A Network Coding Collaborative Download Scheme for Platoon-Based VANETs

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Abstract. Platoon-based Vehicular Ad-hoc Networks (VANETs) can significantly improve the road capacity and facilitate the potential cooperative communication applications. However, the communication links between platoon-based vehicles and the roadside unit (RSU) are unstable, which decrease the throughput and increase the delay, and cause the infotainment resources cannot be downloaded quickly. In this paper, we propose a collaborative download strategy in platoon-based VANETs to solve the problems. On the basis of RSUs support simultaneous communication with multiple vehicles, when a demand vehicle need to download multimedia files, we use the collaborative download request management mechanism to request other vehicles in the same RSU coverage area to participate in the collaborative download process. Besides, to decrease the download time, we divide the required multimedia files into multiple data packets. After the RSUs encode the data packets via linear network coding, the cooperative vehicles forward the received encoded packets to the demand vehicle. We also research the impact of speed and file size on the performance of cooperative download strategy. The simulation results show that the proposed cooperative download strategy can effectively increase throughput and reduce the downloading completion time when download multimedia files, especially when the size of multimedia files is large and the speed of platoon-based vehicles is fast.

Keywords: Platoon-based VANETs · Collaborative download
Request management · Network coding · File segment

1 Introduction

The platoon-based driving pattern [1] can significantly enhance the traffic efficiency, safety and entertainment applications performance for Vehicular Ad-hoc Networks (VANETs). In the platoon, the follower vehicles can trace the road

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without driving operation, so it also known as the formation of semi-automatic driving mode [2,3]. Platoon-based VANETs is committed to providing vehicles with high quality, accurate, real-time vehicle services, which consist of active safety applications [4] and non-safety applications [1], such as traffic safety information and automotive multimedia entertainment resources.

In platoon-based VANETs [5], the drivers and passengers in the follower vehicles have enough time to enjoy the infotainment services, so the demand for multimedia resources is more prominent. However, in the platoon-based VANETs, many of the data services, especially the multimedia infotainment services are usually with large volumes of data, which need a long time to download these resources. Moreover, the low throughput and the unstable communication link between the vehicles and roadside unit (RSU) [5] effect the performance of download, which cannot meet the passengers requirements on multimedia entertainment information.

To solve the problem that the communication links between platoon-based vehicles and RSU are unstable, which decreases the throughput and increases the delay during the downloading process, we propose a network coding cooperative download scheme in platoon-based VANETs. First, a collaborative download request management mechanism is designed, which focuses on the communication protocol between a vehicle in the platoon and other cooperative node, i.e. vehicles or RSU, to support the collaborative download. Then we propose a file segment strategy based on the collaborative download request management mechanism to divide the required files into multiple data packets. Besides, RSU use the linear network coding to encode these data packets and send them to all cooperative vehicles. Finally, a data forwarding mechanism between the vehicle and cooperative vehicles is proposed to ensure that the cooperative vehicles forwards all the received coded packets to the demand vehicle before entering the next RSU coverage area.

The rest of this paper is organized as follows. Section 2 overviews the related work. Section 3 presents our platoon-based VANETs system model for collaborative downloading. We propose a network coding cooperative download strategy in platoon-based VANETs in Sect. 4. Performance evaluation is presented in Sect. 4.3. Finally, Sect. 5 concludes this paper.

2 Related Works

In some earlier works, different collaborative download schemes has been proposed for platoon-based VANETs. Most of them studied collaborative download strategy for traditional VANETs. In [6], the authors proposed a new model for analyzing the connectivity probability to provide better performance in terms of multi-hop delay and there exists an optimal one-hop transmission range to minimize the multi-hop delay. In [7], the authors divided the file into a number of data packets and then used the peer-to-peer (P2P) or BitTorrent methods to collaborative download. In [8,9], instead of considering data distribution from RSU to vehicles, the authors researched Vehicle-to-Vehicle (V2V) data forwarding and information sharing in the RSU coverage blind area. Besides, researchers have introduced network coding into the traditional collaborative download scheme to reduce the data transmission error rate and communication protocol costs. In [10], the authors investigated the application of network coding in collaborative downloading. It analyzed the derive probability distribution and the expected value of the amount of time necessary to deliver all of the information from RSU to the vehicles with network coding, but it only considered the collaboration downloading between the two vehicles. Based on the theory of [10], in [11], the authors extended the two vehicles to multiple vehicles to study the collaborative downloading. However, the above study results cannot be directly applied into platoon-based VANETs. Hence, in [5], the connectivity probabilities are analyzed for the V2V and Vehicle-to-RSU (V2R) communication scenarios for different driving speed in platoon-based VANETs to improve system throughput. In [12], the authors proposed a cooperative retransmission scheme to deliver multimedia data from a traveling vehicle to RSU reliably. But these works did not involve collaborative download studies. Besides, the problems of low system throughput and high downloading delay still exist and are not solved.

Therefore, in this paper, we propose a network coding collaborative download scheme for platoon-based VANETs, which can effectively increase throughput and reduce the downloading completion time when download multimedia files.

3 Syetem Model

The cooperative download system model in platoon-based VANETs is shown in Fig. 1. The system consists of RSU, vehicles that driving in a platoon-based pattern, central control center, etc. Each vehicle is equipped with two independent broadcasting stations to transmit data, which referred to as On-Board Unit (OBU). The RSU has multiple independent broadcasting stations, each of which adopts the beamforming to communicate over the respective channels,

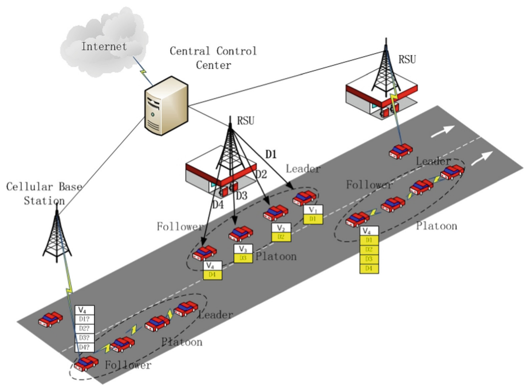

Fig. 1. Collaborative download model for platoon

and supports simultaneously communication with multiple vehicles. Short range communication between OBU of vehicles and RSU can be achieved using IEEE 802.11p [13] protocol in the Dedicated Short Range Communication (DSRC) [14] band. RSU uses optical fiber or microwave technology to access the Internet. When a vehicle want to obtain a specified multimedia resource, the central control center will send the source that vehicle required to RSU, so that RSU can be seen as providers of multimedia resources.

4 Collaborative Download Strategy for Platoon

The collaborative download strategy via network coding in platoon-based VANETs is composed of cooperative download request management mechanism, file segment strategy, V2R data distribution mechanism and V2V data forwarding mechanism. The detailed algorithm is described as follows.

Step 1: When a vehicle in the platoon needs to download the p Mb multimedia files (we call it the demand vehicle), it sends the downloading request to RSU, and then the system executes the collaborative download request management mechanism. The central control center needs to obtain the speed of platoon, the number of collaborative vehicles, the multimedia filename need to be downloaded, and the geographic information of vehicles, etc.

Step 2: Then the central control center executes the multimedia file segment mechanism. It divide the multimedia file into multiple data packets, after calculating the size of each packet, the central control center sends all these packets to RSUs, so that the RSUs are the resource providers.

Step 3: When the platoon driving into the coverage area of the RSU, the RSU will encode the data packets via network coding and send the encoded packets to all collaborative vehicles in platoon, that is the V2R data distribution process. It can also be called V2R data distribution phase.

Step 4: When the last vehicle in platoon leaves the RSU coverage area, the collaborative downloading vehicles will send the encoded packets that they downloaded during the V2R phase to the demand vehicle, which executes the V2V packets forwarding mechanism. It can also be called V2V packets forwarding phase.

Step 5: When the size of encoded packets that the demand vehicle obtained can decode out of the original multimedia file, the download is completed; otherwise, when the vehicles enter the range of the next RSU, they try to obtain the remaining packets. This continues until the demand vehicle can decode the original file.

We call each V2R data distribution phase and its following V2V packets forwarding phase as a round, due to the size of the multimedia file is large, it is obvious that the collaborative downloading strategy cannot download the whole file in one round. The number of rounds that required sending all the encoded packets from RSUs to the vehicles can be used to reflect the time needed to download the whole file. The following subsections provide more detailed information on the proposed collaborative download strategy.

4.1 Collaborative Download Request Management Mechanism

In this subsection, the collaborative download request management mechanism is described detailed. We assume that the vehicle in platoon is the demand vehicle, which needs to download the Mb multimedia file. The operations of the collaborative download request management mechanism are as follows:

- Step 1: The demand vehicle V_k sends collaborative download request to the leader vehicle of the platoon.
- Step 2: The leader vehicle agrees to the request and sends the message to other follower vehicles, which including the information about the demand vehicle, the filename and size of the multimedia file need to be downloaded.
- Step 3: If the vehicle V_p in the platoon owns the needed multimedia resource, it will reply to the leader vehicle and go to Step 4; Otherwise, if other follower vehicles are free now, they reply to the leader vehicle that they will participate in the collaborative download and go to Step 6.
- Step 4: Leader vehicle inform the vehicle that the vehicle V_p owns the resource and cancel the collaborative download request.
- Step 5: The vehicle V_k directly sends the file to the vehicle V_p until the file is downloaded completely.
- Step 6: Leader vehicle collects the information about the follower vehicles that participates in the collaboration, including the MAC address, geographical location, and then sends the information to the demand vehicle V_k.
- Step 7: The demand vehicle V_k sends the downloading request to the central control center through the cellular network.
- Step 8: If the central control center owns the needed file resource, it agrees to download, and go to Step 9, otherwise the collaborative downloading cannot be completed.
- Step 9: The demand vehicle V_k sends the related collaborative download information, such as the collaborative vehicles, the speed of platoon and geographical location to the central control center.
- Step 10: According to the received collaborative download information, the central control center executes the file segment mechanism to divide the original multimedia file into multiple data packets. After calculating the size of each data packet and estimating the rounds needed to complete download, the central control center packages the file segment information, platoon driving information and collaboration information into a collaborative information packet, and then sends the packet to RSUs.
- Step 11: When the vehicles enters the coverage of these RSUs, they connect to RSUs and download the resource immediately. From the above

description of the proposed mechanism, the collaborative download request management mechanism regulates the collaborative request-related operations to make it more systematic, standardized.

4.2 Multimedia File Segment Mechanism

After considered the collaborative download request management mechanism, when a vehicle in platoon requests to download the multimedia file, the central control center will divide the file into multiple data packets and send to RSUs, and then RSUs send the packets to multiple collaborative vehicles. Therefore, in this section, we will describe the multimedia file segment mechanism in detail.

When the RSU simultaneously sends data to multiple vehicles, the signal-to-interference ratio of vehicle V_k can be expressed as:

$$SINR_k = \frac{|h_{k,m}|^2 p_k}{\sum\limits_{i=1, i \neq k}^{K} |h_{i,m}|^2 p_i + \sigma_k^2} \tag{1}$$

where $h_{k,m} = \sqrt{s_{k,m}} h'_{k,m}$ is the composite channel between the RSU and vehicle V_k, $S_{k,m} = (d_{k,m}/d_0)^{-\alpha} 10^{(\mu/10)}$ corresponds to small-scale fading from RSU to the V_k, which includes path loss and shadowing fading. The shadow fading for RSU is modeled as an independent log-normal random variable with standard deviation σ. $d_{k,m}$ denotes the distance between the RSU and V_k, d_0 is used as the reference distance. α indicates the path-loss exponent and μ is a normally distributed random variable with mean σ^2. Also, $h'_{k,m}$ stands for the frequency-flat Rayleigh fading channel coefficient, which is modeled as independent and identically distributed (i.i.d.) complex Gaussian random variable with unit variance. P_k is the transmit power for vehicle V_k, n_k denotes an additive noise whose entries are i.i.d., complex Gaussian, with zero mean and variance. Then the throughput of vehicle can be expressed as σ_k^2:

Then the throughput C_k of vehicle V_k can be expressed as:

$$C_k = W_k \log_2(1 + SINR_k) \tag{2}$$

where W_k is the channel bandwidth.

We set the platoon driving at a constant speed of v kilometers an hour, when the vehicle V_k in platoon driving through the coverage area of the RSU, the distance between the vehicle V_k and the RSU is $d_k = R - vt$, in which t is the running time of vehicle in RSU coverage area, and then the total time that the vehicle V_k driving through the area is $T = 2R/v$. Then the total size of data downloaded by V_k during the period can be expressed as:

$$S_k = 2 \int_0^{\frac{T}{2}} C_k dt \tag{3}$$

To ensure the transmission bandwidth is fully utilized, we will adopt a file segment strategy to divide the file into multiple data packets to simultaneous transmission, in which the size of each data packet after division is smaller than 10Mb. The process of file segment strategy is elaborated as follows.

First of all, after vehicles in platoon driving through a RSU, the size of file downloaded by vehicles are $S_1, S_2, \ldots, S_K$, and then we compare the size of each file and obtain the minimize one S_{min}, if S_{min} is larger than 10Mb, we make the become half of it until $S_{min} < 10$. Finally, S_{min} is the size of data packet.

4.3 *V2R* Data Distribution Mechanism Based on Network Coding

Based on the data distribution mechanism in [10,11], in this section, we focus on encoding the original data packets using random linear network coding to implement V2R data distribution. The performance of the cooperative download strategy is demonstrated by calculating the probability distribution and expected value of the number of rounds required for RSUs to send data packets to the vehicles in platoon.

The number of coded packets that vehicle download from an RSU during its coverage is m_k, and the size of m_k is determined by the speed of the vehicle, the transmission rate and the coverage area of the RSU. We assume that the size of data packet m_k obtained from any RSU is constant, according to the file segment mechanism described above, the size of coded packet is $m_k = [S_k/S_{\min}]$, and the total number of coded packets from all the vehicles in each round is $m_{sum} = \sum_{k=1}^{K} m_k$. n Linear network coding is a block code conducted over a finite field F_q, where $q = 2^n$, and n is a positive integer [15]. During any transmission opportunity, the RSU will encode the segmented data packets $(X_1, X_2, \ldots, X_M)$, where $M = P/S_{\min}$. Besides, the packets after linear coding can be expressed as $\sum_{z=1}^{M} \beta_{i,k,z} X_z$, where $\beta_{i,k,z}$ is the random network coding coefficient selected uniformly in F_q at the ith round for the k th vehicle.

During the collaborative download process, the vehicle can represent a linear combination of M original packets in any received encoded packet. In order to enable the demand vehicle to decode the original packets, it needs to know the random coding coefficient matrix used for all distributions, thus the RSUs embed these coding coefficients in each coded packet. In the t th rounds, the vehicle V_k receivest $\times m_k$ packets, which is $y_1, y_2, \ldots, y_{t \times m_k}$. With the perfect forwarding between cooperating vehicles in the platoon, the demand vehicle can obtain the encoded packets received by all other vehicles. Therefore, after the t th rounds, the number of coded packets D obtained by the demand vehicle can be expressed as

$$D = t \cdot m_{sum} \tag{4}$$

All the data packets obtained by the demand vehicle can be expressed in the form of vector, which is

$$X = (X_1, X_2, X_3, \ldots, X_M) \tag{5}$$

$$Y = A_{D \times M} \cdot X \tag{6}$$

where $A_{D\times M}$ is the coefficient matrix containing all network coding coefficients. Only when $A_{D\times M}$ is full rank that the demand vehicle can recover the original data packets, which is

$$X = A^{-1}Y \tag{7}$$

When the rank of $A_{D\times M}$ is M, the number of total encoded packet D that demand vehicle obtained should require $D \geq M$, from the Eq. (4), we can know. The probability of matrix $t \geq M/m_{sum}$ is full rank increases with t, so we define the time that needed to download all the data packets is $\Gamma = \min_t\{rank(A_{D\times M}) = M\}$. It is obvious that $\Gamma \geq M/m_{sum}$. We will use the probability distribution and expected value of Γ to present the performance of the proposed scheme, and the following lemma gives the probability of rank of matrix $A_{D\times M}$ with random entries in a finite field.

Lemma 1. $A_{t\times n}$ is a random matrix over finite field F_q, and the entry $a_{i,j}$ is picked uniformly in F_q. Suppose that $t \geq n$, the probability of the rank of matrix $A_{t\times n}$ is can be expressed as

$$P(rank(A_{t\times n}) = n) \approx 1 - \frac{1}{q^{(t-n+1)}} \tag{8}$$

where the above approximation is valid when the q is sufficiently large.

According to the approximation of the probability distribution in Lemma 1, the upper limit of the probability of the cooperative download completion time can be further calculated in the following Lemma 2.

Lemma 2. Since $\Gamma = \min_t\{rank(A_{D\times M}) = M\}$ is the coordinate download complete time, then

$$P(\Gamma = t) \leq (1 - \frac{1}{q})(1 - P(rank(A_{(m_{sum}t-1)\times M}) = M)) \tag{9}$$

where the above inequality is valid when the q is sufficiently large.

According to Lemmas 1 and 2, we can estimate the expected value of the completion time of the coordinate download based on network coding, which satisfies the following condition:

$$\frac{M}{m_{sum}} \leq \Gamma \leq \frac{M}{m_{k\_\max}} \tag{10}$$

where $m_{k\_\max} = S_{\max}$ indicates the largest number of encoded packets received by the vehicle in platoon. The expected value of completion time can be expressed as

$$\begin{aligned} \mathbf{E}(\Gamma) &= \sum_{U_{\min}}^{U_{\max}} tP(\Gamma = t) \\ &= (1 - \tfrac{1}{q})q^M \sum_{U_{\min}}^{U_{\max}} t\frac{1}{q^{m_{sum}t}} \end{aligned} \tag{11}$$

where $U_{\max} = M/m_{k\_\max}$, and $U_{\min} = M/m_{sum}$. Then the system throughput during the entire collaborative download process is as follows.

$$C = \mathbf{E}(\Gamma) \cdot m_{sum} \cdot S_{\min} \tag{12}$$

4.4 *V2V* Data Packet Forwarding Mechanism

In order to execute V2V data packets forwarding mechanism smoothly, we assume that the network topology and the communication link is stability and there are no selfish vehicles in the platoon, so the cooperative vehicles will selflessly forward the data packets. The general steps are as follows. First, when the last vehicle leaves the RSU coverage area, each cooperative vehicle forwards the received encoded packet to the demand vehicle. Since each vehicle is equipped with 2 transceivers, it can communicate with two vehicles simultaneously to ensure the packets downloaded from RSU forward to the demand vehicle in the RSU blind zone. Then, the demand vehicle extracts the random coding coefficients from the received encoded data packets and adds them to the coefficient matrix $A_{D\times M}$ as a new row, and then vehicles are able to recover original RSU information when the rank of matrix $A_{D\times M}$ is M.

4.5 Simulation Results and Analysis

In this section, simulation results are shown to demonstrate the efficiency of the proposed cooperative download strategy. For the sake of simplification, we set three vehicles to participate in the collaboration, and they communication with RSUs simultaneously. To verify the performance of our proposed strategy, we will compare the proposed scheme with that without using the collaborative download strategy. In the simulation, we considered the path-loss, shadow fading factors that affect the wireless communication. The simulation parameters are set as shown in Table 1.

Table 1. Simulation parameters

Parameters	Value
Path-loss exponent	3
Shadowing standard deviation	8 dBm
Noise power	0.01 W
Cooperative vehicles power	2.5 W
Limited field space	512
RSU coverage radius	500 m
Initial request file size	700 Mb

Figure 2 describes the size of data that can be download per round when vehicles driving through the RSU coverage area with different speeds. It is obvious that after adopting the cooperative download strategy, more data packets can be obtained in each round, which shows that our proposed cooperative download strategy can reduce the downloading time and improve system throughput.

Figure 3 shows the average number of rounds that needed to complete download with different speeds. It can be seen that no matter the download process

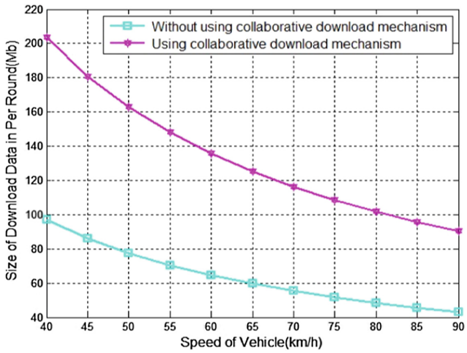

Fig. 2. Size of downloaded data per round with different vehicle speeds

adopts the cooperative download strategy or not, the average number of rounds increase with vehicle speed, but the rounds that cooperative download strategy needed is significantly smaller than that without using the strategy, which shows the advantage of our proposed scheme.

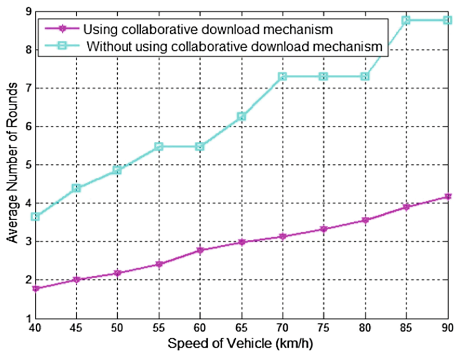

Fig. 3. Average number of rounds for different speed of vehicles

Figure 4 shows the average number of rounds is linearly increase with the amount of demand file data. Comparing the two scenes, it is obvious that the rounds collaborative download strategy needed is smaller than that without using the collaborative download. Besides, the gap of rounds between the two schemes is larger, which shows that when the size of multimedia files is large, the performance of cooperative download strategy is more prominent comparing with download scheme without collaboration.

Figure 5 describes the number of download rounds needed with different file segment mechanisms and the file size. The average number of rounds needed to complete download in our proposed file segment mechanism is less than the size

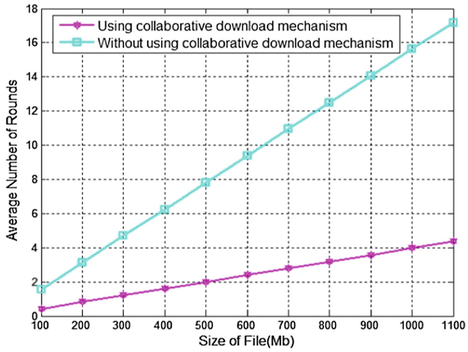

Fig. 4. Average number of rounds with different size of file

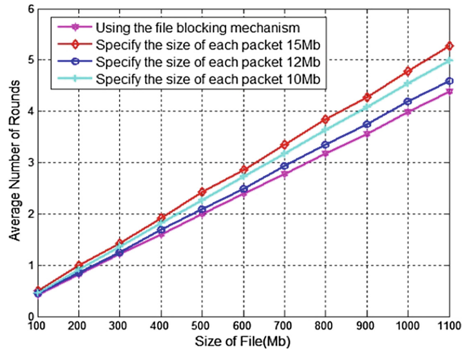

Fig. 5. Average number of rounds for different the size of each packet and file

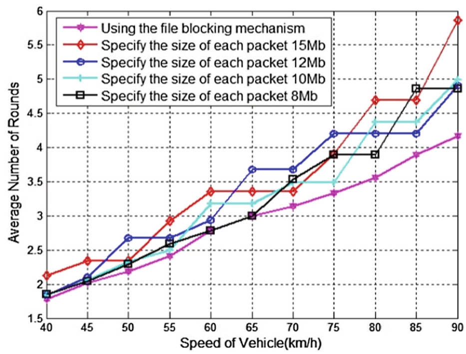

Fig. 6. Average number of rounds for different size of each packet and speed of vehicle

of the packets are directly set to be 15 Mb, 12 Mb and 10 Mb, which can reduce the downloading completion time effectively.

Figure 6 shows the number of download rounds needed under different file segment mechanisms with different speeds. Due to the fact that using the file segment mechanism can make the system stable, when the speed of vehicle is different, our proposed file segment mechanism need less time to complete download.

5 Conclusions

In order to solve the problem of low throughput and long delay in the process of downloading multimedia files, we studied the collaborative download strategy in platoon-based VANETs. The strategy includes collaborative download request management mechanism, file segment mechanism, V2R data distribution mechanism based on network coding and V2V package forwarding mechanism. The simulation results demonstrate that by using the collaborative download strategy, the system throughput is significantly improved and the downloading completion time is reduced.

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References

1. Hall, R., Chin, C.: Vehicle sorting for platoon formation: impacts on highway entry and throughput. Transp. Res. Part C Emerg. Technol. **13**(5), 405–420 (2005)
2. Kenney, J.B.: Dedicated short-range communications (DSRC) standards in the United States. In: IEEE, vol. 99, no. 7, pp. 1162–1182 (2011)
3. Jiang, D., Taliwal, V., Meier, A., Holfelder, W., Herrtwich, R.: Design of 5.9 GHz DARC-based vehicular safety communication. IEEE Wirel. Commun. **13**(5), 36–43 (2006)
4. Jia, D., Lu, K., Wang, J., Zhang, X., Shen, X.: A survey on platoon-based vehicular cyber-physical systems. IEEE Commun. Surv. Tutor. **18**(1), 263–284 (2016)
5. Shao, C., Leng, S., Zhang, Y., Vinel, A., Jonsson, M.: Performance analysis of connectivity probability and connectivity-aware MAC protocol design for platoon-based VANETs. IEEE Trans. Veh. Technol. **64**(12), 5596–5609 (2015)
6. Li, X., Hu, B.: Multi-hop delay reduction for safety-related message broadcasting in vehicle-to-vehicle communications. IET Commun. **9**(3), 404–411 (2015)
7. Shrestha, B., Niyato, D., Han, Z., Hossain, E.: Wireless access in vehicular environments using BitTorrent and bargaining. In: IEEE Global Telecommunications Conference, pp. 1–5 (2008)
8. Chen, B.B., Chan, M.C.: MobTorrent: a framework for mobile Internet access from vehicles. In: IEEE INFOCOM, pp. 1404–1412 (2009)

9. Fiore, M., Barcelo-Ordinas, J.M.: Cooperative download in urban vehicular networks. In: 6th IEEE International Conference on Mobile Adhoc and Sensor Systems, pp. 20–29 (2009)
10. Firooz, M.H., Roy, S.: Collaborative downloading in VANET using network coding. In: IEEE International Conference on Communications ICC, pp. 4584–4588 (2012)
11. Zhu, W., Li, D., Saad, W.: Multiple vehicles collaborative data download protocol via network coding. IEEE Trans. Veh. Technol. **64**(4), 1607–1619 (2015)
12. Jia, D., Zhang, R., Lu, K., Wang, J., Bi, Z., Lei, J.: Improving the uplink performance of drive-thru Internet via platoon-based cooperative retransmission. IEEE Trans. Veh. Technol. **63**(9), 4536–4545 (2014)
13. Taliwal, V., Jiang, D.: Mathematical analysis of IEEE 802.11 broadcast performance in a probabilistic channel. DaimlerChrysler Technical Paper (2005)
14. Kenney, J.B.: Dedicated short-range communications (DSRC) standards in the United States. IEEE **99**(7), 1162–1182 (2011)
15. Ho, T., Medard, L., Shi, J., Effros, L., Karger, D.: On randomized network coding. In: Allerton Conference on Communication, Control, and Signal Processing, pp. 1–10 (2003)