Coalitional Graph Game of Multi-Hop Clustering in Vehicular Ad-Hoc Networks

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RESEARCH

Coalitional graph game of multi-hop clustering in vehicular ad-hoc networks

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Abstract

Road traffic information can be collected over a vehicular ad-hoc network (VANET) and utilized in many intelligent traffic system applications. A clustering mechanism is used to create a cluster of vehicles to facilitate the data collection from vehicles to road side units (RSUs) acting as sink nodes. Unlike previous works that focus on cluster lifetime or throughput, we propose a coalitional graph game (CGG) technique to form a multi-hop cluster with a largest possible coverage area for a given transmission delay time constraint to economize on the number of RSUs. Vehicles decide to join or leave the coalition based on their individual utility that is a weighted function of number of members in the coalition, relative velocities, distance to sink nodes, and transmission delay toward the sink nodes. The stability of cluster formation is proved by using a discrete-time Markov chain. Our results show that the proposed game model always yields a stable coalition structure that satisfies the objective, and the solutions vary with the weights given to individual components in the utility function.

Keywords: Clustering; Coalitional graph game; Game theory; Vehicular ad-hoc network (VANET)

1 Introduction

Vehicular ad-hoc networks (VANETs) are becoming increasingly important in wireless communication among vehicles by enabling vehicles to exchange data in a multi-hop fashion without the aid of a wired infrastructure. Exchanged data in VANETs allows for implementing a wide variety of intelligent transportation system (ITS) [1, 2] applications such as traffic monitoring, safety warning, driving decision, autonomous driving, transportation payment, to name a few. In this paper, we focus on data collection from vehicles where data flows from vehicles into a road side unit (RSU) via multi-hop clustering. For such a system, the cost of RSU installation and maintenance is expensive. Therefore, it is desirable to have a connected network area per RSU as large as possible to economize on the number of RSUs.

A wide variety of metrics have been used in previous works based on different goals to cluster vehicles, including relative velocity, position, distance from centroid, signal strength, signal-to-noise ratio, mean connection time, propagation delay ratio, direction changing, vehicle's ID, and vehicle's degree. For example, the relative velocity is commonly used to maximize the link stability and cluster life time at the expense of the cluster coverage area. Most previous works focus on how to maintain cluster stability and prolong the cluster life time, or to form clusters with high throughput. In our work, we focus on expanding the multi-hop clusters coverage

to avoid new RSU installations while keeping the packet transmission delay from vehicles to RSUs below the constraint.

The contributions of this paper are following :

- We propose a coalition graph game (CGG) model to form a multi-hop clustering for vehicles to cooperatively gather, aggregate, and forward data to a sink node or an RSU.
- Our proposed work maximizes the cluster area of network for a given transmission delay constraint. The stability of cluster formation is proved by using a discrete-time Markov chain.

The remainder of this paper is organized as follows. In Section 2, we review related works on clustering techniques in VANETs and discuss their limitations and issues. In Section 3, we develop coalition graph game (CGG) model to form a multi-hop clustering for vehicles. In Section 4, we model the proposed CGG model by using a discrete-time Markov chain to analyze the stability of cluster formation. In Section 5, the performance evaluation and simulation results to demonstrate the effectiveness of the proposed model are presented. Finally, the discussion and conclusion are offered in Section 6.

2 Related Work

We can classify VANET clustering into many categories depending on clustering metrics and grouping mechanisms – flat and hierarchical clustering, centralized and decentralized clustering, single-hop and multi-hop clustering, single-metric and multi-metric clustering, uplink (vehicles-to-RSU) and downlink (RSU-to-vehicles) clustering. In flat clustering, there is no rank among cluster members. Every vehicle in the flat cluster can independently connect together as peer-to-peer, broadcasting, or flooding. In hierarchical clustering, the rank is assigned for every vehicle in the cluster to enable inherent tree-based routing. Early works in hierarchical clustering use node IDs in the Cluster Head (CH) selection [3, 4], which is not robust against mobility. Clustering techniques aiming to prolong the cluster lifetime use received signal strengths [5] or node locations from GPS to derive the relative velocities of nodes [6, 7]. Cluster stability can also be improved by the minimum distance and minimum relative velocity between CH and its members [8]. However, those clustering techniques yield clustering diameters that are limited to at most two hops.

Multi-hop clustering using relative mobility to select CHs is proposed in [9], where each node will connect to its neighbor that is already a CH or cluster member (CM) of a cluster to form a stable multi-hop cluster. The effects of number of hops, the density of CMs, and the vehicle velocity on the successful data delivery and delay are also evaluated. In [10], each node selects one of its one-hop neighbors as the target to join based on the relative velocity, the current number of followers, and the historical cluster belonging information. Robust Mobility-Aware Clustering (RMAC) [11] selects CHs based on relative node speeds, locations, and directions. Then single-hop clusters will be merged to form a multi-hop cluster with a larger cluster size. However, the degradation of throughput performance as the cluster enlarges has not been investigated. Other approaches to form multi-hop clusters are proposed in [12, 13]. Dynamic Backbone-Assisted Medium Access Control (DBA-MAC) [12]

forms a linear backbone topology among vehicles for multi-hop connection. So, the data transmission may have high delay under a zigzag backbone. Cluster-Based Location Routing (CBLR) [13] creates multiple single-hop clusters that are merged into a multi-hop cluster where a border node in each cluster is assigned as the gateway to relay traffic from one CH to another. Both works form clusters to route traffic among vehicles in the network but do not consider the delay transmission constraints in the cluster formation.

Another line of works applies game theory to multi-hop clustering, where various types of metrics are combined to form a payoff or utility function. Vehicles are competitors or players in the game and each player chooses the best action strategy to join and un-join clusters to obtain the best utility. Game patterns can be both selfishly and cooperatively but every competition has the same purpose of finding the equilibrium point or the best strategy of all players. In [14], an Evolutionary Game Theoretic Approach for Stable and Optimized Clustering in VANETs (EGT) is proposed that balances the population size of clusters by applying iterative evolutionary process until the utility is converged. However, the clusters are of single-hop with a link connecting CH to RSU. Each vehicle has a strategy to select a cluster to join a membership. The metrics used in the utility function are channel capacity and throughput. The RSU acts as the centralized node to compute the total throughput. In each iteration, the replicator adjusts the proportion of population between clusters to find the equilibrium point and the cluster stability is proved by using the Lyapunov function. For cooperative game theory, in [15], the coalitional game is modeled to deliver downlink packets from an RSU to mobile nodes. The social network analysis (SNA) is used to group mobile nodes in the game to reduce the complexity of coalitional formation and filter out those which cannot help the coalition. Nash bargaining game is applied to find the optimal probabilities that mobile nodes will help others in the same coalition, derive the utility function, and then analyze the stability of coalitional structure by using a discrete-time Markov chain. However, the solution space of the coalitional game grows as the factorial complexity, and the distributed iterative merge-and-split rules are developed to find a stable coalition-formation structure. The model for up-link packets from vehicles to an RSU is yet to be developed.

In many scenarios, not only membership of coalition affects the utility but also the relationship between members in coalition. The works in [16] and [17] consider the coalitional graph game where players have a relationship that can be modeled by a graph and such relationship affects the utility of each player. It was shown that for two coalitions with the same finite number players, varying the link structure will change the utility of each player. However, only a single-hop coalition modeled by an undirected graph is considered in [16, 17]. A multi-hop coalition modeled by a directed graph remains to be studied.

3 Method

3.1 CGG Model and Assumptions

We consider a set of vehicles in a suburban or urban road network with one or more RSUs where individual vehicles collect and transmit data to a nearby RSU via other vehicles. The goals are to form a multi-hop cluster covering an area as

large as possible with a given transmission delay time constraint from the vehicles to RSUs. Each vehicle is assumed to be equipped with a GPS device and sensors so that the local knowledge about its position, velocity, movement direction are known and data related to surrounding events of interest can be collected for transmission to RSUs. We also assume that the radio transmitter has adjustable transmission ranges and two separate communications channels are available so that data transfer and clustering traffic do not interfere.

A coalition is defined as the cooperation between nodes in taking data from all offspring nodes to a parent node. The vehicles are grouped as clusters to form a coalition. Each cluster has one vehicle as a cluster head (CH) and at least one cluster member (CM) as a child node. Data flows from CM to CH via a single-hop. A coalition merges clusters together and can expand the network area as shown in Figure 1. The CH of one cluster can become a member of another neighboring cluster when it joins the coalition and its status changes to a dual status (both CH and CM simultaneously) referred to as CMH. Routing is automatically formed by the tree structure where data flows from leaf nodes and aggregated when passing each CMH nodes on the route until reaching the sink node. In most cases, the sink node is one of the RSUs, which is a CH and also a parent node in coalition. If no RSU exists, the vehicle that is the current top level node will be the CH instead.

3.2 Cluster and Coalition Formation

The number of clusters to join the coalition is limited by the transmission delay time constraint specified prior to the clustering. We use a coalition formation graph game with non-transferable utility (NTU) to maximize the coalition area A_i while satisfying the transmission delay time T_i from node i to the sink node or its supreme CH node. The coalition formation graph game is a type of the cooperational game theory where the utility is affected by both membership and relation structure between members of the coalition. It can be analyzed with the relational link graph among players in the game. The NTU is a sub-type of the coalitional game with the utility scoring rule being that any player cannot transfer its utility directly to another player in the same coalition but can take some action to support its coalition to increase the utility.

We model the coalition formation of connected multi-hop clusters as shown in Figure 2. The set of all vehicles and RSU, denoted by $N = \{1, 2, 3, \dots, |N|\}$, are players in the game. Each node i has a 2D position (x_i, y_i) and $d_{t_x \rightarrow r_x}$ be the euclidean distance from transmitter node t_x and receiver node r_x . For any vehicle node i , its coalition is denoted by $family(i)$ which is a set of its parent node, itself, and all its successors. The coalition area of node i covering all the family of node i is calculated as

$$A_i = \begin{cases} 0 & ; \text{node } i \text{ is alone (singleton-coalition)} \\ \pi R_{cen \rightarrow bor}^2 & ; \text{otherwise} \end{cases} \quad (1)$$

where the radius $R_{cen \rightarrow bor}$ is the euclidean distance from the centroid of family nodes of i that locates on position (x_{cen}, y_{cen}) to a border node (farthest node) of

family of i , and the centroid (x_{cen}, y_{cen}) of coalition area A_i is just the average of all the family members' position in the coalition.

Let $parent(i)$ be the parent of node i and $offspring(i)$ be a set of all offsprings of node i . T_i is the largest transmission delay time that data travels from any of $offspring(i)$ through node i to $parent(i)$. It is calculated from a maximum transmission time from any node in $offspring(i)$, plus the transmission time from node i to its parent node. If the node i is only one member in the coalition, the transmission delay time is zero because it does not transmit any data. Therefore,

$$T_i = \begin{cases} 0 & \text{; node } i \text{ is alone} \\ & \text{(singleton-coalition)} \\ \left[\max_{j \in offspring(i)} (T_{j \rightarrow i}) \right] + T_{i \rightarrow parent(i)} & \text{; otherwise} \end{cases} \quad (2)$$

$$T_{i \rightarrow parent(i)} = \frac{D_i}{\widehat{TP}_{i \rightarrow parent(i)}} \quad (3)$$

where $T_{i \rightarrow parent(i)}$ is the transmission time from node i to its parent node and D_i is the amount of aggregated data from node i , consisting of data from itself Δ_i and all of its offspring nodes as depicted in Figure 2. The maximum throughput $\widehat{TP}_{i \rightarrow parent(i)}$ between node i and its parent node is approximated based on Gupta-Kumar's model [18] as

$$\widehat{TP}_{i \rightarrow parent(i)} \propto \frac{C_{i \rightarrow parent(i)}}{\sqrt{n \log n}} \quad (4)$$

where n is the number of nodes in the same cluster of node i (including itself, its parent, and its siblings) and $C_{i \rightarrow parent(i)}$ is approximated from the Shannon capacity formula

$$C_{i \rightarrow parent(i)} = B \log_2 \left(1 + \frac{P_{rx}}{N_0} \right) \quad (5)$$

where B is the channel bandwidth, P_{rx} is the received power at $parent(i)$ that has decayed along with the distance from transmitter node, and N_0 is the noise power. Essentially, the maximum throughput $\widehat{TP}_{i \rightarrow parent(i)}$ depends on the distance between nodes and the number of nodes in the cluster.

Any coalition S can be regarded as the subset of N ($S \subseteq N$). Each player attempts to increase its coverage area by joining another coalition and to increase its utility as much as possible. However, a larger coverage area leads to throughput reduction and hence more transmission delay time to the sink node because the longer transmission distance and more interfering nodes. Thus, the utility of each player can be represented as a sum of gain and cost where the gain is the coverage area and the cost is the transmission delay time from its most distant offspring node to its parent node. Each player cannot transfer its utility to another but can join or merge coalition with another to get higher utility altogether.

The utility u_i of node i when joining the coalition can be defined as a function of coalition area A_i and transmission delay time T_i as

$$u_i = (\alpha A_i - \tau T_i) + (\rho_i - \psi_i) \quad (6)$$

where the α and τ are the positive constants to weigh the importance between the coverage area and the transmission delay time. The parameters ρ_i and ψ_i are respectively the reward and penalty. Node i gets a reward ρ_i if it connects to a coalition that has an RSU as a member. We use a constant reward value ρ_i of 100 for a coalition having an RSU and zero otherwise. Node i gets a penalty ψ_i if its velocity is much different with its parent node. In particular, the penalty ψ_i is defined as the magnitude of relative velocity between node i and its parent node.

$$\psi_i = \begin{cases} 0 & ; \text{node } i \text{ has no parent} \\ |\vec{v}_i - \vec{v}_{parent(i)}| & ; \text{otherwise} \end{cases} \quad (7)$$

3.3 Merge and Split Process

The coalition S which contains all nodes in N is called the grand coalition. However, in our game, the grand coalition may be not guaranteed to occur and there may be many coalitions at the same time. Define the coalitional structure $\Gamma = \{S_1, S_2, \dots, S_m\}$ as a set of m coalitions which occur at the same time. If S_m and $S_{m'}$ occur at the same time, each coalition does not contain the same node, $S_m \cap S_{m'} = \emptyset$ for $m \neq m'$.

The members and rank precedence relationship is represented by the arrow sign ($\rightarrow$). The head of the arrow is pointed to the higher-rank node and the tail of arrow to the lower-rank node. The rank level status of each node can be any one in $L = \{UN, CM, CH, CMH\}$, which respectively denotes un-cluster status, cluster member status, cluster head status, and dual status (both CM and CH). The rank level status can be changed during the clustering process due to merging and splitting of nodes. For a given node, its status can change with the following merging and splitting :

- UN to CM or CH to CMH when the node joins other coalition as a child node.
- UN to CH or CM to CMH when other coalition joins the node as its offspring.
- CM to UN or CH to UN when the node leaves its coalition to be a stand-alone node.
- CMH to CM when all its children leave the node.
- CMH to CH when the parent leaves the node.

For example, suppose at the time step t , the coalitional structure is $\Gamma_1 = \{S_1, S_2, S_3\} = \{(1^{UN}), (2^{UN}), (3^{UN})\}$. At time step $t + 1$, if nodes 1 and 2 merge such that $S_1^{new} = (1^{CH} \leftarrow 2^{CM})$, the new coalitional structure will be $\Gamma_2 = \{S_1^{new}, S_3\} = \{(1^{CH} \leftarrow 2^{CM}), (3^{UN})\}$.

The merge and split process is the critical part in our game model. Each node i in current coalition $S_m, S_{m'}$ can join or leave to the new coalition S_m^{new} based on

the merge and split rules. For the merge rule, let the current coalitional structure be $\Gamma_1 = \{S_m, S_{m'}\}$ where $S_m \cap S_{m'} = \emptyset$ for $m \neq m'$. Each current coalition S_m can merge with another current coalition $S_{m'}$ and becomes a new coalition S_m^{new} if all members of all coalitions do not obtain lower utility, i.e., $u_i(S_m^{new}) \geq u_i(S_m)$ and $u_i(S_m^{new}) \geq u_i(S_{m'})$; $\forall i \in S_m^{new}$. The new coalition after merging will be denoted by $\Gamma_2 = \{S_m^{new}\}$.

For the split rule, let the current coalitional structure be $\Gamma_1 = \{S_m\}$. The members of current coalition S_m can split to multiple new coalitions $S_m^{new}, S_{m'}^{new}$ where $S_m^{new} \cap S_{m'}^{new} = \emptyset$ if they obtain higher utility than the current coalition, i.e., $u_i(S_m^{new}) \geq u_i(S_m)$ and $u_i(S_{m'}^{new}) \geq u_i(S_m)$; $\forall i \in S_m$. The new coalition after splitting will be denoted by $\Gamma_2 = \{S_m^{new}, S_{m'}^{new}\}$.

4 Stability Analysis of Cluster Formation

A coalition S_m is called internally stable if no member can improve its utility by leaving or splitting out of the coalition, and called externally stable if it cannot improve its utility by joining or merging with another coalition $S_{m'}$. We need to find the optimal coverage coalition area A_i of the biggest coalition S_m with the constraint that the transmission delay time T_i being less than the limit or expiration time T_{expire} . We can obtain the maximum coverage area by maximizing the utility function of the supreme parent cluster head when its coalitional structure $\Gamma = \{S_1, S_2, \dots, S_m\}$ is in the stable state using the following formulation :

$$A^* = \arg \max_{A_i} [u_i(S_m, A_i, T_i)] \quad (8)$$

subject to : $T_i < T_{expire}$, $u_i \geq 0$, and $A_i \geq 0$, where $(i = i^{CH}) \in S_m$

The maximum utility, if exists, should locate at the concave point or convergence level. At that point or level, where $du/dA = 0$. After calculating the utility of all member nodes in the coalition, the value $v(S)$ of coalition S is the sum of utilities

$$v(S) = \sum_{\forall i \in S} u_i(S) \quad (9)$$

We use a discrete-time Markov chain (DTMC) to analyze the stable coalitional structure. In our model, it can be proved that for all coalition $S \subseteq N$ if the summation of singleton coalition is less than the value of non-singleton coalition. In other words, if $\sum_{i \in S} v(\{i\}) < v(S)$, there will be at least one absorbing state. Since the utility of players will be equal to zero when they act alone ($\sum_{i \in S} v(\{i\}) = 0$), the non-singleton coalition is higher than zero. So, there will be at least one stable steady state in Markov chain.

Let $\Omega = \{\Gamma_1, \Gamma_2, \dots, \Gamma_\gamma\}$ be the state space of a DTMC where γ is the number of possible coalitional structures. Let Q be the transition matrix whose entries are the probabilities $q_{\Gamma_g \Rightarrow \Gamma_{g'}}$ that the coalitional structure changes from current structure

Γ_g to the new structure $\Gamma_{g'}$ in the time step, which is given by

$$Q = \begin{bmatrix} q_{\Gamma_1 \Rightarrow \Gamma_1} & \cdots & q_{\Gamma_1 \Rightarrow \Gamma_g} & \cdots & q_{\Gamma_1 \Rightarrow \Gamma_\gamma} \\ \vdots & \ddots & \vdots & & \vdots \\ q_{\Gamma_g \Rightarrow \Gamma_1} & \cdots & q_{\Gamma_g \Rightarrow \Gamma_g} & \cdots & q_{\Gamma_g \Rightarrow \Gamma_\gamma} \\ \vdots & & \vdots & \ddots & \vdots \\ q_{\Gamma_\gamma \Rightarrow \Gamma_1} & \cdots & q_{\Gamma_\gamma \Rightarrow \Gamma_g} & \cdots & q_{\Gamma_\gamma \Rightarrow \Gamma_\gamma} \end{bmatrix} \quad (10)$$

Let $Z_{\Gamma_g \Rightarrow \Gamma_{g'}}$ be the set of coalitions which can change from current coalitional structure Γ_g to new coalitional structure $\Gamma_{g'}$. An example of the DTMC state transition diagram based on possible coalitional structures of three vehicles $N = \{1, 2, 3\}$ is shown in Figure 3. The transition probability in the matrix Q can be calculated by

$$q_{\Gamma_g \Rightarrow \Gamma_{g'}} = \frac{\left[\sigma_{\Gamma_g \Rightarrow \Gamma_{g'}} \right] \left[u_{i^{CH}}(S_m^{new}) \right]}{\omega_{\Gamma_g \Rightarrow \Gamma_{g'}}} ; S_m^{new} \in \Gamma_{g'}, \quad i^{CH} \in S_m \in Z_{\Gamma_g \Rightarrow \Gamma_{g'}} \quad (11)$$

where $u_{i^{CH}}(S_m^{new})$ is the utility of vehicle i who used to be a member of coalition in $Z_{\Gamma_g \Rightarrow \Gamma_{g'}}$ and has a rank cluster head CH when changes to the new coalition S_m^{new} . This utility can tell the possibility of changing to the new coalition structure. The utility is normalized by dividing by $\omega_{\Gamma_g \Rightarrow \Gamma_{g'}}$ before putting in the matrix Q so that $0 \leq q_{\Gamma_g \Rightarrow \Gamma_{g'}} \leq 1$, where

$$\omega_{\Gamma_g \Rightarrow \Gamma_{g'}} = \sum_{g'=1}^{\gamma} \left[\sigma_{\Gamma_g \Rightarrow \Gamma_{g'}} \right] \left[u_{i^{CH}}(S_m^{new}) \right] ; S_m^{new} \in \Gamma_{g'}, \quad i^{CH} \in S_m \in Z_{\Gamma_g \Rightarrow \Gamma_{g'}} \quad (12)$$

The normalization term $\omega_{\Gamma_g \Rightarrow \Gamma_{g'}}$ is the sum of utilities obtained from vehicle i^{CH} in every possible new coalitional structures, and the $\sigma_{\Gamma_g \Rightarrow \Gamma_{g'}}$ is an indicator variable denoting the merging or splitting of a vehicle to change from the current coalitional structure Γ_g to the new coalitional structure $\Gamma_{g'}$:

$$\sigma_{\Gamma_g \Rightarrow \Gamma_{g'}} = \begin{cases} 1 & ; u_{i^{CH}}(S_m^{new}) \geq u_{i^{CH}}(S_m) \\ 0 & ; \text{otherwise} \end{cases} \quad (13)$$

Then, we can solve for the stationary probability vector from $\vec{\pi} = [\pi_{\Gamma_1} \dots \pi_{\Gamma_g} \dots \pi_{\Gamma_\gamma}]$ from $\vec{\pi} = \vec{\pi}Q$ and $\vec{\pi}e = 1$. This stationary probability vector $\vec{\pi}$ shows the probability that each coalitional structure can be formed. The structure with highest probability will be the most stable structure.

5 Experimental Results

We separate the experiments into two parts. First, we evaluate the static scenario based on the discrete-time Markov chain model to find the stable coalitional structure. Second, we evaluate the dynamic scenario based on simulation of random vehicle movement where the vehicle positions are updated every 0.1 seconds.

5.1 Static Scenario

Because the number of states in the DTMC grows in a factorial class with the number of vehicles, we limit our evaluation to a simple scenario with a set of three players $N = \{1, 2, 3\}$ with positions $(x_1, y_1) = (10, 25)$, $(x_2, y_2) = (20, 30)$, and $(x_3, y_3) = (30, 20)$. Initially, each player acts alone and its state is un-cluster (UN) with the initial coalitional structure $\Gamma_1 = \{S_1 = (1), S_2 = (2), S_3 = (3)\}$. The utility function of each player is zero because it acts alone. From the initial coalition structure, the state can change to one of the 16 possible coalitional structures as shown in Figure 3.

For the weight coefficients $\alpha = 2$ and $\tau = 1$, we calculate the utilities of each vehicle as shown in Figure 4(a) for all 16 coalitional structures. The result shows that the utility of vehicle 2 that acts as a CH has the highest utility in the 9th coalitional structure. We use this utility to calculate and normalize the row sum of the transition probability $q_{\Gamma_g \Rightarrow \Gamma_{g'}}$ and solve for the stationary probability vector $\vec{\pi}$ as shown in Figure 4(b). The result shows that the most stable coalitional structure is $\Gamma_9 = \{(1 \rightarrow 2 \leftarrow 3)\}$, where vehicle 2 acts as a CH and vehicles 1,3 act as CM, as shown in Figure 4(c).

In Figure 5, we vary the weight coefficient $\alpha = 1, 2, \dots, 10$ while keeping τ at 1. The increase of α gives more importance to the coalition area than the transmission delay time. Thus, the coalitional structures that have a larger distance between nodes can be formed to cover the area as large as possible. On the other hand, with a small value of α (e.g., $\alpha = 1$), the coalitions with large distance of link between nodes are unstable and cannot be formed.

Next, we replace vehicle 3 with an RSU to observe if the stable coalition structure changes. In this case, the coalition that has the data flows out of the RSU is not allowed and the transition probability to such state becomes zero. The utility of each node at the weight coefficients $\alpha = 2$ and $\tau = 1$ is shown in Figure 6(a) and the stationary probability result obtained from DTMC is shown in Figure 6(b). Now the most stable coalitional structure is $\Gamma_8 = \{(1 \rightarrow 2 \rightarrow RSU)\}$ as shown in Figure 6(c). This structure has the RSU acts as a CH, vehicle 1 as CM, and vehicle 2 as CMH who relay the data from vehicle 1 to RSU.

5.2 Dynamic Scenario

In the dynamic scenario, we apply a random velocity $\vec{v}_i$ within a range of 0 - 30 m/s to each node except the RSU. Then we update the new position of each vehicle every 0.1 seconds in each iteration by $(x_i, y_i)^{new} = (x_i, y_i) + \vec{v}_i t$ where $t = 0.1$ and update the new utility. The difference from the static scenario is the utility has the penalty value calculated from the relative velocity between a node and its parent node. The coalitional structure that is analyzed by the DTMC keeps changes due to the node position changes. Figure 7. shows the stable coalitional structure in each iteration and the scatter plot of utilities of CH nodes in the stable coalitional structure with the coalitional area. As shown in the sample result in Figure 7(a), the coalitional structure converges to the stable structure for a moment and remains there until the vehicle positions have sufficiently changed. The scatter plot in Figure 7(b) reveals that the optimal areas result when the CH utilities are highest.

6 Discussion and Conclusion

In this paper, we propose the coalitional graph game to model the multi-hop clustering among vehicles and RSUs, where the objective is to maximize the network coverage area subjected to the delay time constraint. From analysis using a DTMC, our model has the stable coalitional structure and yields the largest coalitional area satisfying the transmission delay time constraint which economizes RSU installation and maintenance. The effects of weight coefficients in the utility function on the stable coalition structure solution are also explored. The optimal coverage areas are shown to be those with high utilities of CH nodes. Due to the number of possible coalitional structures that grows with a factorial complexity, the exact solution is computationally infeasible for a large number of vehicles. Our future work is to develop a heuristic algorithm to solve the larger problem size.

Abbreviations

BOR: Border; CBLR: Cluster-based location routing; CEN: Centroid; CGG: Coalitional graph game; CH: Cluster head; CM: Cluster member; CMH: CH and CM simultaneously; DBA-MAC: Dynamic backbone-assisted medium access control; DTMC: Discrete-time Markov chain; EGT: Evolutionary game theory; GPS: Global positioning system; ID: Identification; ITS: Intelligent transport system; NTU: Non-transferable utility; RMAC: Robust mobility-aware clustering; RSU: Road side unit; SNA: Social network analysis; UN: Un-cluster; VANET: Vehicular ad-hoc network.

Declarations

Availability of data and materials

The simulation codes and result datasets used for the evaluation and analysis in this research are available from the corresponding authors on reasonable requests.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

SC and PS conceived the idea. SC designed the model, programmed the simulation codes, collected and analyzed the experimental results, and wrote the manuscript. PS gave overall advice, improved and corrected the model, reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1 Clustering and routing formation of our proposed model

Figure 2 Parameters of our proposed model

Figure 3 DTMC transition diagram of possible coalitional structures of 3 vehicles (1, 2, 3)

Figure 4 DTMC results of three vehicles with weight coefficients $\alpha = 2$, $\tau = 1$

Figure 5 Stationary probability of each coalitional structure for weight coefficient $\alpha = 1, 2, \dots, 10$ and $\tau = 1$

Figure 6 DTMC results while vehicle 3 is replaced by RSU with weight coefficients $\alpha = 2$, $\tau = 1$

Figure 7 Simulation results of dynamic scenario

Figure 1

Figure 2

COALITION AREA of NODE i (if $i = 2$)

Figure 3

Figure 4

(a) Node utility

(b) Stationary probability of each DTMC state

(c) The most stable structure Γ_9

Figure 5

Figure 6

(a) Node utility

(b) Stationary probability of each DTMC state

(c) The most stable structure Γ_8

Figure 7

(a) Stable coalitional structure by sampling 3 rounds

(b) Scatter plot between coalitional area vs. utility value of CH node

Figures

Figure 1

Clustering and routing formation of our proposed model

COALITION AREA of NODE i (if $i = 2$)

Figure 2

Parameters of our proposed model

Figure 3

DTMC transition diagram of possible coalitional structures of 3 vehicles (1, 2, 3)

(a) Node utility

(b) Stationary probability of each DTMC state

(c) The most stable structure Γ_9

Figure 4

DTMC results of three vehicles with weight coefficients $\alpha = 2$, $r = 1$

Figure 5

Stationary probability of each coalitional structure for weight coefficient $\alpha = 1, 2, \dots, 10$ and $r = 1$

(a) Node utility

(b) Stationary probability of each DTMC state

(c) The most stable structure Γ_8

Figure 6

DTMC results while vehicle 3 is replaced by RSU with weight coefficients $\alpha = 2$, $r = 1$

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Figure 7

Simulation results of dynamic scenario