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Enforcing Cooperation among Misbehaving Nodes in Ad Hoc Networks Using Shapley Value to Assign Economic Virtual Currency

[1]M. Anitha and [2]V. Rhymend Uthariaraj
[1]Anna University, 600025 Chennai, India
[2]Department of Information Science and Technology,
Anna University, 600025 Chennai, India

Abstract: Clustering is a major research area in the recent years that is suggested for improving the life expectancy of ad hoc networks. Since the nodes in an ad hoc network are resource constrained they tend to act selfishly and do not cooperate among themselves in performing their services among the clusters. The concept of assigning incentives in the form of virtual currencies to encourage nodes to cooperate for the network services is suggested in existing works. The Vickrey, Clarke and Groves (VCG) mechanism is a game-theoretical approach, used to calculate the incentives to be assigned to nodes to encourage them to be honest of their private information. This study proposes Shapley value based coalition game theory to enforce honest cooperation among the nodes. The solution computes economic incentives to be distributed among the nodes. Empirical and simulation results show that the proposed solution not only assigns economic incentives to enforce cooperation for a common good but also distributes the same fairly among the nodes thereby encouraging them to honestly cooperate in performing the network services.

Key words: Shapley value, coalition games, cluster head, truth-telling dominant strategy, incentives

INTRODUCTION

Ad hoc networks were initiated around 1972 when DARPA (Defense Advanced Research Projects Agency) implemented the revolutionary PRNet (Packet Radio Network) project. Although, continuous research proceeds to address most of the problems encountered by the ad hoc network community, the presence of a real cost-effective commercial solution is yet absent as studied by Chen *et al*. (2004). One of the methods to address the resource constraint challenge of ad hoc networks is to use the concept of clustering whereby nodes in one or more hop distance are grouped into different virtual groups called clusters. Each cluster has at least one leader, referred as its Cluster Head (CH). Each node in the network communicates only with its CH. The CH transmits the aggregated content to the base station. Such aggregation and collection of data from nodes by the CHs reduce the amount of data and control messages exchanged in the network remarkably and also prolong the lifetime of the entire network.

The general classification of clustering algorithms are DS-based, low-maintenance, mobility-aware, energy-efficient, load-balancing and combined-metrics-based as surveyed by Yu and Chong (2005). In all the schemes the network is divided into clusters and the cluster head selection is based on selecting the node with the best value for the parameter chosen as selection criterion. The mechanism should also enforce cooperation among the selfish nodes to behave honestly. The recent works of Zhong *et al*. (2003), Velloso *et al*. (2010) and Govindan and Mohapatra (2012) show the choice of trust or reputation of the nodes as cluster head election criteria to ensure that malicious or self-fish nodes do not get elected as cluster heads. The authors of Anderegg and Eidenbenz (2003), Koltsidas and Pavlidou (2011) and Feng *et al*. (2014) have suggested game theoretical approaches to assign incentives to enforce cooperation among the nodes to honestly take part in the network services and also punish the misbehaving nodes by assigning incentives in relation to the amount of cooperation they render to the network services.

Game theory can be expressed as an analytical framework that uses mathematical tools to study the multifaceted communications among network entities. The two sub-divisions of game theory are cooperative and non-cooperative game theory. The former type studies the cooperative behaviour of entities; this characteristic is seen to be dominant in the design of a rational, vigorous and well-organized approach in communication networks

Corresponding Author: M. Anitha, Anna University, 600025 Chennai, India

Table 1: Analogy between mechanism design parameters and network terminologies

Notation	Mechanism design	Network analogy
N	Players	Nodes
A	Outcomes	Behaviour of nodes
$v_i(a)$	Player i's private information (cost for providing a service)	Node's private information such as cost energy of analysis for forwarding/election of cluster head, level, etc.,
$p_i(v)$	Remuneration received by player i from the mechanism	Incentive given to node for performing some useful function of the network
$\max_{a\in A}\sum_i v_i(a)$	Social welfare maximization (enforcing cooperation among the players)	Enforcing among the nodes to perform their services

that enforce cooperation among their entities. The network scenario can be considered as a packet forwarding game when there is cooperation among the nodes in the network. The latter type studies the behavior of entities whose decisions are independent of each other. Table 1 gives the analogy between the mechanism design parameters and network terminologies.

Generally, most of the existing approaches consider the nodes in the network (the entities) as selfish and rational. The selfish nodes are ruled by their utility functions and care only of their individual profits that they earn in the form of virtual currency. They always choose strategies that will yield them profit. Such currency can be used as a payment for transmitting data packets to other nodes on the network. In the event of a node not possessing sufficient currency it will not be able to transmit its own data packets over the network. If the nodes are not selfish and they perform the network services, they can gain increased currency. The Vickrey, Clarke and Groves (VCG) mechanism which is also a game-theoretical approach is used in existing works to calculate generous currencies to be assigned to nodes to encourage them to be honest of their private information. However, it assigns excess and not economical currency. The proposed research has shown that Shapley value, yet another game theoretical mechanism can be used to distribute the currency obtained as incentives for honest behaviour fairly as well as economically.

VCG MECHANISM

The VCG mechanism as suggested by Vickrey (1961), Clarke (1971) and Groves (1973) when applied to the network scenario considers n nodes and a set A of behaviours (normal, selfish, malicious). The node i is associated with a valuation function v_i and v represents the vector of valuation functions or the players under consideration. The virtual currency to be given to a player for performing well is expressed by $p_i(v)$ and the allocation under valuation v is expressed by f(v). When a vector of valuation functions v is given, the VCG mechanism computes the utility allocation and the virtual currency to be given to the players as shown in Eq. 1 and 2:

$$f(v) = \arg\max_{a\in A} \sum_j v_j(a) \tag{1}$$

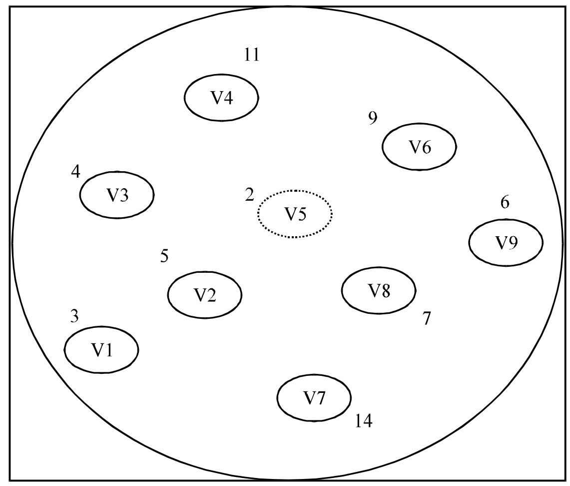

Fig. 1: Cluster formation with v5 selected as cluster head

$$pi(v) = \max_a \sum_{j\neq i} v_j(a) - \sum_{j\neq i} v_j(f(v)) \tag{2}$$

Equation 1 computes the optimal allocation that maximizes the social welfare and Eq. 2 computes the virtual currency to be given to each player for having participated in the information forwarding game. The Clark pivot rule in VCG mechanism sets the first term in Eq. 2 to be the social welfare for all other players as if player i were not present in the game, that is to say, p_i (v) is equal to (the maximum social welfare when player i were absent) (the social welfare of other players when player i is present). This defines player i's externality. Equation 3 defines the payment to be given to the nodes using the VCG mechanism:

$$p_i^{VCG}(v_1, v_2, v_3, ..., v_n) = (\text{social welfare without } i) - (\text{Othor's welfare with } i) \tag{3}$$

The suggested VCG mechanism can be taken to demostrate the constructive effect due to the cooperation among the normal nodes. For this demostration the cluster shown in Fig. 1 is used. The values shown outside the vertices indicate the trust value for each node.

Table 2 shows the trust value of each of the nodes, the cost of analysis that will be incurred by each node

Table 2: Computation of VCG payment for nodes within a cluster

Nodes	v1	v2	v3	v4	v5	v6	v7	v8	v9
Node reputation (r_i)	12	13	9	8.5	15	7	10	12	9
Cost of analysis (e_i)	3	5	4	11.0	2	9	14	7	6
VCG payment (VCG_i)	6	7	10	18.0	-	17	19	10	12

Table 3: Computation of virtual currency using Shapley value

Nodes	v1	v2	v3	v5	v6	v7	v8	v9
Reputation of node (r_i)	12.00	13.00	9.00	8.50	7.00	10.00	12.00	9.00
Cost of analysis (e_i)	3.00	5.00	4.00	11.00	9.00	14.00	7.00	6.00
Shapley value (sh_i)	1.17	1.15	1.20	1.22	1.24	1.19	1.17	1.21
Virtual currency paid (e_i+sh_i)	4.17	6.15	5.20	12.22	10.24	15.19	8.17	7.21

when it participates in the network service say, the leader election process and the incentive computed for each node by the cluster head for having participated in the network service. The node with the least cost of analysis becomes the cluster head. On election the cluster head calculates the premium as 75% of its reputation value and VCG payment to be given to each node for having taken part in the election is computed using (Eq. 3). Since, the intermediate node gets an additional currency it is understood that it ensures truthful revelation of its cost of analysis of the node as the dominating strategy. Taking the case of selfish or malicious nodes, although they do not want to participate in the election process the incentive payment is anyway promised thereby discouraging the node to be selfish or turn malicious during the election process.

The VCG mechanism is satisfactory for scenarios comprising of interactions of longer duration among nodes and for situations where the routing path is not altered drastically in the course of transmission. More meanfully it means that the computations are successful when the nodes are less mobile. Further, solutions with VCG mechanism use its truth dominating strategy to achieve cooperation among the nodes by spending virtual currency in large numbers which is an indirect loss to the network revenue. The mechanism is relaible only in cases of isolating single malicious nodes. If more than one node forms a coalition to misbehave, the mechanism fails.

SHAPLEY VALUE FOR FAIR DISTRIBUTION OF INCENTIVES

In an ad hoc network the nodes are found to form coalition with other nodes either to behave normally or misbehavior. Shapley value has been used to define such concepts of coalitions as suggested by Myerson (1991). The Shapley value as proposed by Shapley (1953) can be applied in situations where the contributions of entities are unequal. The virtual currency to be assigned $\varnothing_I(v)$ is computed as given in Eq. 4:

$$\phi_i(v) = \sum_{S\subseteq N/\{i\}} \frac{|S|!(N-|S|-1)}{N!}\left[v(S\,U\{i\})-v(S)\right] \quad (4)$$

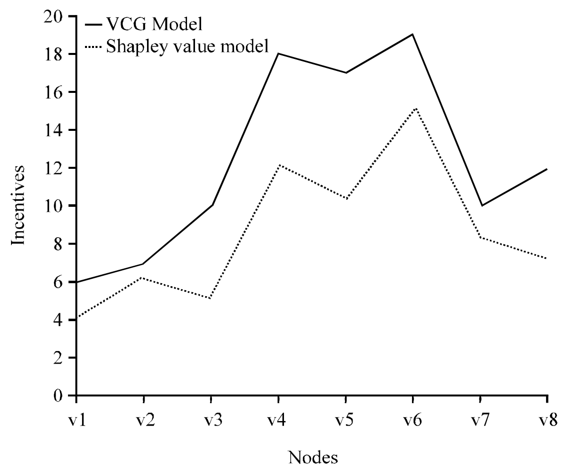

Fig. 2: Comparison between VCG payment model and Shapley value based model

In the Eq. 4, the value [v(S U{i})-v(S)] is the minimal contribution of node i in the coalition S. The weight used in front of this value is the probability that player i faces the coalition S when entering in a random order. The Shapley value, thus distributes the total currency obtained to the nodes, under the assumption that they all collaborate, making it as a "fair" distribution as explained by Roth (1988). The coalition process usually takes place as several rounds of formation. During each round, each node that joins the coalition looks out for a node to associate with. The formation of the coalition is normally fast and the size keeps growing until the grand coalition is reached of all colluding nodes.

Table 3 shows the currency to be given to each of the nodes in the cluster shown in Fig. 2, calculated using Shapley value. The mechanism computes the virtual currency taking into consideration the same reputation values given in Table 2. The currency computed using Shapley value are far less in comaprison with the same calculated using VCG mechanism. Hence it is studied that Shapley value mechanism is a class of budget balanced strategy proof mechanism.

Figure 2 illustrates the currency computed for each of the nodes in the cluster by the cluster head v_5 using both the methods namely, VCG and Shapley value. The total virtual currency paid as incentive, calculated using the Shapley value of each of the nodes is shown to be 18% less than the VCG payment as evident from Fig. 2. It is clearly seen that when compared to the VCG payment, the contribution using Shapley value yields a lesser incentive to be distributed to the nodes and thus it is budget balanced.

CONCLUSION

One of the inherent nature of ad hoc networks namely, cooperation among its nodes has been studied for its services to be performed constructively. The network is expressed as a cooperative game (a subdivision of game theory) as the coalitional game naturally satisfies the properties of an ad hoc network. The concept of Shapley value method under coalition games has been used in this work to fairly distribute incentives to member nodes in a cluster to enforce their cooperation to the network services. Analysis of results infers that the proposed mechanism, using Shapley value assigns budget balanced currency to enforce cooperation among normal nodes in comparison with the VCG mechanism. The proposed mechanism finds the marginal contribution of each node to its network services in terms of its reputation. Hence, it assigns incentives according to the behavior of the nodes. In future works the proposed virtual allocation mechanism can be implemented with other game-theoretical solutions such as Nucleolus and Core and the results could be compared to find these suggestions will yield better results than that obtained using Shapley value.

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