Cooperation-Optimal Protocols: A New Solution Framework for Designing Incentive-Compatible Routing and Forwarding Protocols in Wireless Ad-Hoc Networks

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1. INTRODUCTION

The functioning of many civilian ad-hoc networks depends on the assumption that nodes in the network forward each other's traffic. However, because forwarding packets consumes scarce resources such as battery power, when the nodes in the network belong to different users, they may not have incentives to cooperate. To stimulate cooperation among the nodes, many methods have recently been proposed and evaluated. Although much progress has been made in the last few years, a complete system is still lacking, and *fundamental* issues remain unaddressed.

First of all, the previous approaches focus either on the routing component, assuming that nodes will follow the routing decision (*e.g.*, [1]), or on the packet forwarding component, assuming that the routes are already given (*e.g.*, [2]). There is no previous system which integrates and analyzes both routing and forwarding.

Second, there are fundamental issues unaddressed in both the routing and the forwarding components. First consider the routing component. The classic VCG mechanism has been applied to wireless ad-hoc networks to compute a power-efficient path (*e.g.*, [1]). However, in order to apply the VCG mechanism, the type of a node, *i.e.*, the power levels to reach the node's neighbors, must be privately known to the node. However, in a wireless ad-hoc network, a node alone cannot determine these power levels because it needs *feedbacks* from its neighbors. Since the nodes are non-cooperative, these feedbacks may allow one node to cheat its neighbors in order to raise its own welfare. Such *mutually-dependent types* have not been addressed before, neither in the game theory community nor in the networking community.

Next consider the forwarding component. An ideal forwarding protocol is one such that under the protocol nodes always forward traffic and always forwarding traffic is a *dominant action* of each node; that is, no matter what other nodes do, forwarding traffic always brings the maximum utility to the node. We call such a protocol a forwarding-dominant protocol. A forwarding-dominant protocol is an ideal protocol. An issue that has not been investigated before is whether a forwarding-dominant protocol exists. If not, what is a good and feasible solution concept?

In this short paper, for the forwarding component, we show that there does *not* exist a forwarding dominant protocol. Then we demonstrate that, in the routing component, due to mutually-dependent link costs, a straightforward application of VCG mechanism in [1] does *not* lead to a dominant routing action solution. Finally we briefly discuss the notion of *cooperation-optimal protocols*, a new solution framework for integrated incentive-compatible routing and forwarding in wireless ad-hoc networks.

2. FORWARDING COMPONENT: NON-EXISTENCE OF FORWARDING-DOMINANT PROTOCOL

We first formally define the forwarding-dominant protocol.

DEFINITION 1. *In an ad-hoc game, a* forwarding-dominant protocol *is a protocol in which 1) a subset of the nodes are chosen to form a path from the source to the destination; 2) the protocol specifies that the chosen nodes should forward data packets, and 3) following the protocol is a dominant action of the forwarding subgame.*

Now we show that there is no forwarding-dominant protocol in wireless ad-hoc networks.

THEOREM 1. *There does not exist a forwarding-dominant protocol in wireless ad-hoc networks.*

PROOF. We prove by contradiction. Suppose that there exists a forwarding-dominant protocol. Then we consider a source node S, a destination D, and a node distribution in which there is a link (i, j) on the packet forwarding path such that

- If the power level from node i to j $P_{i,j} < \infty$, which means that node j can receive packets sent by node i;
- $P_{i,l} = \infty$, for any $l \neq j$, which means that any other node cannot receive any packet sent by node i.

Figure 1 shows the setup.

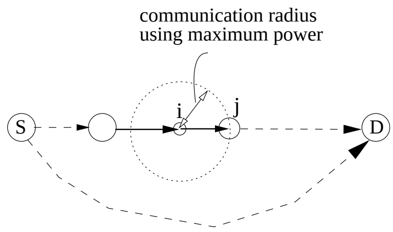

Figure 1: Illustration of the setup for the impossibility result.

We compare two forwarding action profiles. All nodes except node i have the same actions in both profiles. In both action profiles, any node except i, j follows the protocol faithfully. Also in both action profiles, j almost follows the protocol except that it behaves as if it did not receive the data packet with sequence number 0, even if it does receive the packet. However, i has different actions in these two profiles: the action a_i means that i faithfully follows the protocol and forwards all packets; the action a'_i means that i follows the protocol except that it discards the data packet with sequence number 0. Obviously, by no means can the system distinguish these two action profiles, because packet 0 is always discarded and there is no way to know who discards it. Therefore, these two profiles bring the same payment to i. On the other hand, a_i has a greater cost than a'_i because it forwards one more packet. Thus we show that always forwarding is not a dominant action. □

3. ROUTING COMPONENT: CHEATING FEASIBLE BECAUSE OF MUTUALLY-DEPENDENT LINK COSTS

In this section we investigate another fundamental issue: link costs are determined by two nodes together. We will show that ignoring such interaction can cause serious flaws in a protocol.

To be more specific, we first briefly describe a straightforward application of VCG to route discovery. (This is the Ad-Hoc VCG protocol proposed in [1]. We omit some details of [1] to make the presentation clearer.) Suppose that the destination collects the cost for each node to reach each of its neighbors, where a neighbor is a node that the node under discussion can reach at some power level $l \in \mathcal{P}$. Denote the lowest (claimed-)cost path from the source S to the destination D by $LCP(S, D)$; denote the lowest (claimed-)cost path from the source S to the destination D that does not include node i by $LCP(S, D; -i)$. Then the destination simply chooses $LCP(S, D)$ as the packet forwarding path from S to D, and the payment to node i is

$$p_i = cost(LCP(S, D; -i)) - cost(LCP(S, D) - \{i\}),$$

where the function $cost()$ sums the costs of all links on a path, $LCP(S, D) - \{i\}$ consists of the links on the LCP but with the link starting from node i removed, if node i is on the path.

The above description assumes that the cost of each link is known to the transmitter of the link. However, the transmitter of a wireless link needs the receiver's feedback to estimate the link cost, namely the required power level. Handling cheating in estimating link cost is a challenging task. Below we will show that the link-cost estimation scheme of the Ad-Hoc VCG protocol [1] is flawed; therefore their overall protocol does not have incentive compatibility.

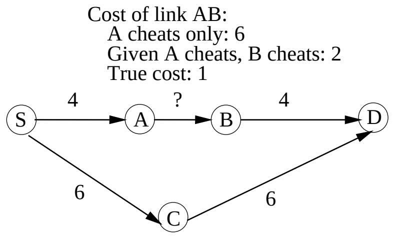

Figure 2: Illustration: VCG alone does *not* guarantee the existence of a dominant solution in routing.

Consider the link-cost estimation algorithm used in the Ad-hoc VCG protocol (see Equation (2) of [1]): the transmitter sends a pilot signal at a given power level P^{emit}; the receiver sends back the ratio R between received power level and target (minimal) power level; and then the transmitter determines its transmission power level $P = P^{emit}/R$ so that the operational power level is achieved at the receiver.

Given this protocol to determine link power levels, we have a simple example shown in Figure 2 to show that a straightforward application of VCG cannot be a dominant-action solution. Suppose that the real cost of link AB should be 1 (*e.g.*, $P^{emit} = 5$ and $R = 5$). Recall that a dominant action of B must be the best choice of B *no matter what actions other nodes (such as A) choose*. Therefore, it is enough for us to consider the following specific action of A (with an attempt to over-claim its link cost): A sends at $P^{emit} = 5$; after receiving the feedback about the ratio R between received and target power level at the receiver, instead of claiming $5/R$, node A claims $5/R * 6$. Then,

- if B does not cheat, the claimed cost of link AB will be $5/5 * 6 = 6$;
- if B chooses a cheating action (to underclaim the cost by reporting R = 15), the claimed cost of link AB can be decreased back to 2.

With this action of A, if B does not cheat, then the LCP is the lower path in the figure: B receives zero payment and has a utility of 0. If B takes the above cheating action, it receives a payment of 12-4-2=6 which covers its cost of 4 on link BD and results in a positive utility of 2. Therefore, with this action of A, it is beneficial for B to cheat. Consequently, truthfully helping A to report the cost is *not* a dominant action of B *by the definition of dominant action*.

Note that this example does *not* involve any collusion, because a colluding group maximizes the group's overall utility in some sense (*e.g.*, sum of group members' utilities), while in our example, we only consider the utility of one single node, B.

Also note that the above example uses a binary estimation scheme. We can show similar examples using other estimation schemes such as the well-known SNR based scheme.

4. COOPERATION-OPTIMAL PROTOCOLS: A NEW SOLUTION FRAMEWORK

Given that there is no forwarding-dominant protocol and that there is no conceptual framework for analyzing integrated routing and forwarding protocols, we now define a new solution framework for wireless ad-hoc networks. Although this framework is defined only for integrating routing and forwarding, we believe that it can be extended to model general, multiple-layer network protocols. Specifically, since the routing and forwarding behavior of a node occurs in two stages: the routing stage and the forwarding stage, we define two *inter-dependent* subgames: the routing subgame (implemented with a routing protocol) and the forwarding subgame (implemented with a forwarding protocol). In a game theoretical analysis, we integrate these two games by considering them as the two stages of a global game which is modeled by an *extensive game*. In this extensive game, the routing subgame is on the top of the game tree, and for each routing decision (represented by a leaf node of the subtree representing the routing subgame), there is a forwarding subgame.

A solution to this global extensive game is the following:

- For each routing decision $\mathcal{R}$, which includes the routing path chosen and the price that will be paid to each node for forwarding each packet, a forwarding solution is a solution to the forwarding subgame tree under the routing decision. Here a forwarding solution determines whether or not a node will forward packets and the net utility of its action. A forwarding solution can be determined by using the solution concepts of either subgame perfect Nash equilibrium or *optimal* solution.
- For the routing subgame, with the utility of each routing decision determined by the forwarding subgame, a routing solution is one such that truthfully declaring a node's link cost is a dominant action, even when a node alone cannot determine the power level to reach its neighbor.

Given the above definition of the global game, now we define that a protocol is a *cooperation-optimal protocol* if following the protocol is the solution of the global game.

To prove the feasibility of designing cooperation-optimal protocols, we design Corsac, a Cooperation-optimal routing-and-forwarding protocol in wireless ad-hoc networks using cryptographic techniques [3]. More specifically, the routing protocol of Corsac uses cryptographic techniques to prevent a node from cheating in the direction where the node can benefit. Thus, a combination of incentive consideration and security techniques allows us to provide an efficient solution to the mutually-dependent-type problem. The routing protocol is also integrated with a novel data forwarding protocol based on cryptographic techniques to enforce the routing decision.

5. REFERENCES

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