

Case of under-bidding: The bid is lower than the cost, i.e., $b_i < v_i$, then there are five possibilities.

1) If $v_i/\delta_i < t^{-i}$, then i gets payoff $t^{-i}\delta_i - v_i$, the same as by bidding v_i.

2) If $b_i/\delta_i < t^{-i} < v_i/\delta_i$, then i gets a negative payoff as $t^{-i}\delta_i - v_i < 0$. By bidding v_i, i gets zero payoff, which is better than a negative payoff.

3) If $b_i/\delta_i > t^{-i}$, then i gets zero payoff, the same as by bidding v_i.

4) If $b_i/\delta_i = t^{-i}$ and $\mathcal{D}_i = \min_{\forall j \in \text{bidder}} \{\mathcal{D}_j\}$, then i gets $t^{-i}\delta_i - v_i < 0$. By bidding v_i, i gets zero payoff, which is better than a negative payoff.

5) If $b_i/\delta_i = t^{-i}$ and $\mathcal{D}_i \neq \min_{\forall j \in \text{bidder}} \{\mathcal{D}_j\}$, then i gets zero payoff, the same as by bidding v_i.

Thus, i has no incentive for under-bidding.

In both the cases i's dominant strategy is to bid its cost v_i -hence the theorem. □

Corollary 2. *In the unit price bid scheme along with A^+FS, bidding the true cost is the dominant strategy for each bidder.*

Proof. Follows from Theorem 2 and Corollary 1. □

4.2 Average Progress Made Per Hop in BaFS

Intuitively, selecting a next hop towards the destination based on the Euclidean distance makes most progress compared to that based on BaFS. However, the greedy distance based forwarding *does not guarantee truthfulness.* On the other hand, progress made per hop (towards the destination) is another important design issue for forwarding algorithms. Thus, we statistically analyze the average progress made per hop in BaFS.

In the basic scheme, a node F selects a neighbor with the least bid as next hop. Let $\mathcal{N}$ be the set of neighbors that are closer to the destination D than F, such that $m = |\mathcal{N}|$. Let ξ be the random variable representing the next hop location, then the expected next hop location is

$$E_\xi = \sum_{i=1}^{m} p_i l_i \ .$$

where p_i is the probability that node i is selected as the next hop, and l_i is i's location. Since i's cost is independent of its location, every node $i \in \mathcal{N}$ has the same probability to be the least bidder. Thus p_i is same for all $i \in \mathcal{N}$. Thus,

$$E_\xi = \frac{1}{m}\sum_{i=1}^{m} l_i \ .$$

If m is large enough, under the assumption of uniform distribution, discrete random variable ξ can be considered as a continuous variable ξ', thus

$$E_{\xi'} = \int l\rho(l)dl \ .$$

where $\rho(l)$ is the probability density function of location. One way to interpret this change in variable is as follows: even though m is small, if such next hop selection runs many times, from the statistical point, it is reasonable to use the expected continuous variable ξ' to estimate the expectation of discrete variable ξ.

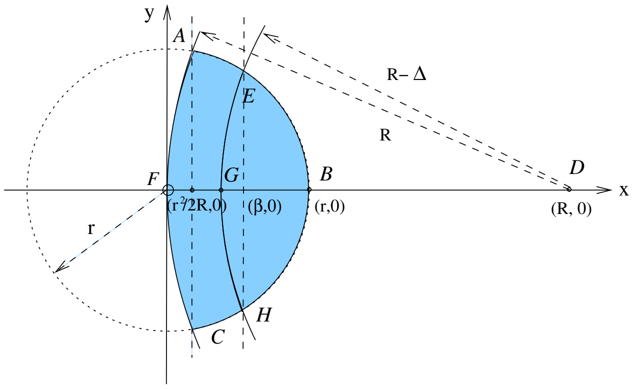


Figure 2: Expected position of a next hop node

The next question is how to calculate ξ'. Under the assumption of uniform distribution, ξ' is just the center of geometry of the shaded area in Figure 2. In the figure, the line connecting the auctioneer F and the destination D is set as x-axis. Without the loss of generality let F be at the origin (0,0), and D be at (R,0). Due to the symmetry of upper part and lower part, ξ' must be located on the x-axis, i.e., its y-coordinate equals to zero. Denote the radio range of node F as r and the distance from F to D as R. ξ''s x-coordinate is calculated as follows:

$$\begin{aligned} E_{\xi'_x} &= \frac{\iint_{FABCF} xdxdy}{\iint_{FABCF} dxdy} \\ &= \frac{\int_0^{\frac{r^2}{2R}} x\sqrt{R^2-(x-R)^2}dx + \int_{\frac{r^2}{2R}}^{r} x\sqrt{r^2-x^2}dx}{\int_0^{\frac{r^2}{2R}} \sqrt{R^2-(x-R)^2}dx + \int_{\frac{r^2}{2R}}^{r} \sqrt{r^2-x^2}dx} . \end{aligned} \quad (1)$$

Since both F and ξ' are on the x-axis, the average progress in the BaFS is $|E_{\xi'_x}|$.

4.3 Average Progress Per Hop in A$^+$FS

In A$^+$FS only those nodes making more progress than $AvgDst$ will be qualified as bidders. As shown in Figure 2, only nodes in the enclosed area $EBHGE$ can be probable candidates to be selected as the next hop. Statistically, the expectation of next hop's position is the geometric center of the shaded area of $EBHGE$ in Figure 2, which can be calculated similar to the geometric center of $FABCF$ if we have G's x-coordinate (for convenience denoted as Δ). With uniform distribution, G is the geometry center of area $FABCF$. Thus Δ can be calculated from Equation 1. Using the value of Δ, the expectation of next hop's x-coordinate can be calculated, similar to the basic scheme as

$$\begin{aligned} E_{\xi'_x} &= \frac{\iint_{EBHGE} xdxdy}{\iint_{EBHGE} dxdy} \\ &= \frac{\int_\Delta^\beta x\sqrt{(R-\Delta)^2-(x-R)^2}dx + \int_\beta^r x\sqrt{r^2-x^2}dx}{\int_\Delta^\beta \sqrt{(R-\Delta)^2-(x-R)^2}dx + \int_\beta^r \sqrt{r^2-x^2}dx} \quad (2) \\ & where\ \beta = \frac{2\Delta R - \Delta^2 + r^2}{2R} . \end{aligned}$$

Thus the average progress made by A$^+$FS is $|E_{\xi'_x}|$.

Table 1 shows the expected progress made using the BaFS and the A$^+$FS with respect to ratio of r/R.

r/R	BaFS	A$^+$FS
2	0.466r	0.721r
3	0.453r	0.702r
4	0.446r	0.693r
5	0.442r	0.687r
6	0.439r	0.682r

Table 1: Expected progress made toward the destination

5 Performance Evaluation

To evaluate the performance of proposed schemes, we conducted extensive simulations using GloMoSim[2]. Unless specified otherwise, the following parameters were used in the simulations. 100 nodes were initially placed uniformly in an area of 600m by 1500m. Nodes used a radio range of 250 meters, and picked a cost randomly between 10 and 30. All nodes followed Random Waypoint mobility model [8] with a maximum speed of 0 m/s to 10 m/s and a pause time of 30 seconds. Each simulation lasted for 900 seconds. To generate the traffic we simulated 10 CBR flows. Each flow sent four 512-byte data packet per second, started at 120 seconds and ended at 880 seconds. Nodes used the 802.11 protocol with DCF as the MAC protocol. Data points represented in graph were averaged over 10 simulation runs, each with a different seed. Simulations focus on the following five metrics:

- Packet delivery ratio. It is the percentage of the total number of packets received by the intended receivers to the total number of packets originated by all nodes.

[2]http://pcl.cs.ucla.edu/projects/glomosim/

- Average hop count. This is the average number of hops needed from a source to a destination.
- Average end-to-end delay. This is the average delay incurred by all packets received by the intended receivers.
- Overpayment ratio. This is the ratio of payment for all intermediate nodes to their cost.
- Total payment. This is the total amount paid to all intermediate nodes.

Note that ***TGF** does not* introduces any additional control packets compared to the pure geographic forwarding algorithm. In both the algorithms, the overhead is only due to the *hello* messages. ***TGF*** needs only one additional field (4 bytes) in each *hello* message. The overhead incurred by the ***TGF*** is .66 hello packet per node per second.

Since ***TGF*** is the first algorithm to address truthfulness in the context of geographic forwarding, we compared the results among the proposed different schemes. In the following discussion and in the graphs, UiFS represents unit price bid scheme along with BaFS, and DIST represents the distance-based greedy forwarding. Our simulation emphasized on the effect of node mobility and the effect of the number of nodes on the proposed schemes.

5.1 Effect of Mobility

5.1.1 Packet Delivery Ratio

Figure 3(a) shows the packet delivery ratio with respect to maximum node speed. All the four schemes show almost identical behavior, and deliver more than 99% of packets. With the given node density, nodes in various schemes can find feasible next hops and forward packets to the destinations. As the mobility increases, the packet delivery ratio drops slightly. This is because with the fixed *hello* message interval, the neighbor information is more likely to be outdated. Thus, a supposed neighbor may have already moved out of the radio range, resulting in more packets being dropped.

5.1.2 Average Hop Count

Figure 3(b) shows the average hop count for a packet to reach the destination with respect to maximum node speed. We observed that different schemes result in different hop counts, in the descending order of BaFS, A^+FS, UiFS and DIST. DIST needs lowest average hop count since it always selects the node closest to the destination as the next hop. BaFS needs more hops than other schemes since it does not take into account the progress (distance) while selecting a next hop. A^+FS needs less hops than BaFS because it selects a node that makes enough progress towards the destination as the next hop. In UiFS, the more closer a node is to the destination, the lesser its unit price, and the higher the probability of the node being selected as the next hop. In other words, nodes making more progress towards the destination are more likely (depending upon their bid value) to be selected as the next hop. For all schemes, more hop counts are needed in a static network than in a mobile network. This is because mobility randomizes the position of source-destination pairs as well as the intermediate nodes, and increases the network connectivity.

5.1.3 End-to-end Delay

Figure 3(c) shows the end-to-end delay with respect to maximum node speed. We observed that performance of all schemes are similar to those in Figure 3(b), and curves here are identical to their corresponding parts: DIST has the shortest end-to-end delay, followed by UiFS, then A^+FS, with BaFS incurring the largest delay. This is because the more hops a packet travels, the more delay it incurs. Nevertheless, the delay difference between various schemes are very small.

5.1.4 Overpayment Ratio

Figure 3(d) shows the overpayment ratio with respect to maximum node speed. BaFS has the lowest overpayment ratio since it always finds the lowest bidder and pays it with the second lowest bid. A^+FS has a slightly higher overpayment ratio than BaFS since the bidders in this scheme constitute only a fraction of those in BaFS. UiFS incurs highest overpayment ratio. In UiFS, the second least unit price multiplying the distance progress made towards the destination, instead of the second least bid, will be paid to the winner. Thus, the scheme incurs higher overpayment than the other schemes.

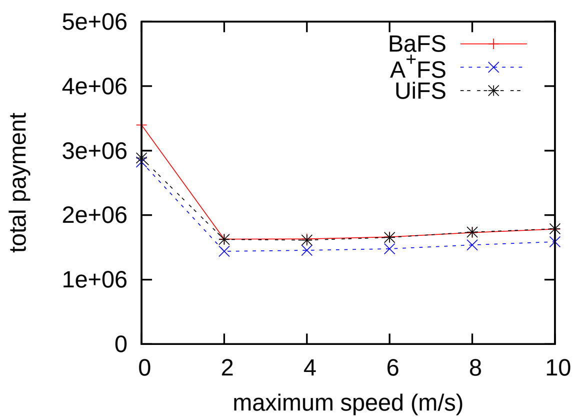
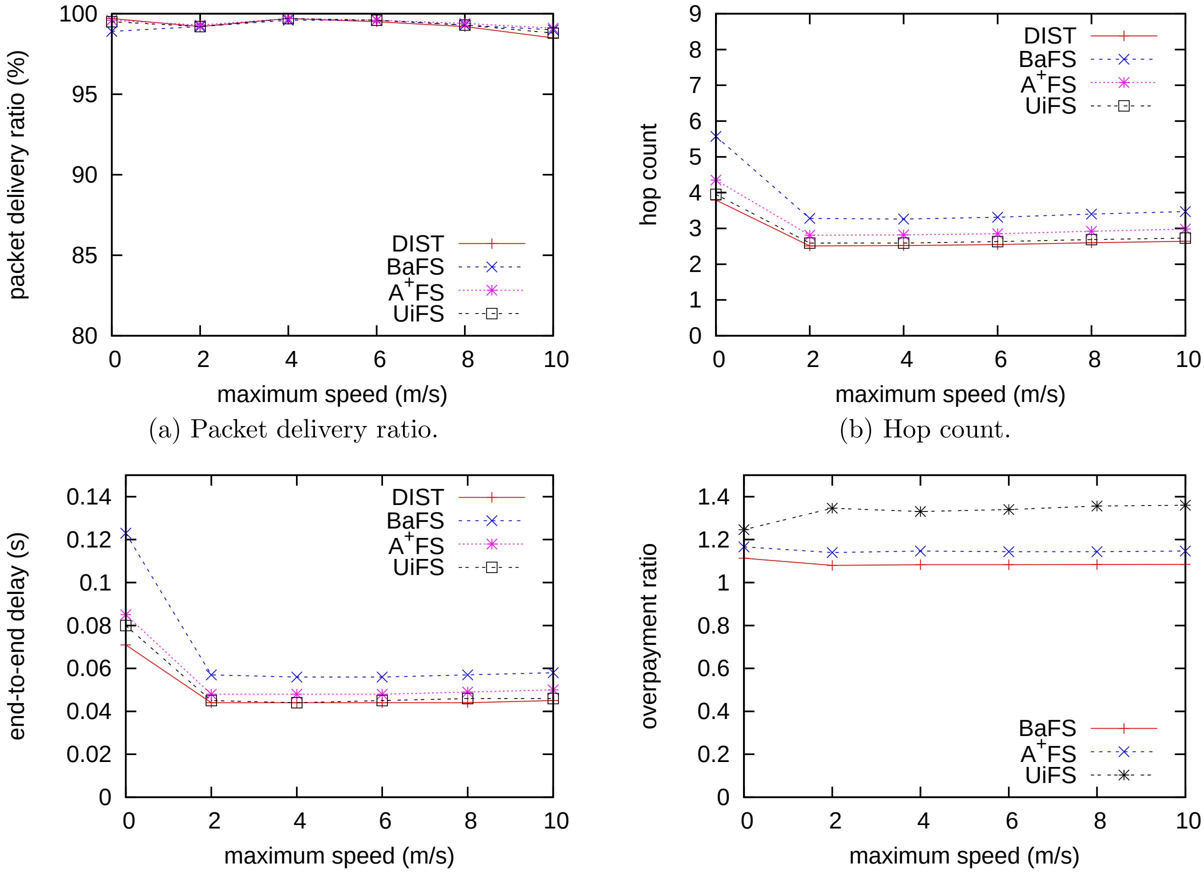


Figure 4: Payment of different schemes with respect to mobility

5.1.5 Total Payment

Figure 4 shows the total payment incurred with respect to maximum node speed. A^+FS needs the least total payment. Although its overpayment ratio is a little bit



(a) Packet delivery ratio. (b) Hop count.

(c) End-to-end delay. (d) Overpayment ratio.

Figure 3: Performance of different schemes with respect to mobility

higher than that of BaFS, it needs less hops. The decrease in the average hop count over-weighs the increase in the overpayment ratio, and thus the overall payment is less than the other two schemes. UiFS needs fewer hops but incurs higher overpayment ratio, whereas BaFS incurs lowest overpayment ratio but needs the highest hops. Overall, UiFS and BaFS incur similar amount of payment.

The above result shows that A$^+$FS has a low end-to-end delay and incurs the least total payment, and thus performs better than BaFS and UiFS from the stand point of source nodes.

5.2 Effect of Node Density

5.2.1 Packet Delivery Ratio

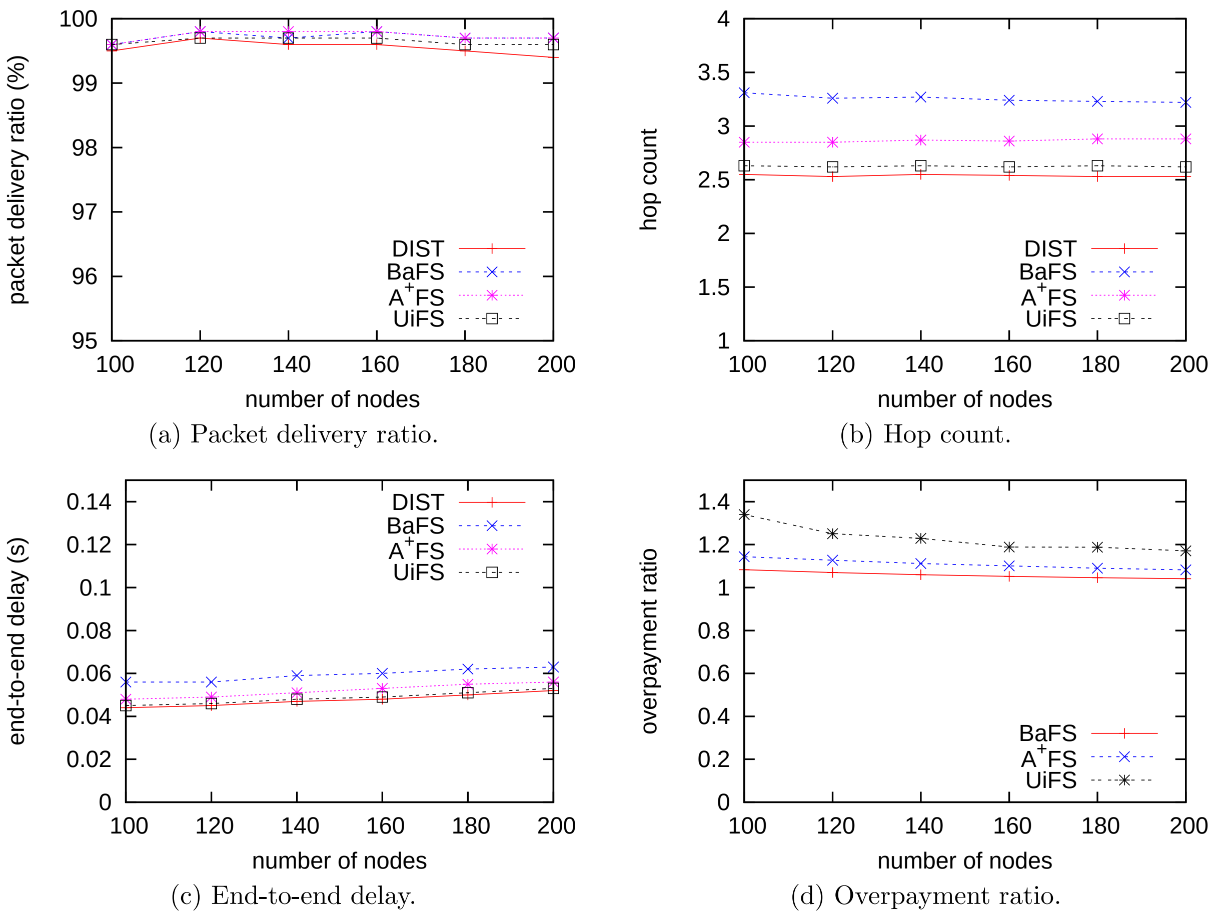
Figure 5(a) shows the packet delivery ratio with respect to node density, with a maximum node speed of 6 m/s. All the four schemes show almost identical behavior, and deliver more than 99.4% packets to the destinations. DIST delivers a slightly fewer packets than the other three schemes. This is because DIST always select the node closest to the destination, and it is more likely to be far away from the sender than those selected by other schemes. Under mobile scenarios, such nodes are more likely to move out of the sender's radio range, resulting in more packets being dropped.

5.2.2 Average Hop Count

Figure 5(b) shows the average hop count for a packet to reach the destination with respect to node density, with a maximum node speed of 6 m/s. We observed that different schemes result in different average hop counts, due to the reason discussed in Section 5.1.2. As the node density increases, the average hop count incurred by DIST, A$^+$FS and UiFS change little while that incurred by BaFS decreases a little bit.

5.2.3 Average End-to-end Delay

Figure 5(c) shows the end-to-end delay with respect to the node density, with a maximum node speed of 6 m/s. As the node density increases, the end-to-end delay increases a little for all four schemes. With a fixed *hello* message interval, an increase in the number of nodes incurs more *hello* messages, resulting in more contention for the radio channel. Thus, data messages are likely to need more time to get the channel, resulting in a longer delay. Nevertheless, all these end-to-end delays are very low as



(a) Packet delivery ratio. (b) Hop count.

(c) End-to-end delay. (d) Overpayment ratio.

Figure 5: Performance of different schemes with respect to node density

the highest one is only 0.063 second.

5.2.4 Overpayment Ratio

Figure 5(d) shows the overpayment ratio with respect to node density, with a maximum node speed of 6 m/s. As the node density increases, the overpayment ratio decreases for all the three auction-based schemes, especially for BaFS. With a fixed cost range, an increase in nodes is more likely to decrease the cost difference between the best bid and the second best bid, i.e., the second best bid is more likely to be close to the best bid.

5.2.5 Total payment

Figure 6 shows the total payment incurred with respect to node density, with a maximum node speed of 6 m/s. A$^+$FS incurs the least payment, UiFS incurs higher payment, and BaFS incurs the highest payment. This is due to the reason discussed in Section 5.1.5. As the node density increases, the total payment decreases for all the three schemes. With a fixed cost range, the more the number of nodes (bidders), the higher the probability that the second best bid is close to the best bid, i.e., the second best bid is more likely to decrease as the node density increases. Since the payment is determined by the second best bid, the total payment will decrease.

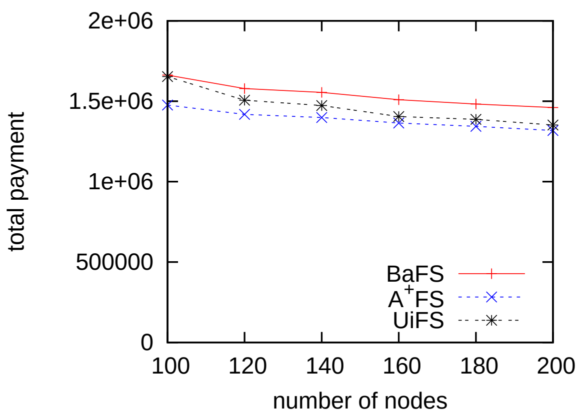


Figure 6: Payment of different schemes with respect to node density

6 Related Work

The problem of nodes cooperation in MANETs has been an active research area [2, 25]. Marti et al. [14] were the first to deal with selfish nodes problem. They proposed two tools, watchdog and pathrater, to mitigate routing misbehavior (including selfish nodes) in ad-hoc networks. Buchegger et al. [3, 4] proposed CONFIDANT protocol to monitor the behavior of nodes, evaluate the reputation of corresponding nodes and punish selfish nodes. Other schemes based on neighbor watching include [15, 16, 17, 22].

The use of virtual money (called nuglet or credit) to stimulate nodes cooperation has been suggested in [5, 6]. A node earns money by providing forwarding service to other nodes and has to pay to get service from other nodes. Security modules independent of nodes are used to protect the nuglets or credit value from modifications and other attacks. Salem et al. [19] proposed a charging and rewarding scheme in multi-hop cellular networks. Fratkin et al. [11] proposed APE (Ad hoc Participation Economy) system, which uses a banker node to assure the payment consolidation and its integrity, to avoid the use of security modules [5]. Zhong et al. [24] proposed a solution, Sprite, for stimulating cooperation among nodes. Every node reports the digest of received or forwarded packets to a central service, Credit Clearance Service (CCS). The CCS determines the charge and credit to each node involved in the packets forwarding. These proposals pay each intermediate node the same amount of money for forwarding a packet. To pay (reimburse) nodes according to their cost is much more challenging, which is not dealt in these proposals.

Srinivasan et al. [20] applied the well-known Prisoners Dilemma problem to address the selfish node in ad hoc networks. They proposed a distributed and scalable acceptance algorithm, called GTFT based on which nodes decide whether to accept a relay request or not. Specifically, each node decides if it will help other nodes for packet forwarding based on if it receives enough help from other nodes. This algorithm does not use the concept of virtual money, i.e., no money will be paid to the intermediate nodes.

Mechanism design was introduced to address selfish nodes problem recently. All proposals [2, 7, 10, 25] aim at topology-based routing. Anderegg and Eidenbenz [2] proposed ad-hoc VCG, the first truthful and cost-efficient routing protocol by applying VCG mechanism to ad-hoc networks. However, it needs global knowledge of the network and incurs a high overhead of $O(n^3)$, where n is the number of nodes in the network, resulting in low network performance. Zhong et al. [25] proposed a similar solution which combines cryptography with VCG mechanism to guarantee the truthfulness. It also requires the global knowledge of the network and incurs even higher overhead than ad-hoc VCG. Chen and Nahrstedt [10] proposed iPass, an auction system for topology-based routing. In iPass, a node sets auction for its own resource (i.e., battery power and bandwidth) instead of its neighbors. Each flow sets a bid for needed bandwidth for all possible intermediate nodes. The auctioneer gives its power and bandwidth to the winner flow which offers the highest price. However, to set the auction, iPass requires that any intermediate node needs at least two flows to pass through it concurrently. Besides, the source pays each intermediate node the same amount of money for packet forwarding, taking no consideration of their cost diversity. Also it didn't specify how to select next hop and thus to find a path from the source to the destination. Cai and Pooch [7] proposed a protocol, named $TEAM$, in an attempt to provide a truthful and low-cost method. In this protocol, a node overhearing a sender and a receiver becomes a re-director of data forwarding, i.e., the sender sends data to the re-director and then the re-director forwards the data to the receiver. The payment to the redirector is the power saving of this redirection. However, it has the following shortcomings. First, the sender saves nothing and gets worse service due to more hops used. Second, the re-director may get less payment than its cost and thus has no incentive to forward packets.

7 Conclusion

Nodes cooperation in multihop ad-hoc networks is a key issue for the proper functioning of routing protocols. While the existing geographic routing protocols for ad-hoc networks exhibit better scalability compared to topology-based routing protocols, they do not address the issue of selfish nodes in ad-hoc networks. In this paper, we presented ***TGF***, a truthful protocol for geographic routing in mobile ad-hoc networks with selfish nodes. ***TGF*** uses auction-based forwarding schemes, viz., BaFS, A^+FS and unit price bid scheme that selects a next hop based on the winner of the auction. To stimulate nodes cooperation, all BaFS, A^+FS and unit price bid scheme provide incentive to nodes forwarding packets properly, and prevent nodes from cheating over their cost. We theoretically proved that all three schemes guarantee truthfulness, i.e., nodes maximize their utilities only when they reveal their true cost. We also statistically analyze the average progress made per hop for BaFS and A^+FS. Our simulation results show these schemes provide high packet delivery ratio and have low average hop count and low end-to-end delay without compromising the overpayment to the nodes.

Acknowledgements

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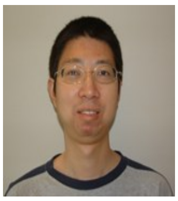

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