Node Control and a Charging and Accounting Approach to Ad-Hoc Networks

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I. Introduction

Mobile ad hoc networks (MANETs) [3] are networks of mobile nodes with a limited transmission range. Despite this, it is possible to perform long-distance data transmissions through other mobile nodes in the system since every mobile node is simultaneously both an end-user and a router in such networks. On the other hand, every mobile node has autonomy of action and has an interest in spending its resources (such as battery power) for foreign data forwarding. To provide an incentive for mobile nodes to cooperate, a charging and accounting scheme must be employed.

We focus on a scheme presented in [5] that is based on a new approach for the charging and accounting problem in MANETs. This approach provides an incentive for cooperation by means of remuneration and thus differs from existing approaches in this area in that there are no security mechanisms and/or special hardware devices in nodes that force them to follow legalities and rules, bearing in mind that nodes can behave dishonestly. Instead, system control issues are imposed on special nodes (police nodes), which perform node monitoring from time to time. Police nodes belong to a central authority (CA) that manages resources for monitoring, so that these resources should be covered by collected receipts from penalties imposed on misbehaving nodes. Thus, the management of monitoring requires the development of an applicable mechanism that should increase the profits of the central authority under varying conditions.

For this reason, we consider the problem as an inspection game [2] between police nodes that represent the central authority (i.e., the inspector) and regular nodes (the inspectees). The aim of the theoretical game model presented in this paper is to provide the central authority with advice about how many resources to allocate for network monitoring. The model assumes a random police node distribution over the network, as well as a fixed value for the penalties. This is then extended to relax some strong assumptions upon which the approach presented in [5] relies. In particular, the optimal punishment is discussed, as well as the assumption of perfect monitoring, which assumes that the data collected by police nodes are always reliable and correct.

Our proposed mathematical model is based on a Passenger Ticket Control Model (PTC) [1] originally proposed for the Munich Transport and Fares Tariff association (MVV). The purpose of the PTC is to suggest how to find the optimum frequency of control through which MVV could reach its goals. Our game model is adapted to the design of an applicable mechanism, based on a Nash equilibrium, that provides advice for monitoring efforts as a strategy for the allocation of police nodes and that demonstrates that a node will not benefit from misbehaving when this strategy is chosen. The mechanism relies on tried and true, reliable methods, thus making it applicable and effective.

The remainder of this paper is organized as follows. The next section describes the Passenger Ticket Control Model. Section III presents the approach for charging and accounting in ad-hoc networks. Section IV provides a solution that adapts the models in previous two sections. Section V extends the solution presented in Section IV to the relaxation of assumptions in [5]. Section VI concludes the paper with an outline for future work.

II. Passenger Ticket Control Model

The Passenger Ticket Control Model (PTC) is presented in [1] as an example of the application of inspection games. This is a two-player game problem in which the control system is an inspector (first player) and the passenger is an inspectee (second player). The purpose of this mathematical model is to give advice to the MVV to make the deployment of distributed randomly inspectors economically attractive.

If f denotes the normal fare, b denotes the fine, and e denotes the costs of control per passenger ($e < b$), then the possible payoffs for two players an inspector and a passenger, respectively are, as seen in the normal form in Figure 1:

$(f-e), -f$ inspectors control the system and passengers act legally
$f, -f$ inspectors do not control the system and passengers act legally
$(b-e), -b$ inspectors control the system and passengers act illegally
0, 0 inspector do not control the system and passengers act illegall

inspector\passenger	Legal behavior (q)	Illegal behavior (1-q)
Control (p)	(f-e), -f	(b-e), -b
No control (1-p)	f, -f	0, 0

Figure 1. The PTC game model.

To enable MVV to perform the desirable control management, an optimum strategy of inspectors is developed using a Nash equilibrium concept [7]. There is no pure strategy equilibrium because of the cyclical preferences of the players (see the directions of the arrows in Figure 1). It is assumed that the inspector controls the system with probability p, whereas the passenger behaves legally, with probability q. The pair of mixed strategy equilibrium (p^*, q^*) is comprised of the strategies of two players, so that if one of them follows this strategy, that will be the best response for any choice of action for the other player [8]. The expected payments of two players are denoted by E_1 and E_2, respectively, and, according to the game model, equal:

$$E_1(p,q) = (f-e)pq + (b-e)p(1-q) + f(1-p)q,$$
$$E_2(p,q) = -fpq - bp(1-q) - f(1-p)q.$$

The equilibrium payoff of the first player is E_1^*, and that of the second one is E_2^*. Thus:

$$p^* = \tfrac{f}{b}, \qquad E_1^* = f(1-\tfrac{e}{b}), \qquad (1)$$
$$q^* = 1-\tfrac{e}{b}, \qquad E_2^* = -f. \qquad (2)$$

In the case of a passenger's illegal conduct with a probability of $(1-q^*) > 0$, his expected payoff, on the average, remains the same; i.e., the gain from free-riding is balanced by the imposed fine.

When the passenger chooses q^* as his strategy, the costs of inspectors, which check passengers (with any p) and collect funds in the form of fines imposed on free-riders, are ultimately compensated by the collected fines. Indeed, if ep denotes the mean costs of the inspectors controlling the system per node, and if $bp(1-q)$ is the profit from the collected fines, then

$$ep - bp(1-q) = p(e - b(1-q^*)) = 0.$$

Choosing p^* by the MVV for optimum control makes the passenger indifferent in choosing his strategy. Choosing the legal behavior strategy, the passenger pays $-f$, that is equal to the expected payoff $-bp^*$ of the passenger that chooses to behave illegally (1).

III. Charging and Accounting Approach in Ad-Hoc Network

In [5], the novel and yet simple approach of combining a cooperation mechanism and a monitoring system to solve the charging and accounting problem in MANETs is proposed. The incentive for cooperation is provided by means of remuneration. Intermediate nodes receive some kind of virtual money (e.g., digital coins) that is preloaded into the packet by the sender for correctly performed forwarding. Encouragement for nodes to behave correctly is based on the following idea.

The approach uses as an analogy modern society, in which individuals may behave in accordance with generally accepted rules or may deviate from them. The latter, however, run the risk of being caught and punished by the police. Likewise, there is no guarantee that each ad-hoc node will follow rules that significantly weaken requirements for additional resources and overhead, in contrast to existing approaches. The compliance of nodes is enforced by a small number of special *police nodes*, which are randomly distributed within the network. Police nodes monitor nodes from time to time and report collected information to the central authority for processing. The central authority ensures that there will be a reward for these contributing nodes, and, moreover, it supports the monetary system and manages monitoring resources based on a theoretical game model that is developed in this paper in Section IV. In addition, the central authority identifies nodes involved in the infraction of rules and determines a punishment for them.

In [5], an infinite penalty for misbehaving nodes is assumed (e.g., misbehavior leads to exclusion from the network), whereas the gain from cheating is said to be finite. Considering both of these assumptions, as well as the assumption that nodes are rational, it follows that there is no reason for rational nodes to behave dishonestly since the average loss is greater than the average gain derived from cheating. Thus, nodes will not cheat if there is a risk of being caught, i.e., if there is a small probability that any illegal action on the part of a node will be detected. In the next section, we show that the correctness of the approach is not affected when the unrealistically assumed infinite punishment is replaced. We find the optimal strategy for the central authority, thereby leading to the nodes' indifference about whether or not to act illegally.

To illustrate an application of the approach, a simple model is presented in which the sender places several coins into the packet, and every intermediate node takes one coin and forwards the packet to the next hop towards the destination (for example, using a position-based routing protocol [6]).

The approach is based on the assumption that the police nodes observe, collect, and always report to the central authority correct and error-free data. After an optimum punishment value is discussed (see Subsection V, A), we relax this assumption of perfect monitoring in Subsection V, B.

IV. Adapting the Passenger Ticket Control Model to the Nodes Control in Ad-Hoc Networks

Like the PTC problem, we consider our situation (see Section III) to be a two-player inspection game in which a police node (representing the CA) plays the role of an inspector and a regular node is an inspectee. The node (the first player) may or may not cheat, whereas the CA (the second player) regulates the allocation of resources for monitoring.

Monitoring of nodes in our system has a character similar to the inspection of passengers in the public transportation problem. During monitoring at a certain location, a police node may observe a number of nodes which are in its transmission range, similar to a number of passengers in a public transportation vehicle that is being inspected. The fact that the police node cannot be detected by nodes is an additional feature, in contrast to the inspector in the PTC.

A solution for the problem we consider is like a game solution using a Nash equilibrium, as in the PTC (see Section II). The following occurs, such that if f denotes the average expenditure of a node, when it acts legally; g denotes the node's average gain from illegal actions[1]; b denotes the penalty for a misbehaving node; and e denotes the costs of monitoring per node ($e < b$), then the game could be presented in the normal form (see Figure 2), where $(p, 1-p)$ is the mixed strategy of the first player (the probability assigned to monitoring/no monitoring), and $(q, 1-q)$ is the mixed strategy of the second player (the probability assigned to legal/illegal behavior). Additional costs/gains are not taken into account, since they do not affect players directly.

police node\node	Legal behavior (q)	Illegal behavior (1-q)
Monitoring (p)	(f-e), -f	(b-e-g), (-b+g)
No monitoring (1-p)	f, -f	-g, g

Figure 2. The nodes control game in Ad Hoc Networks.

Like the PTC, the game has no pure strategy equilibrium because of the cyclical preferences of the players. We denote the mixed strategy equilibrium of two players by (p^*, q^*) and expected payments by E_1 and E_2, respectively, which, according to the game model, equal:

$$E_1(p,q) = (f-e)pq + (b-e-g)p(1-q) + f(1-p)q - g(1-p)(1-q),$$
$$E_2(p,q) = -fpq + (g-b)p(1-q) - f(1-p)q + g(1-p)(1-q).$$

[1]It should be noted that the gain is controlled by the CA. Indeed, in case a node wishes to save resources when paying for a packet transmission, the forwarding nodes, which perform packet forwarding correctly for such a wrongly paid transmission, must still be rewarded by the CA. Also, coins that have not been honestly gained will be finally submitted to the CA for exchange

The mixed strategy Nash equilibrium of the first and second players (p^* and q^*, respectively) is:

$$p^* = \frac{f+g}{b}, \quad (3)$$
$$q^* = 1 - \frac{e}{b}. \quad (4)$$

The received optimal control probability p^* makes the node indifferent about his two possible action choices, based on the same explanation that is given in the PTC. In actuality, equation (3) holds when probability p^* is chosen, because a node which behaves legally pays $-f$, on the one hand, and pays $-bp^* + g$ when it behaves illegally, on the other.

As was already mentioned in the PTC, the expenditure outlay for control is compensated by the penalty collected when a node chooses q^*. In fact, the difference between the expenditure for monitoring per node (ep) and the gain from the penalty ($bp(1-q)$) is zero for any p only if the node chooses q^*.

The equilibrium expected payoffs for two players E_1^*, E_2^* in the mixed strategy pair (p^*, q^*) are:

$$E_1^*(p^*, q^*) = f(1 - \frac{e}{b}) - \frac{eg}{b},$$
$$E_2^*(p^*, q^*) = -f.$$

The expected payoff of the second player from his mixed strategy $(1 - q^*) > 0$ remains the same, so we can draw the same conclusion as in the case of the PTC: the payoff of the legally behaving node is the same as that of the node that behaves illegally and whose illegally achieved gain is negated by the imposed penalty.

V. Solution extensions

A. Optimal penalty

The desired deterrence effect in the system could be achieved by the tradeoff between frequency of monitoring and severity of punishment, when the CA may change both the probability of control p and the punishment b periodically. As is usual in economics and legal literature, in order to determine a punishment as severe as possible, under the assumption that individuals are risk neutral (e.g., [10], [4]), we choose the optimal punishment as the maximal one. Otherwise, it would be possible to increase the punishment in order to save on monitoring resources [4]. Also, as is usual in this type of literature, it is assumed that the transfer of the imposed punishment to the CA is preformed without any overhead costs. In practice, existing costs should be included in the penalty [10], and this will be investigated in our future work.

B. Perfect Monitoring

In real ad-hoc networks, a police node may observe, collect, and then report false or inaccurate information to the CA (e.g., due to interference, receiving errors, etc). As a result of possible errors, an honest node could be mistakenly penalized - let us assume that it happens with probability ϵ_C - and an attacker could be mistakenly justified - let us assume that that may happen with probability ϵ_A. Moreover, it could become attractive for nodes to act illegally if and only if the gain derived from cheating minus the punishment is greater than the loss caused by a false or incorrect accusation [10], i.e.,:

$$g - p(1-\epsilon_A)b > -p\epsilon_C b \Leftrightarrow$$
$$g > (1 - \epsilon_A - \epsilon_C)pb \Leftrightarrow \quad (5)$$
$$p < \frac{g}{(1-\epsilon_A-\epsilon_C)b}$$

Thus, p, at least, must satisfy the following equation[2]:

$$p = \frac{g}{(1-\epsilon_A-\epsilon_C)b} \quad (6)$$

The deterrence decreases due to both types of errors (see right side of (5)) and could be improved by increasing the frequency of monitoring [10]. Besides increasing deterrence, this additional expenditure of resources would decrease the probability of punishing the node falsely, thereby decreasing the node's disinclination to cooperate, which may then be advantageous to the CA [9].

Since both types of errors decrease the deterrent factor, as a consequence, social welfare is also decreased [10]. Once again, a node will cheat if and only if $g \geq pb$. The social welfare is denoted as[3]:

$$\int_{pb}^{\infty} (g - m) z(g) dg - r(p),$$

where m denotes the expected harm[4]; $z(g)$ is a density function of gains; and $r(p)$ denotes a function that shows how many resources are required to achieve probability p ($r' > 0, r'' \geq 0$). The first-order condition to find the optimal detection probability is:

[2] It is assumed that $(1 - \epsilon_A) > \epsilon_C$ [9]

[3] This is the conventional social welfare function that is used in legal and economics literature [4] [9]

[4] "expected" because it is not always possible to estimate the exact value of harm [9]

$$(m - pb)(Z'(pb)) = r'(p), \qquad (7)$$

where $Z'()$ is the cumulative distribution function of $z()$. From (7) it follows that:

$$m > pb, \qquad (8)$$

which means that the expected punishment (see the right-hand side of inequation (8)) is less than the value of the harm (left-hand side of inequation (8)) which is incurred by society due to the node's cheating. In other words, some "under-deterrence" is optimal ([4], [9]). After substituting (6) for p into (8), we get:

$$m > \frac{g}{1-\epsilon_A-\epsilon_C}. \qquad (9)$$

From (9) we can see that the right side is increased in $(1 - \epsilon_A - \epsilon_C)$. If g is increased to the point of $m \leq g$, then it will be beneficial for a node to behave illegally [10]. Thus, as long as (9) is satisfied, a node will not cheat.

In general, it is obvious that the percentage of erroneous monitoring is, at most, identical to the percentage of interference/errors. Since the percentage of interference/errors is low, it follows that the percentage of erroneous reports, as well as the probability of penalizing or rewarding a node falsely, is likewise low. Punishment resulting from inaccurate monitoring is deemed to be acceptable from the perspective of an individual node, because it will still generally profit from the situation. This situation is also reasonable from the perspective of the CA, which will always profit.

VI. Conclusions and future work

In this paper we have presented a theoretical game model that provides advice to the CA about the allocation of resources for node monitoring in Mobile Ad-Hoc networks. The solution is based on the existing theoretical game model developed for controlling the public transportation system. The solution is then extended to the relaxation of assumptions in the paper which first proposed the idea [5], particularly the infinite punishment assumption and the perfect monitoring assumption.

In our future work, we will investigate ways to distribute police nodes in the network. Also, non-monetary punishment will be studied, as well as a combination of both kinds of penalties. In the future, using simulation to aid in measurement, we hope to be able to show that performance can be optimized at a fraction of the cost. Based on this simulation model, we can then demonstrate its applicability in practice with a prototype implementation.

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