Truthful Routing for Wireless Hybrid Networks

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***Abstract*— Wireless hybrid networks combine the characteristics of both cellular and mobile ad hoc networks. In wireless hybrid networks, it is often assumed that each individual mobile node will faithfully follow the prescribed protocols without any deviation. However, these mobile devices, when owned by individual users, will likely do what is the most beneficial to their owners, i.e., act "selfishly". Therefore, an algorithm or protocol intended for selfish wireless devices must be designed. In this paper, we specifically study how to design routing protocols in wireless hybrid networks with *selfish* nodes. We first present a VCG-based routing protocol for hybrid networks, and show it is truthful but could be expensive. Then we modify the VCG-based routing protocol to make it more efficient for hybrid networks in term of total payment. However, we prove that nodes could lie up their costs in the modified method. Moreover, we propose a novel routing protocol based on first-price path auctions [1], which can achieve a Nash equilibrium with low total payment.**

Keywords-Non-cooperative computing, truthful routing, game theory, wireless hybrid networks, payment, strategyproof

I. Introduction

Wireless hybrid network is a network consisting of both cellular base stations (or access points) and ad hoc wireless devices. Fig.1 shows an example of wireless hybrid network, which contains 5 access points and 10 mobile devices. Wireless devices can communicate with other devices through either the base stations or an ad hoc path (relayed by small number of other mobile devices). For example, if node l wants to send a message to node z, it can first send the message to access point y and let it forward to z, or it can use node x as the relay node to form a peer-to-peer link. Wireless hybrid networks have several advantages over the pure cellular networks and pure ad hoc networks [2]–[4]. For example, the coverage of the network can be increased due to the extension of ad hoc components. In Fig.1, mobile devices u, n and t are outside the transmission ranges of any access points, however through the ad hoc links they are connected to the network. For the same reason, the number of base stations can also be smaller than the pure cellular networks. Due to these benefits and many potential applications in various areas, wireless hybrid networks recently draw lots of attentions [2]–[7]. Most previous works in hybrid networks deal with various important problems such as routing, QoS, security, power management, and mobility modelling. However, there are still many challenges left.

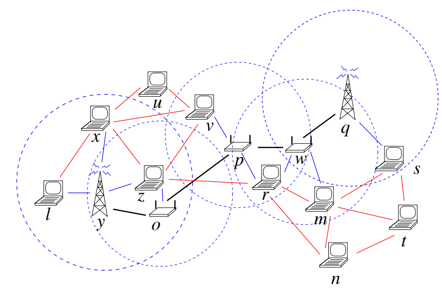


Fig. 1. An example of wireless hybrid networks. Black links are wired links connecting access points, blue links are one-hop wireless links between access points and mobile devices, red links are ad hoc links between mobile devices.

In wireless hybrid networks, a source node communicates with far off destinations by using access points or intermediate nodes as relays. A common assumption made by the majority of wireless routing protocols is that each wireless node will follow the prescribed protocols without any deviation, e.g., a node is always assumed to relay data packets for other nodes if it is asked to do so by the routing protocols. However, this may not be true in reality: the wireless nodes could be owned by individual users and thus they will perform in their own interests; the wireless nodes are often powered by batteries only, thus it is not in the best interest of a node to always forward the data packets for others. If a node refuses to relay the data while the routing protocol assumed that it will, the throughput of the network may decrease and even the network connectivity may be broken. The root cause of the problem is, obviously, there exist no incentives for wireless nodes to be altruistic. Therefore, if we assume that all nodes are selfish and wish to maximize their own net gains at all times, providing incentives to wireless nodes is a must to encourage contribution and thus maintain the robustness and availability of wireless networking systems. Thus, a stimulation mechanism is required to encourage the wireless nodes to provide service to other nodes.

Dealing with selfish users has been well-studied in game theory and economics. Recently, there have been a sequence of results [8]–[10] published in the theoretical computer science area that tried to solve various problems when the agents are selfish and rational. Here an agent is *rational* if it always chooses a strategy that maximizes its own gain. A common setting in all these results is that each agent incurs a cost if it is selected to provide the service. For example, in wireless networks, each node will incur an energy cost when it is asked to relay the data for other nodes. Several protocols [11]–[15] have also been proposed recently to address the non-cooperative issue in wireless ad hoc networks. In this paper, we are interested in designing a routing protocol for wireless hybrid networks that will compensate a relaying node with a monetary value that is at least its actual cost. We first adapt a VCG-based ad hoc routing protocol [16] for hybrid networks, and show that it is truthful (,i.e, nodes reveal their true costs) but could be expensive in term of total payment. Then we try to modify the VCG-based protocol to reduce the payment, but unfortunately we can prove that the modified VCG method is not truthful anymore. Finally, to achieve both truthfulness and efficiency, we propose a novel efficient routing protocol based on first-price path auctions [1].

The rest of this paper is organized as follows. First, we introduce our communication models, the problem to be solved in this paper), and related works in Section II. We then study the strategy-proof mechanisms for truthful routing in hybrid networks in Section III (VCG-based) and Section IV (First-Price-Auction-based). We conclude our paper in Section V.

II. Preliminaries

A. Network Models

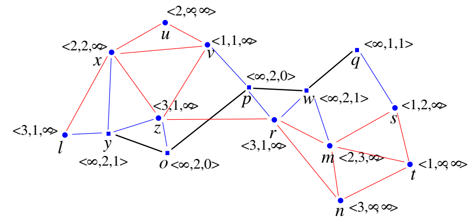
In this paper, we study two different models of wireless hybrid networks: one consisting of mobile devices with unadjustable transmission ranges (node weighted model) and the other consisting of mobile devices with adjustable transmission ranges (link weighted model). For both models, usually the communication links are needed to be symmetric since each receiver has to send an acknowledgment packet directly to the sender after it received the data. Fig.2(a) illustrates the underlying communication graph for the network in Fig.1. Assume that the network has n_{md} mobile devices $V_{md} = \{v_1^{md}, \cdots, v_{n_{md}}^{md}\}$ and n_{ap} access points $V_{ap} = \{v_1^{ap}, \cdots, v_{n_{ap}}^{ap}\}$. Then the communication graph is represented by an undirected graph $G = (V, E)$, where $V = V_{md} + V_{ap}$ is the set of mobile devices and access points, $E = \{e_1, e_2, \cdots, e_m\}$ is the set of links. Here m is the total number of links in the graph G. Let $n = n_{md} + n_{ap}$ be the total number of nodes in the graph.

For the node weighted model, we assume that each mobile device in the network has a fixed transmission range, so that the cost for a mobile device to relay a message is a fixed constant for this device. Since we have three kinds of links in hybrid networks: *ad hoc links* (al), *cellular links* (cl) and *wired links* (wl), we will have a cost triple $c_i = \langle c_i^{al}, c_i^{cl}, c_i^{wl} \rangle$ on each node v_i where the elements are corresponding the costs for relaying message on each type of links. We use different colors (red, blue and black) in Fig.1 and Fig.2 to distinguish the types of links. Then we can define the node weighted model as a node weighted graph $G = (V, E, t, c)$, where $t = (t_1, t_2, \cdots, t_m)$ be the link type vector for all links and $c = (c_1, c_2, \cdots, c_n)$ be the cost vector of all nodes. Fig.2(a) gives an example of the node weighted model. Notice that for mobile device v_i the cost of wired links $c_i^{wl} = \infty$ and for access point v_j the cost of ad hoc links $c_j^{al} = \infty$.

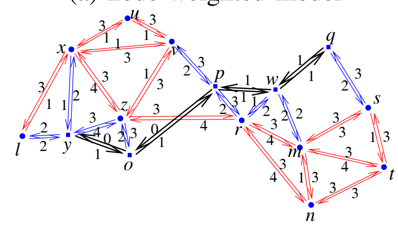
In the link weighted model, each mobile device can adjust it transmission range regarding the demand of communication. This will be much more power efficient for each device and the network. Therefore, we model the communication graph as a directed link weighted graph $\overrightarrow{G} = (V, E, c)$, where a constant c_i is the relaying cost for link e_i, for $1 \le i \le 2m$. Fig.2(b) gives an example of the link weighted model. Notice that all costs of the links $\overrightarrow{v_i v_j}$ coming from a node v_i are only known by node v_i. The costs of links are unsymmetric, i.e., $c_{\overrightarrow{v_i v_j}}$ may not equal $c_{\overrightarrow{v_j v_i}}$, since they are measured by two different nodes v_i and v_j based on their own views.

One important observation is that the node weighted model can be converted into the link weighted model. This can be done by assigning the corresponding node weights to each outgoing links from that node. Therefore, we will only use the link weighted model to demonstrate our protocols hereafter.

The following assumptions are adopted in this paper: (1) each mobile device is selfish and *rational*: it tries to maximize its own benefit; (2) the cost to relay a transit traffic for each node is a private information, it is only known by the node itself by considering all facts which may affect its own benefit (such as remaining power, transmission range, environment, etc.); (3) access points are cooperative, i.e. they will reveal their costs[1] truthfully, since they are owned by the network service provider; (4) the source of the routing will pay the selected relay nodes; (5) the network is *bi-connected*, which implies that if we remove a node the network is still connected. The last assumption is necessary to prevent some nodes from being monopoly and charging arbitrary cost, in addition to increase network robustness.



(a) node weighted model



(b) link weighted model

Fig. 2. Network models: all symmetric links in the network shown in Fig.1. Here disks represent mobile devices, while squares represent access points.

[1] We can also set the costs of access points as zeros, if we consider that the mobile user already pay the service fee to the network service provider. However, in this paper, we assume the user still need to pay the network service provider for particular uses of the access points for relaying messages.

B. Problem Statement

If a mobile node v_i wants to send data to another mobile device v_j, typically, the path with minimum sum of relaying cost (least cost path), say $\mathsf{LCP}(v_i, v_j, c)$, is used to route the packets. We use $\|\mathsf{LCP}(v_i, v_j, c)\|$ to represent the sum of the relaying cost of $\mathsf{LCP}(v_i, v_j, c)$. To stimulate cooperation among all wireless nodes, node v_i pays some nodes of the network to forward the data for it. Thus, each node v_l on the network declares a cost d_l (a cost triple in the node weighted model or a set of costs for all outgoing links in the link weighted model), which is its claimed cost to relay the packets. Note that here d_l could be different from its true cost c_l. Then the routing algorithm selects a route P (such as the least cost path $\mathsf{LCP}(v_i, v_j, d)$) according to the declared cost vector d. For each node v_l, node v_i computes a payment $p_{ij}^l(d)$ according to the declared cost vector d. The *utility*, in standard economic model, of node v_l is $u^l = p_{ij}^l(d) - x_l(ij) \cdot c_l$, where $x_l(ij)$ indicates whether v_l relays the packet. We always assume that the wireless nodes are rational: it always tries to maximize its utility u^l. Here, the cost c_i is based on per packet or per session, whichever is appropriate. If the payment scheme is not well-designed, a node v_j may improve its utility by lying its cost, i.e., declares a cost d_j such that $d_j \neq c_j$. The objective of this paper is then to design a payment scheme such that each node v_j has to declare its true cost, i.e., $d_j = c_j$, to maximize its utility. Using the standard assumption from economic model, we assume that the wireless nodes do *not* collude to improve their utility. In summary, we want to design strategy-proof routing protocols for a selfish wireless hybrid network with the following properties. 1) *Incentive Compatibility*: a mobile device will reveal its true cost to maximize its utility no matter what the other devices do. 2) *Individual Rationality*: a mobile device is guaranteed to have non-negative utility if it reports its type truthfully no matter what other devices do. 3) *Polynomial Time Computability*: all computations (the computation of the output and the payment) are done in polynomial time.

C. Priori Arts

The most well-known and widely used incentive based method to solve the non-cooperative problem is so called VCG mechanism family. Several mechanisms [16]–[18], which essentially belong to VCG mechanism family, have been proposed in the literature to assure the cooperation for routing problem in a general network.

Routing has been an important part of the algorithmic mechanism-design from the very beginning. Nisan and Ronen [17] provided a polynomial-time strategyproof mechanism for optimal unicast route selection in a centralized computational model. In their formulation, the network is modelled as an abstract graph $G = (V, E)$. Each edge e of the graph is an agent and has a private type t_e, which represents the cost of sending a message along this edge. The mechanism-design goal is to find a least cost path $\mathsf{LCP}(x, y)$ between two designated nodes x and y. The valuation of an agent e is $-t_e$ if the edge e is part of the path $\mathsf{LCP}(x, y)$ and 0 otherwise. Nisan and Ronen used the VCG mechanism for payment.

Feigenbaum *et. al* [18] then addressed the truthful low cost routing in a different network model. They assume that each node k incurs a transit cost c_k for each transit packet it carries. For any two nodes i and j of the network, $T_{i,j}$ is the intensity of the traffic (number of packets) originating from i and destined for node j. Their strategyproof mechanism again is essentially the VCG mechanism. They gave a distributed method such that each node i can compute a payment $p_{ij}^k > 0$ to node k for carrying the transit traffic from node i to node j if node k is on the $\mathsf{LCP}(i, j)$. Anderegg and Eidenbenz [16] recently proposed a similar routing protocol for wireless ad hoc networks based on VCG mechanism again. They assumed that each link has a cost and each node is a selfish agent.

There is a vast literature on the mechanism design or implementation paradigm in which some mechanisms are designed to achieve the socially desirable outcomes in spite of users' selfishness. Some of these approaches use Nash equilibrium rather than dominant-strategy (VCG uses dominant-strategy). That is, they assumed that simultaneous selfish play leads to a self-consistent Nash equilibrium, in which no agent can improve its utility by deviating from its current strategy when other agents keep their strategies.

Recently, Salem *et al.* [7] proposed an incentive mechanism that is based on a charging/rewarding scheme and that makes collaboration rational for selfish nodes in hybrid networks. However, they paid a fixed payment to relay nodes for unit packet without considering the costs which relay nodes spent.

III. VCG-based Truthful Routing

A. Truthful VCG-based Payment Scheme

Our VCG-based payment scheme is similar with the ad hoc one [16], except some special handling with access points.

Assume that the node v_s has to send a packet to v_t through the relay of some other nodes. It pays these relay nodes to compensate their costs (a set of costs for their outgoing links) for carrying the transit traffic incurred by v_s. The output of the algorithm is the path connecting v_s and v_t with the minimum cost, which is known as $\mathsf{LCP}(v_s, v_t, d)$. Assume $\mathsf{LCP}(v_s, v_t, d) = v_s, \cdots, v_k, v_l, \cdots, v_t$. The payment scheme is based on the VCG. The payment for node v_k is

$$p_{st}^k(d) = \begin{cases} 0, & if \quad v_k \notin \mathsf{LCP}(v_s, v_t, d) \\ d_{v_k v_l}, & if \quad v_k \in \mathsf{LCP}(v_s, v_t, d) \cap V_{ap} \\ \|\mathsf{LCP}_{-v_k}(v_s, v_t, d)\| - \|\mathsf{LCP}(v_s, v_t, d)\| + d_{v_k v_l}, & \\ & if \quad v_k \in \mathsf{LCP}(v_s, v_t, d) \cap V_{md} \end{cases} \tag{1}$$

Here $\mathsf{LCP}_{-v_k}(v_s, v_t, d)$ denotes the least cost path between node v_s and v_t if we remove node v_k and all its adjacent links from the original graph. Notice that for an access point v_k in $\mathsf{LCP}(v_s, v_t, d)$ the payment is just its claim cost $d_{v_k v_l}$, since we always assume the access points are cooperative, i.e, they always claim their true costs.

For example, assume we want to send an unit packet from node r to node t in Fig.2(b). The most cost-efficient path is $\mathsf{LCP}(r, t, d) = r, w, q, s, t$ with $\|\mathsf{LCP}(r, t, d)\| = 2 + 1 + 2 + 1 = 6$. Since nodes w and q are access points, the payments are their claim costs (also true costs), i.e., $p^w_{rt}(d) = 1$ and $p^q_{rt}(d) = 2$. For mobile device s, we need to calculated its payment. The shortest path without node s is $\mathsf{LCP}_{-s}(r,t,d) = r,n,t$ with $\|\mathsf{LCP}_{-s}(r,t,d)\| = 4+3 = 7$. Thus, we have the VCG payment for node s $p^s_{rt}(d) = 7-6+1 = 2$.

This payment falls into the VCG mechanism, so it is strategy-proof. In other words, the mechanism satisfy *incentive compatibility* property: if $d_{kl} = c_{kl}$, node v_k maximizes its utility $p^k_{st}(d) - x_k \cdot c_{kl}$. Here $x_k = 1$ if $v_k \in \mathsf{LCP}(v_s, v_t, d)$, otherwise $x_k = 0$. Also it is not hard to prove that the other two properties: *individual rationality* and *polynomial time computability*. All the proofs are similar those in [16] and [17]. Due to space limit we ignore them here.

B. Inefficiency and Simple Modification Does Not Work

The VCG mechanism has the attractive property that the each node's dominant strategy is to reveal its true cost, however, the VCG mechanism can lead to the customer paying far more than the true cost of the cheapest path. The overpayment is because a bonus needs to be paid to every relay node on the path. Remember in Equation (1), node v_s pays each mobile node v_k on $\mathsf{LCP}(v_s, v_t, d)$ more than its actual cost to make sure that it will not lie about its cost. The overpaid value is the improvement of the LCP due to the existence of node v_k. It is not difficult to construct a network example such that the over-payment of a node v_k could be arbitrarily large. This is extraordinary inefficient for wireless networks. Consider the network shown in Fig.3, the node v_i for $1 \le i \le n+1$ are the mobile devices while v_{n+2} is the access point. Assume that we want to send packet from node v_s to v_t. The least cost path is $v_s, v_1, v_2, \cdots, v_n, v_t$ with cost n. Using VCG mechanism, the payment to node v_i is $p^i_{st} = \|\mathsf{LCP}_{-v_i}(v_s, v_t, d)\| - \|\mathsf{LCP}(v_s, v_t, d)\| + d_{v_i v_{i+1}} = 2n - n + 1 = n+1$. Notice that path $\mathsf{LCP}_{-v_i}(v_s, v_t, d)$ is the path v_s, v_{n+1}, v_t whose cost is $2n$. Therefore, the total payment of the least cost path will be $n(n+1)$, which is $n+1$ times the true cost of the path. Thus, we say that the VCG-method is an expensive method since the overpayment ratio can be arbitrarily large. Beside the overpayment problem, in some cases, the payment to the lowest-cost path in VCG-method may even greatly exceed the true cost of the second-cheapest path. Consider again the example in Fig.3. The total VCG payment of the selected path is $\frac{n+1}{2}$ times the payment when choose the path v_s, v_{n+1}, v_t, while the cost of the second shortest path is only 2 times of the shortest path. In addition, notice that since the only relaying node in path v_s, v_{n+2}, v_t is access point v_{n+2} who must claim its true cost. In other words, if we choose the path v_s, v_{n+2}, v_t then it only costs $3n$, while VCG-method selects the least cost path and spends $n(n+1)$. This is not reasonable for the source node or system. Thus, it is very natural for use to make the following modification: after applying VCG-method, we check whether there exists a path from the source to the target using only access points as the relaying nodes; if there exists, we compare the true cost of this path with the total payments of the path VCG-method selects, and use the cheaper one as the final routing path. We called this method *modified VCG-method*.

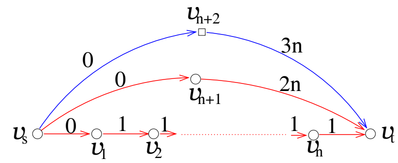


Fig. 3. Link's paradox for unicast.

Notice that the modified VCG-method is not a VCG-method anymore, since the output changes (maybe not the optimum path in term of total cost). Unlike VCG method, we can prove that the modified VCG method is not truthful.

Theorem 1: The modified VCG method is not truthful.

Proof: Naturally, one conjecture that some relay nodes on the shortest path $\mathsf{LCP}(v_s, v_t, c)$ but not selected due to the large payment may have incentive to lie down their costs in order to reduce the payment. However, the following example shows the contrary. In the same network shown in Fig.3, we select path v_s, v_{n+2}, v_t instead of the shortest path $v_s, v_1, \cdots, v_n, v_t$ under the modified VCG-method. Now considering the scenery when node v_1 reveal its cost as $n+1-\epsilon$ for a small positive ϵ. The shortest path does not change, and VCG-payment to node v_i is $1+\epsilon$ for $2 \le i \le n$. The total payment of the path $v_s, v_1, \cdots, v_n, v_t$ is $(n-1)\cdot(1+\epsilon) + (n+1) = 2n + (n-1)\cdot\epsilon = 2n+1$ when $\epsilon = \frac{1}{n-1}$. Thus, we will choose path $v_s, v_1, \cdots, v_n, v_t$ with relay nodes instead of the access points v_{n+2}. Therefore, node v_1 will benefit from cheating. ■

IV. First-Price-Auction-based Routing

Due to the possible arbitrarily high overpayment of VCG mechanism, Immorlica *et al.* in [1] proposed to use first-price auctions instead of VCG mechanism. They studied first-price auction mechanisms for auctioning flow between given nodes in a graph. The first-price auctions want to achieve a *Nash Equilibrium* (NE), in which no agent can improve its utility by deviating from its current strategy when other agents keep their strategies. Unfortunately, they showed that a NE does not necessarily exist in pure strategies. Then they introduced the concept of a strong ε-NE, in which there is no group of agents who can deviate in a way that improves the payoff of each member by at least ε. They proved an upper bound on the payment of any such equilibrium and showed that the payment is essentially not more that of the corresponding VCG payment, and often it is much less. They presented a modified first-price auction that explicitly drives the first-price auction towards a strong ε-NE. Here, we borrowed their idea that is to pay a bonus to nodes that increases as their declared costs decrease. This encourages nodes to submit low claims. In addition, the routing algorithm will select the path with some probability that increases as the claimed cost decreases. In other words, the mechanism outcome is a lottery over paths instead of a single path: every edge is on a selected path with at least a small probability, and edges off the shortest path are given an incentive to bid their true cost. The mechanism is given in Algorithm 1. We assume that there is a value B such that no edge has cost greater than B. Notice that there are two parameters α and τ in the algorithm, they are selected to be small positive constants such that $\alpha < (2m)^{-2}B^{-1}$ and $\tau < \alpha(2m)^{-1}B^{-1}$. The mechanism starts by computing a collection of paths $\{P_e\}$. The efficient way to do the computation is discussed in [1]. The mechanism then asks for costs of each edge e claimed from each node. The least cost path is almost always picked; however, with a small probability, one of the paths from the collection is picked instead. In addition, each edge is paid a small bonus that depends on the claimed cost. The selection probability and bonus are chosen to ensure that it is optimal for every edge that is not on the lowest-price path to bid its true cost. In [1], Immorlica *et al.* showed that ε-NE exist in this mechanism. Most importantly, they also bounded the total payment of this mechanism. Notice that the values α and τ can be chosen small enough to make the probabilities $\{\sigma_P\}$ and bonuses $f_e(\mathbf{d})$ arbitrarily small. Thus, the total payment to edges not on the shortest path is very small. Moreover, the first price auction method will not lead the link's paradox as VCG-method does. However, the drawbacks of this method are 1) the complex computation for the collection of paths $\{P_e\}$ and 2) multiple rounds of performance may be need to achieve the NE.

Algorithm 1 First Price Auction Routing Scheme

1: For each node v_i, consider each outgoing link $e = \overrightarrow{v_i v_l}$. Find P_e, a path from source v_s to target v_t through e. Let $\mathcal{P} = \{P_e\}_{e \in G}$. Note that an edge e may appear in multiple paths in $\mathcal{P}$.
2: Every node claims the costs for its outgoing links. Let $\mathbf{d} = (d_1, \cdots, d_e, \cdots, d_{2m})$ be the all claimed costs for all $2m$ directed links in G.
3: For each path $P \in \mathcal{P}$, compute $\sigma_P = \alpha - \tau \sum_{e \in P} d_e$, where α and τ are two adjustable parameters.
4: Select each path $P \in \mathcal{P}$ with probability σ_P; with probability $(1 - \sum_{P \in \mathcal{P}} \sigma_P)$, select the least cost path. Call the selected path P^*.
5: Pay each edge $e \in P^*$ its claimed cost d_e.
6: Pay each edge $e \in G$ the sum $f_e(\mathbf{d}) = \sum_{P \in \mathcal{P}, P \ni e} f_e^P(\mathbf{d})$, where $f_e^P(\mathbf{d}) = \alpha(B - d_e) + \tau d_e \sum_{j \in P} d_j - \tau \frac{d_e^2}{2}$.
7: For each node v_i, we sum up the payments to all its adjoined outgoing edge $e = \overrightarrow{v_i v_j}$ and make it as the final payment to node v_i. In other words, p_{st}^i includes the bonus $\sum_{\overrightarrow{v_i v_j} \in G} f_{\overrightarrow{v_i v_j}}(\mathbf{d})$ plus the claimed cost $d_{\overrightarrow{v_i v_j}}$ if $\overrightarrow{v_i v_j} \in P^*$. For nodes are not in P^*, the payments are only the bonuses.

V. Conclusion

In this paper we studied the strategyproof pricing mechanism that stimulates cooperation for unicast routing in wireless hybrid networks. We first modelled a hybrid network as a node (or link) weighted graph, and showed the node weighted can be converted to the link weighted. Then, we proposed two pricing mechanism for routing: VCG-based and first-price-auction-based. The VCG-based routing mechanism is truthful (i.e. each node will declare its true cost) and easy to implement for selfish hybrid networks. However, as all VCG mechanisms, the proposed scheme pays each relay node more than its declared cost to prevent it from lying, thus the overpayment could be large in the worse case. Also since in hybrid networks access points are cooperative, this will cause that the output of the VCG method is not the most efficient one in term of total payment. Then, our first-price-auction-based method adapts the idea from [1] to address the overpayment problem of VCG-based method. The total payment of the first-price-auction-based method is bounded. As future works, we will implement our protocols in network simulators and evaluate their performances. Our protocols assume that nodes will not collude and once paid a node will forward the packet. However, in practice, collusion is very common and a paid node may not forward the packet. Therefore, we also leave the study of collusion and methods which ensure that a paid node will forward packets as our future works.

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