

Content Distribution in Vehicular Networks using Coalitional Graph Game

Xiang Fei*, Xi Luan*, Na Yi*, Xiaoning Zhang*, Jianjun Wu*

*Institution of Advanced Communications, EECS, Peking University, China

Email: feixiang@pku.edu.cn, just@pku.edu.cn

Abstract—The popular content distribution (PCD) problem in Vehicular Ad-hoc Networks (VANETs) is considered. We model this problem as a coalitional graph game in which the on-board units (OBUs) try to form a peer-to-peer (P2P) network where one OBU transmits files to multi OBUs but receives from only one OBU each time, to complete the data dissemination efficiently. In this game, the OBUs engage in bilateral negotiations which result in a bilaterally agreement of forming a directed link among OBUs. Once the network is constructed, the OBUs will transmit the content pieces to each other. We study this game under a form of myopic dynamics which is carried out by each OBU in a distributed way. Furthermore, the network formed in this game is a pairwise stable network. Simulation results show that the proposed approach performs better comparing with the non-cooperative case.

Keywords—Vehicular Ad-hoc Networks, popular content distribution, coalitional graph game, myopic, pairwise stable

I. INTRODUCTION

Vehicular Ad-hoc Networks (VANETs) play an important role in vehicular communications nowadays as they provide numerous applications ranging from traffic safety, efficiency to infotainment [1]. Recently, a new application in VANETs, named popular content distribution (PCD), has drawn lots of attentions for its applications in both safety and non-safety-related information dissemination scenarios. In PCD process, the OBUs, which are the vehicles driving on the road, try to download popular multimedia contents provided by the roadside units (RSUs).

The OBUs in PCD are interested in a single large file when driving through RSUs' coverage area with high speeds. Unlike downloading services especially the broadcasting services in traditional cellular networks where downloading services are accomplished by direct transmissions from the base station to the mobile users. The OBUs in PCD problem may fail to receive the entire file directly within the limited time from the RSUs. The OBUs may need to communicate with others after leaving the RSU's coverage to finish the file dissemination process. Inspired by the P2P protocols on the Internet [2], a peer-to-peer (P2P) network using vehicle-to-vehicle (V2V) communications can be constructed among the OBUs to finish the file dissemination process. However, the static methods in typical P2P networks may be inefficient and not applicable due to the high node mobility and error-prone wireless channel in VANETs.

A mobile P2P file sharing system for VANETs was introduced in CodeTorrent [3], in which the communication was limited within single-hop neighbors. Game theory was introduced in

vehicular access to coordinate V2V communications in [4]. The authors proposed a pull-based, peer-to-peer content downloading protocol named SPAWN in [5]. However, the peer and content selection mechanisms in SPAWN that extended from BitTorrent are not available for vehicles to download popular contents.

In this paper, we formulate the PCD problem in VANETs as a coalitional graph game which has been applied to many graph-based communication scenarios recently [6]. The game is under a form of myopic dynamics which is carried out by OBUs in a distributed way and converges into a pairwise stable network. We use the coalitional graph game to coordinate the V2V communication in which one OBU could transmit files to multi OBUs but receive from only one of the other OBUs. This method not only considers the content request and channel capacity but also increases the performance of the network comparing with the non-cooperative case.

II. SYSTEM MODEL

Consider the PCD problem in a VANET with M OBUs (SU) aiming at completing the dissemination of the popular multimedia contents through K PU channels. We formulate this problem as a coalitional graph game in which the OBUs form a directed pairwise stable graph. Once the network is formed, the OBUs would cooperatively proceed the data dissemination. We assume that the communication is limited between the OBUs with a line of sight (LOS) named "neighbors". The popular content which is equally divided into N segments, ought to be possessed by all OBUs. Let $\mathcal{M}$, $\mathcal{N}$, $\mathcal{M}_i$, and $\mathcal{K}$ denote the set of OBUs, the set of segments, the set of the neighbors of OBU i and the set of PU channels. Due to the high mobility and error-prone wireless channel, each OBU in $\mathcal{M}$ only receives parts of all the $\mathcal{N}$ segments directly from the RSU, and the rest are gradually achieved by the V2V communications in which one OBU could transmit files to multi OBUs but receive from only one of the other OBUs each time. Let $\mathcal{N}_i$ denote the set of segments possessed by OBU i . We assume that the initial elements in $\mathcal{N}_i$ are randomly distributed in $\mathcal{N}$.

In this paper, we suppose that the data traffic in each of the $\mathcal{K}$ PU channels is a Poisson process and the package arriving rate is λ per time slot. Thus, the probability that no primary traffic occupies channel k is denoted by $P_0 = e^{-\lambda}$. All OBUs are equipped with a omnidirectional antenna. In each slot, the OBU i broadcasts to its neighbors, and receives from at most one neighbor. For the existing links, we consider the pathloss without

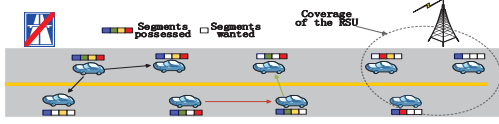


Figure 1. System model of the content distribution problem in VANETs.

small-scale fading, and the V2V channel capacity between OBU i and OBU j in the k -th channel is directly given by

$$c_{i,j}^k = \begin{cases} W_k \log_2(1 + \beta_i d_{i,j}^{-n}(t)), & \text{LOS exists} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where W_k is the bandwidth of the k -th channel, n is the pathloss exponent, $d_{i,j}$ is the distance between OBU i and j , β_i represents signal-to-noise rate (SNR) at transmitters. Without loss of generality, let $W_1 = W_2 = \dots = W_k = W$, $\beta_1 = \beta_2 = \dots = \beta_k = \beta$.

In this paper, we consider the OBUs mobility model reference to the freeway mobility model (FMM) proposed in [7]. A reduced form model is shown in Figure 1, where a dual-lane one-way traffic road is mapped. The OBUs are distributed on the dual-lane road randomly at the beginning of the simulation and was allowed to change lines if needed to reflect the network changing. Denote $v_i(0)$ which is randomly distributed in $[v_{min}, v_{max}]$, as the initial speed of OBU i . v_{min} and v_{max} are the minimum and maximum speed of the OBUs. Let d_{min} be the security distance maintained between two contiguous OBUs in the same lane. For any OBU i , with j_1 ahead in the same lane, j_2 ahead and j_3 behind in the other lane, OBU i can change to the other lane if and only if: $d_{i,j_1}(t) \leq d_{min}$, $d_{i,j_2}(t) \geq d_{min}$ and $d_{i,j_3}(t) \geq d_{min}$. Otherwise, OBU i decelerates to $v_i(t+1) = v_{min}$ if $v_i(t) \geq v_{j_1}(t)$. For any OBU $i \in \mathcal{M}$, if $d_{i,j_1} \geq d_{max}$, then OBU i speed up to $v_i(t+1) = v_{max}$. In case of OBU $i \in \mathcal{M}$ don't have to change speed, the speed of OBU i satisfies:

$$v_i(t+1) = \begin{cases} \min(v_i(t) + a, v_{max}), & p \\ v_i(t), & 1-2p \\ \max(v_i(t) - a, v_{min}), & p \end{cases} \quad (2)$$

In non-cooperative manner, the OBUs in $\mathcal{M}$ do not coordinate with each other for the V2V communication. The OBUs broadcast their content requests to their neighbors and randomly response to their neighbors' content requests. For any OBU $i \in \mathcal{M}$ who would response other OBUs' request (i.e., wants to transmit packets) will individually sense the $\mathcal{K}$ channels, then access the channel whose sensing results is empty using the carrier sense multiple access with collision avoidance (CSMA/CA) protocol.

III. COALITIONAL GRAPH GAME

Due to the random establishment of V2V links in non-cooperative manner for the PCD problem, the links may be inefficient for communication and some OBUs may even have no "neighbor" to be connected to. Thus the whole network may suffer from low data throughput. In this section, we formulate the PCD problem in VANETs as a coalition graph game. The

game is under a form of myopic dynamics which results in a directed graph $G(V, E)$ with V denoting the set of the OBUs and E denoting the set of the V2V links. For any $i, j \in V$, $ij \in E$ means that a directed link from i to j exists. Denote d_i^{in} and d_i^{out} as the in-degree and out-degree of OBU $i \in \mathcal{M}$ in the graph, then d_i^{in} and d_i^{out} satisfies $0 \leq d_i^{in} \leq 1$.

A. Utility Function

Denote the possibility of successful transmission from OBU i to j by $P_{i,j}$. For a successful transmission in channel $k \in \mathcal{K}$, the channel should not be occupied by a primary user and none of OBU j 's neighbors except i can transmit at the same channel.

Let H_1 denote the hypothesis that channel $k \in \mathcal{K}$ is actually occupied by a primary user, and H_0 the alternative hypothesis. Also, let H'_1 denote the hypothesis that the sensing result of OBU i shows that channel k is occupied by a primary user, and H'_0 the alternative hypothesis. The probability of miss and false alarm are denoted by P_m and P_f . Thus, the probability of correct empty decision is given by [8]:

$$P(H_0|H'_0) = \frac{P(H_0)P(H'_0|H_0)}{P(H'_0|H_0)P(H_0) + P(H'_0|H_1)P(H_1)} \quad (3)$$

where $P(H_0) = P_0$, $P(H_1) = 1 - P_0$, $P(H'_0|H_1) = P_m$, and $P(H'_0|H_0) = 1 - P_f$.

Totally speaking, there are KP_0 channels available for V2V communications and OBU i accesses one of them. Thus, the possibility that all the OBUs in $\{\mathcal{M}_j \setminus i\}$ do not transmit at the same channel of OBU i is given by:

$$P_1 = \left(\frac{KP_0 - 1}{KP_0}\right)^{|\mathcal{M}_j| - 1} \quad (4)$$

Thus, the probability of successful transmission is given by

$$P_{i,j} = P(H_0|H'_0)P_1 \quad (5)$$

We assume both segments received from and transmitted to other OBUs in the network would bring corresponding profits. The utility function of OBU i given by $\pi_i(G)$ is related with segments successfully transmitted and the network graph $G(V, E)$.

When OBU i transmits segments to multi neighbors, it may need to calculate the set and the sequence of the segments to be transmitted, to get a high utility. We propose a greedy algorithm for choosing the segments broadcasted by each OBU $i \in \mathcal{M}$. Let $\mathcal{N}_{i,j} = (\mathcal{N} \setminus \mathcal{N}_j) \cap \mathcal{N}_i$ represents the set of useful segments that OBU i can offer to OBU j . Denote $\Omega_i = \{j | ij \in E\}$ as the set of OBUs that OBU i connects to. Then the set of the segments that OBU i could offer to Ω_i is given by $\mathcal{N}_{i,b} = \bigcup_{j \in \Omega_i} \mathcal{N}_{i,j}$, where the

first segment in $\mathcal{N}_{i,b}$ has the maximum weight factor, and the last segment in $\mathcal{N}_{i,b}$ has the minimum weight factor. The weighting factor of a segment $n \in \mathcal{N}_{i,b}$ is defined as the number of OBUs in Ω_i that wanted segment n . Given that, OBU i transmits the segments in $\mathcal{N}_{i,b}$ sequently in each slot. The transition time in each slot is T . Denote $\mathcal{N}_{j,r}^k$ as the set of segments that OBU j receives from OBU i in the k -th channel, given by:

$$\mathcal{N}_{j,r}^k = \mathcal{N}_{i,b} \{1 \sim \lfloor \frac{c_{j,i}^k T}{s} \rfloor\} \cap \mathcal{N}_{i,j},$$

Denote γ_{out} and γ_{in} as the pricing factor. Then the corresponding benefit of the transmitted segments and the received segments, denoted by $\pi_i^{out}(G)$ and $\pi_i^{in}(G)$, is given by

$$\pi_i^{out}(G) = \begin{cases} \max_k \sum_{j \in \Omega_i} \gamma_{out} P_{j,i} \mathcal{N}_{j,r}^k, & d_i^{out} \geq 1, k \in K \\ 0, & d_i^{out} = 0 \end{cases} \quad (6)$$

$$\pi_i^{in}(G) = \begin{cases} \gamma_{in} P_{j,i} \mathcal{N}_{i,r}, & d_i^{in} = 1, j \in E \\ 0, & d_i^{in} = 0 \end{cases} \quad (7)$$

For transmitting or receiving data, a certain channel is occupied by OBU i , which will increase the probability of transmission collisions. For the link from OBU i , potential collisions are limited in $\mathcal{M}_i \setminus \Omega_i$. For the link from OBU j to OBU i , the interference is confined in $\mathcal{M}_j \setminus \Omega_j$. Thus the cost is given by the following function with $\gamma_{cost} > 0$ as the pricing factor.

$$C_i(\lambda_{out}^i, \lambda_{in}^i) = \begin{cases} \gamma_{cost}[(\mathcal{M}_i - d_i^{out}) + d_i^{in} \frac{(\mathcal{M}_j - d_j^{out})}{d_j^{out}}], & d_i^{out} > 0, j \in E \\ \gamma_{cost} d_i^{in} (\mathcal{M}_j - d_j^{out}), & \text{otherwise} \end{cases} \quad (8)$$

Given the benefit formulated in (6),(7) and the cost in (8), the utility function of any OBU $i \in \mathcal{M}$ is given by:

$$\pi_i(G) = \pi_i^{in}(G) + \pi_i^{out}(G) - C_i(\lambda_{out}^i, \lambda_{in}^i) \quad (9)$$

B. Dynamics of Network Formation

In this section, a myopic dynamic including three stages at every round is proposed for our coalitional graph game. Myopic dynamics refer to the property of the dynamics that at any given round, nodes update their strategic decisions only to optimize their current utility which is in contrast to dynamics that consider forward looking strategies [9]. In our proposed dynamics, one OBU can transmit segments to multi OBUs but receive from only one of the other OBUs. The proposed algorithm is a dynamic process of iterated local actions without central coordination, and the network turn out to be a directed graph.

Given the current transmission graph $G(V, E)$, the available actions for any OBU i can be: (1) request to set up a new link ij , if $ij \notin E$. (2) accept OBU j 's request for the link ji , if $d_i^{in} = 0$. (3) break current link ij , if $ij \in E$. (4) break current link ji , if $ji \in E$. (5) a combination of item 1 ~ 4.

Consider a coalitional graph game where each OBU selects other OBUs to connect to or to be connected from. Formally, in each round, OBU i selects $f_i \in \mathcal{M}$ to accept connections from, and a subset $T_i \in \mathcal{M}$ of OBUs to connect to. Denoting (f_i, T_i) as the state of OBU i , the strategy space of OBU i is $S_i = \{(f_i, T_i) | f_i \in \mathcal{M}, T_i \in \mathcal{M}\}$. An directed link is formed between OBU i and j , if $j \in T_i$ and $i \in f_j$. All links are formed in this way. Denote $s_i = G'_{s_i}(V, E')$ as the graph $G(V, E)$ formed when OBU i plays a strategy and the corresponding OBUs accept it while all other OBUs maintain their vector of strategies. At each round, only one new link should be added or replaced.

TABLE I. DYNAMICS FOR COALITIONAL GRAPH GAME

A randomly selected OBU $i \in \mathcal{M}$ engages in the Dynamics
1. achieve necessary information from its "neighbors" in $\mathcal{M}_i$, and calculate the set of practicable strategies.
2. OBU i plays a practicable local strategy $s_i = (f'_i, T'_i) \in P_i$ as defined.
a) OBU i choose to unilaterally break the link $ik, k \in T_i$ if doing so improves its utility.
b) OBU i requests to form link ij with OBU $j \in T'_i, j \notin T_i$
OBU j accept the link (by adds ij or replaces one or more of its current links with ij), if doing so improves its utility.
3. Update the graph $G(V, E)$ and OBUs' strategies.
Multi rounds are carried out until convergence to a final pairwise stable network $G^*(V, E^*)$.

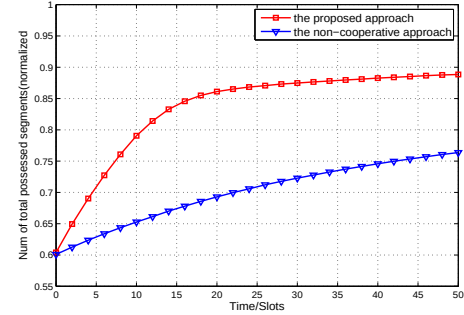


Figure 2. Total possessed segments of all OBUs in the network by the proposed approach and the non-cooperative approach as a function of time.

For any OBU $i \in \mathcal{M}$ with the state (f_i, T_i) , we call a strategy $s_i = (f'_i, T'_i) \in S_i$ as a practicable local strategy if: (1) $\pi_i(G'_{s_i}) \geq \pi_i(G)$ (2) $\pi_{f'_i}(G'_{s_i}) \geq \pi_{f'_i}(G), \forall f'_i \neq i, f'_i \in N$ (3) $\pi_{t'_i}(G'_{s_i}) \geq \pi_{t'_i}(G), \forall t'_i \neq i, t'_i \in T'_i, t'_i \notin T_i$ where G is the current graph, G'_{s_i} is the consequent graph by strategy s_i and corresponding OBUs' actions. Denote $P_i \in S_i$ as the set of practicable strategies for OBU i . Table I give a summarize of the dynamics we proposed.

As the link formation requires the consent of two OBUs to form one link(i.e., inherently bilateral), we consider a notion of stability named pairwise stability. Generally, pairwise stability requires that both no unilateral deviations are profitable and that no two nodes can conspire to improve their utility. In our coalitional graph game, as no OBU $i \in \mathcal{M}$ can improve its utility by an unilateral deviation or a bilateral deviation due to the dynamic method, the final network graph $G^*(V, E^*)$ is pairwise stable. Simulation results in the next station verify this.

IV. SIMULATION RESULTS

The performance of the proposed approach in Table I is simulated in various environmental conditions and compared with the non-cooperative manner in this section. The parameters are given by $M = 4 \sim 12, K = 8, P_f = P_m = 0.1, n = 4$ and $\lambda = 0.1$. We do the simulation under a highway scenario with $v_{max} = 40m/s, v_{min} = 20m/s, \alpha = 0.2m/s^2$ and $p = 0.1$.

The number of total possessed segments for both the proposed approach and the non-cooperative method with $M = 6; N =$

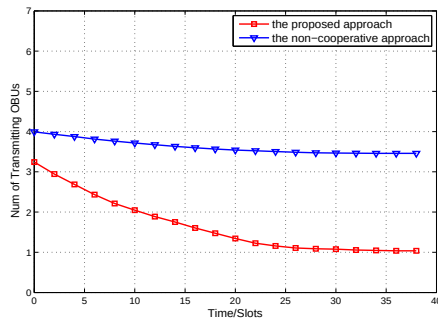


Figure 3. Total number of transmitting OBUs in the network by the proposed approach and the non-cooperative approach as a function of time.

100 was shown in Figure 2. The vertical coordinate has been normalized by the total demand NM and the initial content density possessed by the OBUs at the beginning of the V2V transmission is set to be $\rho_0 = 0.6$. As it shows, the number of total possessed segments increase with time by both methods, but our proposed approach performs a better performance. In non-cooperative manner, the OBUs in $\mathcal{M}$ do not coordinate with each other for the V2V communication. They broadcast their content requests to their neighbors and randomly response to their neighbors' content requests. In our proposed approach, as the OBUs make decisions based on the benefits of both ends cooperatively, the network graph formed in each time slot would be efficient, which, in result, increases the total performance.

The number of transmitting OBUs in the network as a function of time for both the proposed approach and the non-cooperative method with $M = 5, N = 80$ is shown in Fig. 3. The number of transmitting OBUs by the proposed approach declines to a low level compared with the non-cooperative method. In non-cooperative manner, as a result of data collisions, the successful data transmission rate is low, thus the potential users decrease slowly. In our proposed approach, the segments are transmitted to more than one OBUs which decrease the potential collisions and increase the total performance of the network. With more segments possessed by OBUs, the potential users decrease, which lowers the utility for broadcasting and consequently leads to the descending number of transmitting OBUs.

V. CONCLUSION

In this paper, we propose a myopic dynamic method for the network formation of the coalitional graph game to address the PCD problem in VANETs. In the proposed game model, the OBUs cooperate with each other to form an efficient P2P network. During the content distribution process, one OBU transmits segments to multi OBUs but receives from only one OBU. The myopic dynamics converges to a final pairwise stable network. Simulation results show that our approach has a better performance compared with the non-cooperative method.

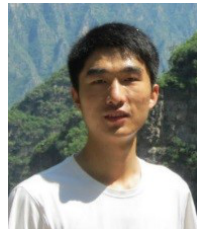
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Xiang Fei received his bachelor degree in communication engineering from Nankai University, Tianjin, P.R. China, in 2012. Since 2012, he has been a postgraduate student in Institution of Advanced Communications, Peking University, China. His research interests are in the area of satellite mobile communications compatible with LTE. Email: nkfeixiang@gmail.com.



Jianjun Wu received his B.S., M.S. and Ph.D. degree from Peking University, Beijing, P. R. China, in 1989, 1992 and 2006, respectively. Since 1992, he has joined the School of Electronics Engineering and Computer Science, Peking University, and has been appointed as an associate professor since 2002. His research interests are in the areas of satellite communications, wireless communications, and communications signal processing. *The corresponding author. Email: just@pku.edu.cn.