UNIVERSITY OF LEEDS

This is a repository copy of *Improving the uplink performance of drive-thru internet via platoon-based cooperative retransmission*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/83271/

Version: Accepted Version

Article:

Jia, D, Zhang, R, Lu, K et al. (3 more authors) (2014) Improving the uplink performance of drive-thru internet via platoon-based cooperative retransmission. IEEE Transactions on Vehicular Technology, 63 (9). 4536 - 4545. ISSN 0018-9545

https://doi.org/10.1109/TVT.2014.2315741

Reuse
Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Improving the Uplink Performance of Drive-Thru Internet via Platoon-based Cooperative Retransmission

Dongyao Jia, Rui Zhang, Kejie Lu, Jianping Wang, Zhongqin Bi, and Jingsheng Lei

***Abstract*—For many vehicular safety applications, it is critical to timely and reliably deliver multimedia data from a traveling vehicle to a roadside *access point* (AP) in an error-prone vehicular ad hoc network (VANET), which is a typical uplink scenario for *drive-thru Internet*. To achieve this goal, we propose a cooperative retransmission scheme that exploits a common phenomenon in reality, in which consecutive vehicles can naturally form a *platoon* to reduce the energy consumption. We develop a 4-D Markov chain to model the proposed scheme and analyze the uplink throughput of drive-thru Internet, which also reveals some fundamental relationships among traffic flow, platoon parameters, and system throughput. We conduct extensive simulation in Omnet++ to validate our scheme and the analytical model. Numerical results show that the proposed platoon-based cooperative retransmission scheme significantly improves the uplink throughput of drive-thru Internet, considerably decreases the total transmission times for a given quantity of upload data, and, hence, achieves a greener mobile multimedia communication.**

***Index Terms*—Vehicle platoon, vehicular ad-hoc networks (VANETs), Drive-Thru Internet, platoon-based cooperative retransmission, multimedia.**

I. INTRODUCTION

Vehicular ad-hoc networking (VANET) is a promising technology that can play a critical role for future *intelligent transportation system* (ITS), which can support both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. One important application of V2I communication is to transmit traffic-safety related multimedia information to the roadside *access points* (APs). Nevertheless, due to the nature of mobile and wireless communications, the transmission in VANET is often error-prone, and thus it is very challenging to timely and reliably deliver multimedia data from a traveling vehicle to a roadside AP, which is a typical uplink scenario for *drive-thru Internet*.

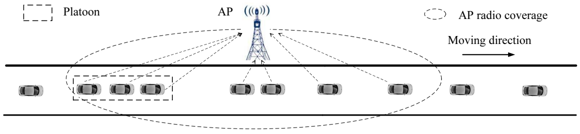


Fig. 1. An example of uplink application in drive-thru Internet.

In the literature, a lot of work has been done to study the transmission performance in drive-thru Internet [1]–[4]. To tackle the transmission error problem, one general retransmission approach, namely, the automatic-repeat-request (ARQ) scheme, has been applied in IEEE 802.11 *medium access control* (MAC) sublayer with an acknowledgement (ACK) procedure. However, the binary exponential backoff procedure invoked by an error transmission will bring unpredictable delay of real-time video clips at APs. This situation will become more severe in case of dense traffic flow with drastic contention among vehicles. Moreover, with the standard ACK procedure, only an entirely correctly received frame will be acknowledged. Therefore, the whole frame will be retransmitted even if there is only one bit error occurred, which may significantly degrade the uplink throughput in the error-prone VANET environment.

To improve the uplink performance of drive-thru Internet, in this paper, we propose a cooperative retransmission scheme that exploits a nature phenomenon in real traffic conditions, in which consecutive vehicles on the same direction can form a *platoon*, within which a following vehicle maintains a small distance to the preceding one and all vehicles move at approximately the same velocity [5], as shown in Fig. 1. Compared to the standard ARQ scheme, the proposed retransmission scheme has the following key features:

1) To start the retransmission at the earliest time through cooperative retransmission: Due to the broadcast nature of wireless communication, when a vehicle uploads a data frame to AP, its neighbor vehicles within the transmission range can receive the data frame simultaneously. Consequently, a neighbor vehicle which has the next transmission opportunity can retransmit the over-heard data frame in the previous transmission on behalf of its source vehicle. Through such a cooperative retransmission scheme proposed in the MAC sublayer, the retransmission can be finished in a shorter time.

To implement the proposed scheme, we should choose suitable neighbor vehicles as the cooperative retransmitters. As

---

Dongyao Jia, Rui Zhang, and Jianping Wang are with the Department of Computer Science, City University of Hong Kong, Hong Kong, China. Kejie Lu is the corresponding author and is with College of Computer Science and Technology, Shanghai University of Electric Power, China, and the Department of Electrical and Computer Engineering, University of Puerto Rico at Mayagüez, Puerto Rico, USA. Zhongqin Bi and Jingsheng Lei are with College of Computer Science and Technology, Shanghai University of Electric Power, China.

This work was supported in part by Hong Kong General Research Funding under project CityU 9041787, the National Science Foundation of China (No. 61272462), and by the CityU Project No. 9231101. This work was also supported in part by Natural Science Foundation of China (No. 61272437, 61373152) , Innovation Program of Shanghai Municipal Education Commission (No. 13ZZ131, 14ZZ150), Foundation Key Project of Shanghai Science and Technology Committee (No. 12JC1404500,), Project of Shanghai Science and Technology Committee (12510500700) and Shanghai Oriental Scholar Program.

Manuscript submitted on February 19, 2015.

aforementioned, consecutive vehicles naturally form *platoons* in practice. This *platoon-based* driving pattern in highway is regarded as a promising driving manner, which can not only reduce the energy consumption considerably due to streamlining of vehicles in a platoon minimizing air drag, but also facilitate more efficient information dissemination and sharing among vehicles in the same platoon [6]. Thus, we regard a platoon as a cooperative group unit, within which a vehicle can retransmit the frame for neighbors if the delivery of the frame failed in the previous transmission due to the error-prone VANETs environment.

2) To increase the payload efficiency by selective retransmission: Inspired by the proposed scheme in [7] and [8], we partition a long data frame into several blocks and only retransmit the blocks that encounter errors in the previous transmission. In this way, we can minimize the amount of retransmission data and enhance the utilization rate of the bandwidth accordingly. To realize this idea, we devise an additional negative acknowledgement (NACK) frame to inform the sender which blocks are supposed to be retransmitted.

To evaluate the performance of the proposed scheme, we develop an analytical model based on the well-known Bianchi two-dimensional Markov chain [9]. Specifically, taking into account the block partition and cooperative transmission, we formulate a 4-D Markov chain to represent the cooperative retransmission behavior from a microscopic perspective. The analytical model shows that the proposed scheme has more chances to retransmit the frame at the earliest time and the system throughput is significantly improved.

We also conduct extensive simulations to validate the theoretical analysis and the proposed scheme. The results show that the platoon-based cooperative retransmission scheme can significantly improve the uplink throughput of drive-thru Internet. Moreover, the results can also comprehensively demonstrate the fundamental relationships among traffic flow, platoon parameters, and system throughput.

Our main contributions in this paper are threefold. First, we propose a novel *platoon-based* cooperative retransmission scheme which can significantly improve the uplink performance of drive-thru Internet. Second, we build an analytical model to evaluate the proposed scheme, and the analytical model reveals that cooperative retransmission is considerably helpful to minimize a frame transmission time even in dense traffic flow scenarios. In addition, block partition also significantly improves the system throughput in serious error-prone VANET environments. Last, our scheme and analytical model have been validated via extensive simulations in Omnet++.

The organization of this paper is described as follows. In Section II, we first overview related work, including IEEE 802.11 MAC performance analysis and existing cooperative retransmission schemes. In Section III, we elaborate the platoon-based cooperative retransmission scheme for enhancing the throughput performance of drive-thru Internet. In Section IV, we develop the analytical model of the retransmission scheme based on Markov chain and derive the saturated uplink throughput of drive-thru Internet. In Section V, we present numerical results, before concluding the paper in Section VI.

II. RELATED WORK

In this section, we present the related work on IEEE 802.11-based MAC performance analysis and optimization, as well as the features of traffic flow in platoon-based driving pattern.

A. CSMA/CA Performance Analysis

The performance analysis of IEEE 802.11 carrier-sensing multiple access with collision avoidance (CSMA/CA) protocol has been extensively studied in the past decade. Most of them assume the saturated conditions, i.e., each node in the network has packets to send at any time. In [9], Bianchi first introduced a two-dimensional Markov chain model to evaluate the CSMA/CA protocol with binary exponential backoff scheme. Based on Bianchi's model, various enhanced models have been proposed aiming at different application scenarios, such as considering error-prone channel conditions [10], introducing the concept of backoff decrement probability [11], refining backoff process by anomalous slots [12], etc.

Based on the the aforementioned analytical models, some recent researches have investigated the system performance of the standard VANET MAC protocol-IEEE 802.11p and drive-thru Internet scenario [2]–[4], [13]–[17]. In [16], the authors proposed an analytical model for the throughput of the enhanced distributed channel access mechanism in the IEEE 802.11 MAC sublayer, taking into account contention window and arbitration interframe space (AIFS) for different access categories, and an internal-collision-resolving mechanism. To evaluate the impact of node mobility on the drive-thru throughput, Luan et al. [2] investigated the impact of vehicle mobility on the achievable drive-thru throughput and proposed a 3-D Markov-chain-based model to represent the status of the moving node in the drive-thru process, in which the spatial zone of the node is taken into account. Different from Bianchi's model, which represents the transition between backoff counter values and stages from microscopic perspective, in [4] the authors modeled the packet transmission in drive-thru Internet as a renewal reward process from macroscopic perspective.

In this paper, we extend Bianchi's model to analyze the platoon-based cooperative retransmission scheme, considering the error-prone channel in the drive-thru Internet scenario.

B. Cooperative communications in MAC sublayer

Several cooperative communication schemes have been proposed for the IEEE 802.11 MAC sublayer with distributed control [3], [18]–[21]. A cooperative MAC scheme named rDCF [18] exploits the multi-rate capabilities of the IEEE 802.11 networks. Relay nodes are chosen upon the link quality to shorten the transmission time of a frame. Similarly in [19], by leveraging the overheard transmissions, the nodes with low data rate can select the helper nodes with high rate to minimize the total transmission time. A novel protocol called vehicular cooperative MAC is proposed in [20] which utilizes the broadcast nature of wireless media to maximize the system throughput for information downloading scenarios. Helper nodes are selected to rebroadcast the frames when some vehicles encounter frames loss from an RSU. To overcome poor link quality in limited drive-thru Internet region, a vehicle-to-vehicle relay (V2VR) scheme [1] is proposed aiming to extend the service range of roadside APs and maintain high throughput within the extended range.

C. Platoon-based Traffic Flow

In term of vehicle traffic, the statistics of time headway is regarded as the fundamental parameter to describe the traffic flow distribution, where time headway is defined as the time (or, equivalently, distance) between two consecutive vehicles passing the same point and traveling on the same direction. Normally, time headways are assumed to be independent and identically distributed random variables. Since the 1960s, many time headway distribution models have been proposed, among which the typical representatives include exponential distribution, normal distribution, gamma distribution, and log-normal distribution. It is verified in [22] that log-normal distribution fits well the intermediate traffic demand level, between 700 and 1700 vehicles per hour (vph). In [23], Chen et al. employed a unified car-following model integrated with Markov process description to simulate different driving scenarios. Headway time is verified to be log-normally distributed by NGSIM Trajectory Data. Therefore, we assume that the individual vehicle is log-normal distribution in this paper.

III. COOPERATIVE RETRANSMISSION SCHEME

In this section, we present a novel platoon-based cooperative retransmission scheme for IEEE 802.11 MAC sublayer which can significantly improve the uplink throughput of drive-thru Internet.

A. Transmission Frame Format

In the scenario of drive-thru uplink Internet, the AP is called receiver which is the only destination receiving data from all vehicles in the drive-thru coverage, while all vehicles sending data are called senders. The main idea of the retransmission scheme is to enable cooperative communication in the IEEE 802.11p MAC sublayer so that one sender can retransmit blocks for its neighbors within the same platoon in case of previous transmission error.

To adopt cooperative retransmission, as mentioned in Section I, some additional functions should be implemented compared with the legacy IEEE 802.11 MAC sublayer. First, when the MAC layer receives a packet from the upper layer, it will partition the packet into equal-sized blocks and append each block by error check fragment such as CRC code so that the receiver can identify which block are transmitted with error. These partitioned blocks then will be stored in the transmission buffer of the MAC layer.

Second, besides the blocks that belong to the current sender, the blocks from other senders within the same platoon will also be temporarily saved in the transmission buffer if the current sender correctly received these blocks. Then the sender decides if these blocks will be retransmitted with its own blocks based on the receiver's response (NACK or ACK) to the original senders of these blocks. Note that in this circumstance each sender within the same platoon needs to implement this process after receiving ACK/NACK, regardless whether the destination of ACK/NACK is in accordance with itself or not.

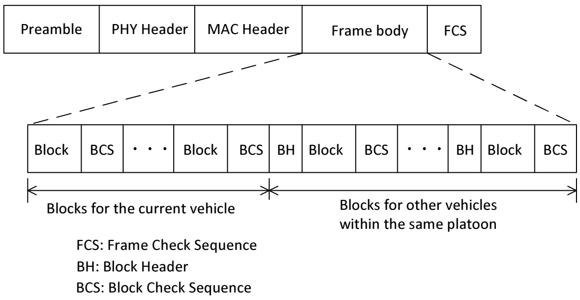


Fig. 2. The format of a data frame.

The corresponding structure of the data frame is illustrated in Fig. 2, where each block in the frame has its own check sequence, i.e. *block check sequence* (BCS). In addition, a *block header* (BH) is also added to indicate the information about the blocks that belongs to other senders in the network. The BH can include the address of the sender, the size of the block, the sequence number of the packet, and the sequence number of the block in the original frame. Note that the index of each block of the current sender and the block size can be stored in the MAC header, which implies that there is no need to add BH for them because the former one can be realized by a bit map. In addition, platoon ID should also be added to the MAC header, which can be used for other senders to identify if the received frame comes from the same platoon.

When receiving an error frame, the receiver will send a NACK to notify which blocks need to be retransmitted in the next frame. Therefore, NACK should include a bitmap indicating which blocks are corrupted.

B. Platoon-based Cooperative Retransmission Scheme

Next, we address the platoon-based cooperative retransmission scheme in the MAC sublayer from two sides.

1) Frames sending process: Once a sender obtain the transmission opportunity through CSMA/CA precedure, it first partitions upper layer packet to be sent into equal-sized blocks in MAC sublayer, these blocks together with neighbors' blocks failed in the previous transmission will be sent to the receiver.

If a sender has retransmitted a frame (NOT blocks) for a maximum number of attempts without receiving an ACK frame, it will drop the frame that is stored in the transmission buffer and initiate another transmission for a new frame. Other senders will also drop the blocks that belong to the frame from their transmission buffer. Meanwhile, the receiver will clear the blocks belonging to the frame that previous received.

Note that a sender should transmit his own frame one by one, that is, only if the frame has been successfully transmitted, or has been dropped due to maximum retry limit, the sender can initiate another transmission for a new frame.

2) Frames Receiving process: For the AP, the only final receiver, if the received blocks are correct, they will be stored in the reception buffer. If all blocks in the same frame are correct, they will be assembled and forwarded to the upper layer. Then the receiver will send ACK to the sender that originated the transmission. In case the one or more received blocks have error, the receiver will use NACK to inform the corresponding sender which blocks need to be retransmitted.

For the senders, when a sender receives correct blocks from its neighbors, it temporarily stores the blocks in the transmission buffer if there is still available space. If a sender receives NACK from the AP, no matter whose destination is, it will update the current transmission buffer to be retransmitted based on the bitmap indicated in the NACK. While in case a sender receives ACK from the AP, it will drop the blocks belonging to the frame from the transmission buffer.

Note that in the platoon-based cooperative retransmission scheme, the value selection of the system parameters may significantly affect the uplink performance of the drive-thru Internet, such as platoon size and block size, which will be demonstrated in the following sections.

IV. AN ANALYTICAL MODEL FOR THE SATURATION THROUGHPUT PERFORMANCE

In this section, we develop an analytical model to evaluate the saturated uplink throughput of drive-thru Internet under the platoon-based cooperative retransmission proposed in section III. To this end, we first build a 4-D Markov chain to model the cooperative scheme and calculate the uplink throughput for a given number of vehicles in the coverage area of AP, then based on the result, further estimate the total system throughput in the platoon-based traffic flow scenario.

A. Uplink Throughput for A Given System Size

To conduct the analysis, we first make the following assumptions and specifications.

1) There are total N contending vehicles within the coverage of the AP and N_p vehicles in one platoon. We also assume that any two vehicles in one platoon can directly communicate with each other.
2) We assume a simple noise model in the physical layer: bit errors independently and uniformly occur only in the frame body with a fixed bit error rate (BER) ϵ. The probability that a data frame body encounter transmission error is denoted as q. Data frame header and control frame including ACK/NACK are error free[1]. Due to close space and similar mobility among vehicles in the same platoon, we assume error free transmission within one platoon.
3) At any time instance, a vehicle always has a frame ready to be transmitted. In other words, we only consider the saturated traffic scenario.
4) Let N_b be block size, the overhead for block checksum and header be fixed for each block, denoted as N_c bytes. We assume a fixed frame length with L_0 blocks.
5) To simplify the analysis, we ignore the overhead for both extra checksum for each block and block bitmap index in NACK frames. In addition, we do not consider the impact of limited transmission buff size on the system performance.
6) We assume all vehicles have the same fixed access category in IEEE 802.11p MAC sublayer, which means no internal collision occurs in this condition. In addition, we only consider RTS/CTS access mode in the MAC sublayer, therefore the effect of hidden and exposed terminals can be effectively eliminated under this circumstance.

TABLE I
NOTATIONS

$b(t)$	backoff time counter at time t
$c(t)$	number of blocks in the data frame to be delivered at time t
$r(t)$	cooperative transmission stage at time t
$s(t)$	backoff stage at time t
L_0	block number in one frame
M	the maximum number of times the contention window may be increased
$M+f$	the maximum frame retry limit
N	the number of contending vehicles within the coverage of the AP
N_b	block size
N_c	overhead for block checksum and header
N_p	platoon size
p	conditional collision probability
p_{suc}	probability of a successful frame transmission in the same platoon
p_τ	transmission probability
$p_{\tau c}$	cooperative retransmission probability
q	transmission error occurred in a block
R	the fixed transmission range
R_d	data transmission rate
δ	propagation delay
ϵ	bit error rate (BER)
σ	slot time

The notations used in the analysis are summarized in Table I.

We develop our analytical model based on Markov chain analysis in [9]. Specifically, we extend it to a 4-D Markov chain to represent the dynamic behavior of the backoff process for the proposed platoon-based cooperative retransmission scheme. As illustrated in [9], we let $s(t)$ be the backoff stage at time t, $b(t)$ be the backoff time counter at time t. Because we partition a frame into blocks, we let $c(t)$ denote the number of blocks in the data frame that shall be delivered at time t. In addition, for the proposed platoon-based cooperative retransmission scheme, we can divide a frame's whole transmission process into two stages: (1) the frame initially is transmitted only by its original sender. (2) the frame can be transmitted by both the original sender and cooperative senders. Consequently, we add a state variable $r(t)$ to indicate the cooperative transmission stage at time t. Thus we formulate a 4-dimensional Markov chain $\{s(t), b(t), c(t), r(t)\}$ representing the state of the proposed scheme at time t.

Next, we identify the possible value of the 4-D Markov chain state. Let W be the minimum backoff window size, M be the maximum number of times the contention window may be increased, $M+f$ be the maximum frame retry limit. Then

---

[1] The assumption is reasonable because IEEE 802.11 standard defines that frame header and control frame shall be transmitted at the lowest data rate. Consequently, the probability that errors occur in the control frames and header of data frame is generally smaller than the probability that errors occur in the payload of the data frame

we can derive the maximum window size W_i at stage i:

$$W_i = \begin{cases} 2^i W, 0 \le i \le M \\ 2^M W, M < i \le M+f \end{cases} \tag{1}$$

Based on the assumption, the maximum value of $c(t)$ is L_0. For $r(t)$, we can set a binary value to it, where 0 stands for the first stage in which the frame is only transmitted by its original sender, while 1 stands for the second stage in which frame will be transmitted by both the cooperative senders and original sender.

The steady state probability of state $\{s(t) = i, b(t) = k, c(t) = l, r(t) = o\ \}$ is defined as: $b_{i,k,l,o} = \lim_{t\to\infty} Pr[s(t) = i, b(t) = k, c(t) = l, r(t) = o]$, where $i \in [0, M+f], k \in [0, W_i - 1], l \in [1, L_0], o \in [0, 1]$. To derive $b_{i,k,l,o}$, we calculate the transition probabilities of the 4-D Markov chain according to the value of cooperative transmission stage separately.

(1) In the first stage of a frame's whole transmission process, in which the frame is only transmitted by its original sender.

$$\begin{aligned} &P\{i, k, L_0, 0|i, k+1, L_0, 0\} = 1, \\ &i \in [0, M+f], k \in [0, W_i - 2] \end{aligned} \tag{2a}$$

$$\begin{aligned} &P\{i+1, k, L_0, 0|i, 0, L_0, 0\} = \frac{p}{W_{i+1}}, \\ &i \in [0, M+f), k \in [0, W_{i+1} - 1], \end{aligned} \tag{2b}$$

$$\begin{aligned} &P\{0, k, L_0, 0|i, 0, L_0, 0\} = \frac{1-p}{W_0} \cdot (1-q)^{L_0}, \\ &i \in [0, M+f), k \in [0, W_0 - 1] \end{aligned} \tag{2c}$$

$$\begin{aligned} &P\{i+1, k, j, 1|i, 0, L_0, 0\} = \frac{1-p}{W_{i+1}} \cdot \binom{L_0}{j} \cdot q^j \cdot (1-q)^{L_0 - j}, \\ &i \in [0, M+f), k \in [0, W_{i+1} - 1], j \in [1, L_0] \end{aligned} \tag{2d}$$

$$\begin{aligned} &P\{0, k, L_0, 0|M+f, 0, L_0, 0\} = \frac{1}{W_0}, \\ &k \in [0, W_0 - 1] \end{aligned} \tag{2e}$$

where parameter q can be estimated, based on the assumption, by using

$$q = 1 - (1 - \epsilon)^{8(N_b + N_c)} \tag{3}$$

$P\{i, k, L_0, 0|i, k+1, L_0, 0\}$ in Eq. (2a) accounts for the fact that the backoff counter is decreased by one after i times failed transmission all due to collision. In this case, other cooperative senders cannot receive the frame from the original sender. $P\{i+1, k, L_0, 0|i, 0, L_0, 0\}$ in Eq. (2b) describes the case of unsuccessful transmission by the original sender due to collision at backoff stage (i). $P\{0, k, L_0, 0|i, 0, L_0, 0\}$ in Eq. (2c) accounts for a successful transmission by the original sender. $P\{i+1, k, j, 1|i, 0, L_0, 0\}$ in Eq. (2d) accounts for the fact that unsuccessful transmission by the original sender due to error-prone channel, however, as illustrated in the assumption, the frame no doubt will be successfully received by other cooperative senders in this case. $P\{0, k, L_0, 0|M+f, 0, L_0, 0\}$ in Eq. (2e) describes that, once the backoff stage reaches the retry limit of $M+f$, the frame is discarded if the transmission is not successful and backoff stage will be reset to 0.

(2) In the second stage of a frame's whole transmission process, in which the frame is transmitted by both cooperative senders and the original sender.

$$\begin{aligned} &P\{i+1, k, l, 1|i, 0, l, 1\} = \frac{p}{W_{i+1}} + \frac{1}{W_{i+1}}[(1-p) \cdot q^l], \\ &i \in [1, M+f), k \in [0, W_{i+1} - 1], l \in [1, L_0] \end{aligned} \tag{4a}$$

$$\begin{aligned} &P\{0, k, L_0, 0|i, 0, l, 1\} = \frac{1-p}{W_0} \cdot (1-q)^l, \\ &i \in [1, M+f), k \in [0, W_0 - 1], l \in [1, L_0] \end{aligned} \tag{4b}$$

$$\begin{aligned} &P\{i+1, k, j, 1|i, 0, l, 1\} = \frac{1-p}{W_{i+1}} \cdot \binom{l}{j} \cdot q^j \cdot (1-q)^{l-j}, \\ &i \in [1, M+f), k \in [0, W_{i+1} - 1], j < l, l \in [1, L_0], j \in [1, L_0] \end{aligned} \tag{4c}$$

$$\begin{aligned} &P\{0, k, L_0, 0|M+f, 0, l, 1\} = \frac{1}{W_0}, \\ &k \in [0, W_0 - 1], l \in [1, L_0] \end{aligned} \tag{4d}$$

$$\begin{aligned} &P\{i, k, l, 1|i, k+1, l, 1\} = (1 - p_{suc}) + p_{suc} \cdot q^l, \\ &i \in [1, M+f], k \in [0, W_i - 2], l \in [1, L_0] \end{aligned} \tag{4e}$$

$$\begin{aligned} &P\{i, k, j, 1|i, k+1, l, 1\} = p_{suc} \cdot \binom{l}{j} \cdot q^j \cdot (1-q)^{l-j}, \\ &i \in [1, M+f], k \in [0, W_i - 2], j < l, l \in [1, L_0], j \in [1, L_0] \end{aligned} \tag{4f}$$

$$\begin{aligned} &P\{0, k2, L_0, 0|i, k1, l, 1\} = \frac{p_{suc}}{W_0}(1-q)^l, \\ &i \in [1, M+f], k1 \in [1, W_i - 1], k2 \in [0, W_0 - 1], l \in [1, L_0] \end{aligned} \tag{4g}$$

Eq. (4a)-Eq. (4d) accounts for the similar cases to Eq. (2b)-Eq. (2e) that the original sender transmits the frame during the second stage of the transmission process. However, during each backoff slot for the original sender, the cooperative senders may have the opportunity to transmit the frame that has not been completely transmitted. $P\{i, k, l, 1|i, k+1, l, 1\}$ in Eq. (4e) describes the case that the remain blocks of the frame is not changed due to unsuccessful transmission or transmission with fully error blocks by the cooperative sender during one backoff slot. $P\{i, k, j, 1|i, k+1, l, 1\}$ in Eq. (4f) accounts for the fact that part of the frame has been transmitted by the cooperative senders during one backoff slot. $P\{0, k2, L_0, 0|i, k1, l, 1\}$ in Eq. (4g) describes the fact that the remainder of the frame has been successfully transmitted by the cooperative senders.

Since the steady-state probabilities must satisfy

$$1 = \sum_{i=0}^{M+f} \sum_{k=0}^{W_i-1} \sum_{l=1}^{L_0} \sum_{o=0}^{1} b_{i,k,l,o} \tag{5}$$

we can numerically solve the steady-state probabilities of the 4-D Markov chain given p, p_{suc} and q.

In Eq. (4), p_{suc} denotes the probability that only one transmission occurs in the cooperative senders in the same platoon, which can be calculated by

$$p_{suc} = (n_p - 1)p_\tau(1 - p_\tau)^{n-2} \tag{6}$$

According to the procedure in binary exponential backoff, a transmission is initiated by its original sender if and only if $k = 0$, we can derive the transmission probability p_τ by

$$p_\tau = \sum_{i=0}^{M+f} \sum_{l=1}^{L_0} \sum_{o=0}^{1} b_{i,0,l,o} \tag{7}$$

Since a frame collision can occur only if there are two or more senders transmitting the frame in the same slot, we can calculate p by

$$p = 1 - (1 - p_\tau)^{n-1} \tag{8}$$

By using the relationship in Eq. (7), Eq. (6) and Eq. (8), we can obtain both p_τ and p numerically.

In addition, the transmission is also initiated by the cooperative senders in our proposed scheme. We can similarly calculate the cooperative transmission probability $p_{\tau c}$ by

$$p_{\tau c} = p_{suc} \cdot \sum_{i=1}^{M+f} \sum_{k=1}^{W_i-1} \sum_{l=1}^{L_0} b_{i,k,l,1} \tag{9}$$

To calculate the saturation throughput, we define the following parameters. S denotes the normalized throughput, $E[PL]$ is the expected time duration for transmitting error-free frames, while $E[T]$ is the expected value of time slot durations. Then we have the following equation

$$S = \frac{E[PL]}{E[T]} \tag{10}$$

According to the 4-D Markov chain, both the original sender and the cooperative senders all contribute to the total saturation throughput S. To simplify the analysis, we first calculate the saturated throughput created by the original sender, then take into account the saturated throughput created by the cooperative senders.

(1) The saturated throughput created by the original sender.

There are three types of probability for a generic time slot: p_i denotes channel being idle; p_s denotes a successful transmission (note that successful transmission here merely means the sender has the opportunity to transmit frames without collision, regardless error bits in frames); p_c denotes transmission collision. We have the following equations.

$$\begin{cases} p_i = (1 - p_\tau)^n \\ p_s = np_\tau(1 - p_\tau)^{n-1} \\ p_c = 1 - (1 - p_\tau)^n - np_\tau(1 - p_\tau)^{n-1} \end{cases} \tag{11}$$

Accordingly, we denote σ, T_s, and T_c as the time duration of a generic slot being idle, having a successful transmission and collision. σ equals the fixed slot time which is given in the IEEE 802.11 standard. Because we only consider RTS/CTS access mode of IEEE 802.11p in this paper, T_s and T_c can be calculated by

$$\begin{aligned} T_s =& T_{AIFS} + T_{RTS} + \delta + T_{SIFS} + T_{CTS} + \delta \\ &+ T_{SIFS} + T_{DATA} + \delta + T_{SIFS} + T_{ACK}/T_{NACK} + \delta \end{aligned} \tag{12}$$

$$T_c = T_{RTS} + \delta + T_{SIFS} + T_{ACK} + T_{AIFS} + \delta \tag{13}$$

where T_{RTS} is the RTS frame transmission time, T_{CTS} is the CTS frame transmission time, T_{ACK}/T_{NACK} is the ACK/NACK transmission time, T_{AIFS} is an extension time of the backoff procedure in DCF, which is calculated by $T_{AIFS} = AIFSN \times \sigma + T_{SIFS}$. Here the value of $AIFSN$ is allocated by access category in IEEE 802.11p. Since the frame length of NACK is approximately equal to that of ACK, we assume $T_{ACK} \approx T_{NACK}$. T_{DATA} denotes average packet size of a successful transmission, which can be divided into two parts:T_h and T_{Do}, where T_h is the transmission time periods of the frame header, T_{Do} is the transmission time of its own blocks. T_{Do} is calculated by

$$T_{Do} = \frac{8(N_b + N_c)}{R_d} \cdot \frac{\sum_{i=0}^{M+f} \sum_{l=1}^{L_0} \sum_{o=0}^{1} \left(b_{i,0,l,o} \cdot l \right)}{p_\tau} \tag{14}$$

The corresponding T_{PLo} is the time duration for transmitting error-free packets by the original sender, which can be calculated by

$$T_{PLo} = \frac{(8L_0N_b)}{R_d} \cdot \frac{\sum_{i=0}^{M+f} \sum_{l=1}^{L_0} \sum_{o=0}^{1} \left(b_{i,0,l,o} \cdot (1-q)^l \right)}{p_\tau} \tag{15}$$

(2) The saturated throughput created by the cooperative senders.

The successful cooperative transmission p_{sc} is given by

$$p_{sc} = np_{\tau c}(1 - p_{\tau c})^{n-1} \tag{16}$$

We denote T_{Dc} as the transmission time of the blocks retransmitted by cooperative senders. Similarly, we can derive T_{Dc} as follows:

$$T_{Dc} = \frac{8(N_b + N_c)}{R_d} \cdot \frac{\sum_{i=1}^{M+f} \sum_{k=1}^{W_i-1} \sum_{l=1}^{L_0} \left(p_{suc} \cdot b_{i,k,l,1} \cdot l \right)}{p_{\tau c}} \tag{17}$$

The corresponding T_{PLc} is the time duration for transmitting error-free packets by cooperative senders, which can be calculated by

$$T_{PLc} = \frac{(8L_0N_b)}{R_d} \cdot \frac{\sum_{i=1}^{M+f} \sum_{k=1}^{W_i-1} \sum_{l=1}^{L_0} \left(p_{suc} \cdot b_{i,k,l,1} \cdot (1-q)^l \right)}{p_{\tau c}} \tag{18}$$

Combined with the above equations Eq. (10)-Eq. (18), we can derive the uplink throughput of drive-thru Internet for a given vehicle number in the coverage area of AP.

$$S = \frac{p_s T_{PL} + p_{sc} T_{PLc}}{p_i \sigma + p_s T_s + p_{sc} T_{Dc} + p_c T_c} \tag{19}$$

B. *Platoon-based Drive-Thru*

In this part, we further evaluate the uplink throughput of drive-thru Internet in real traffic flow with platoon-based driving pattern. Upon the above analysis, a general time slot is normally millisecond-level. Therefore, we assume there is no vehicle entering or leaving the AP coverage during each time slot. Then we can statistically analyze the system in a steady state, ignoring the transient behavior of a specific vehicle.

As addressed in Section II-C, the original distribution of individual vehicle is log-normal, which is expressed as:

$$f(t_h;\mu,\theta)=\frac{1}{\sqrt{2\pi}\theta t_h}\exp\left(-\frac{(\log t_h-\mu)^2}{2\theta^2}\right), t_h>0 \quad (20)$$

where t_h represents the possible value of the time headway, μ is the scale parameter and θ is the shape parameter.

In the steady state of a traffic flow, we assume that vehicles run at about the same velocity V_{stb}, which is a constant. Therefore, we can get the corresponding distance headway for individual driving patterns:

$$s_h \approx v_{stb}t_h. \quad (21)$$

Obviously, s_h is subject to log-normal distribution. Then the number of vehicle n within the transmission range R of the AP is $n=\left[\frac{2R}{s_h}\right]=\left[\frac{2R}{v_{stb}t_h}\right]$, where [] denotes the integer part. We can further derive the probability $P_r(n=N)=P_r(N\leq n<N+1)$ by the following equation.

$$P_r(n=N)=\int_{2R/(N+1)v_{stb}}^{2R/Nv_{stb}} f(t_h)dt_h \quad (22)$$

Thus the overall network throughput under the platoon-based traffic flow can be calculated as:

$$E[S]=\frac{\sum_{n=1}^{\infty} S\cdot P_r(n)}{\sum_{n=0}^{\infty} P_r(n)} \quad (23)$$

V. NUMERICAL RESULTS

In this section, we conduct extensive simulation experiments to validate theoretical analysis in previous sections and to evaluate the performance of the proposed platoon-based cooperative retransmission scheme. In the rest, we first explain the simulation settings, then we extensively discuss the impact of system parameters (such as block size, platoon size, velocity) on the uplink performance of drive-thru Internet.

A. *Simulation Settings*

We use the well-known simulation tool OMNeT++ with INETMANET framework to conduct our experiments. We have also modified IEEE802.11 MAC sublayer protocols in the INETMANET package to implement our proposed cooperative retransmission scheme. We use this model to analyze the performance of the MAC sublayer in saturated scenarios. The simulation parameters are based on the IEEE 802.11p standard, as listed in Table II.

TABLE II
PARAMETER SETTING

Parameter	**Value**	**Parameter**	**Value**
R_d	6 Mbps	σ	13 μs
T_{SIFS}	32 μs	T_{AIFS}	71 μs
T_{ACK}/T_{NACK}	71 μs	T_{RTS}	71 μs
T_{CTS}	71 μs	T_h	40 μs
δ	2 μs	W_{min}	15 time slots
W_{max}	63 time slots	M	2
$M+f$	4	N_c	4 Bytes
R	450m	v_{stb}	30m/s

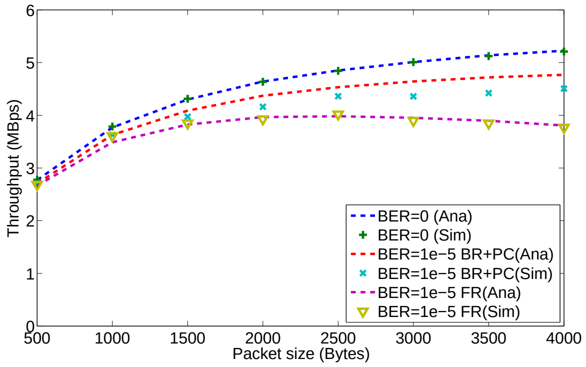


Fig. 3. Throughput vs. packet size ($N=10, N_p=5, N_b=500$ bytes).

To evaluate the system performance under various traffic flow scenarios, we conduct the simulation under different traffic flow rate conditions. As aforementioned, the vehicle time-headway is log-normal distributed. The value of θ obtained from freeway traffic is about 0.4, which normally does not vary very much over different traffic flow levels [5]. The stable velocity of traffic flow is set to $30m/s$. Thus by setting different values of μ, we can simulate the traffic scenarios with various traffic flow rates. Based on the parameters specified in Table II, we can derive that 10 vehicles in the coverage of AP corresponds to the mean traffic flow rate 1000vph, while 30 vehicles in coverage of AP corresponds to 3000vph.

B. *Uplink Performance*

To demonstrate the performance of the proposed scheme, we compare it with the standard retransmission approach in IEEE 802.11 MAC sublayer. In all the figures, we use FR to indicate the frame retransmission (FR) scheme of the traditional approach, and we use BR+PC to indicate the proposed scheme with both block partition and cooperative retransmission, where PC stands for platoon cooperation.

We first investigate the impact of packet size on uplink throughput of drive-thru Internet. Here we set system parameters: $\epsilon=10^{-5}$, $N=10$, $N_p=5$ and $N_b=500$ bytes. Simulation results and analytical results are both illustrated in Fig. 3, where we can observe that simulation results match very well with analytical results for all retransmission schemes. In this figure, we take the performance of FR when $\epsilon=0$ as the reference. Obviously, the saturation throughput is monotonically increasing with the packet size in case of $\epsilon=0$. This is mainly because the increase of packet size will decrease the overheads. Nevertheless, we can see that the FR scheme cannot perform well in case of $\epsilon=10^{-5}$. In such a case, the maximum throughput for FR is about 4 Mb/s, when the packet size is about 2300 Bytes. For the BR+PC scheme, we can observe that the system throughput can still increase with the increase of packet size, which outperforms FR in the

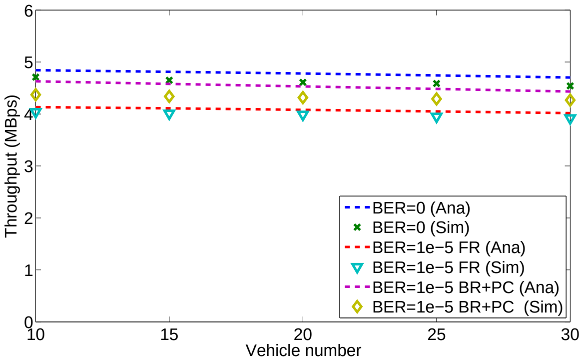


Fig. 4. Throughput vs. vehicle number.

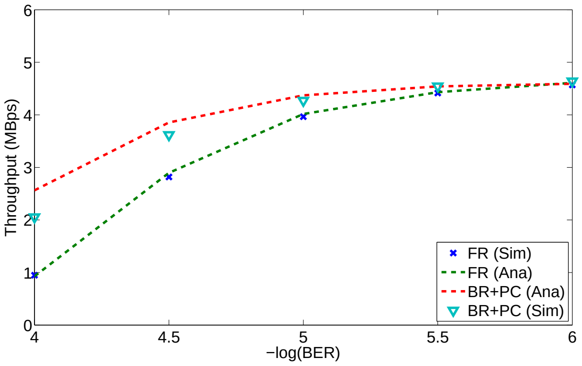


Fig. 5. Throughput vs. BER.

same error condition. Therefore, the proposed platoon-based cooperative retransmission scheme can significantly improve the uplink performance of drive-thru Internet.

Fig. 4 represents the relationship between the uplink throughput S and the number of vehicles N in the coverage of AP, where we set the system parameters with $N_p = 5$, $N_b = 500$ and $L_0 = 4$. We change N to estimate the uplink throughput under different traffic flow rates. Clearly, the analytical results agree with the simulation results for all retransmission schemes. In addition, S will decrease as N increases for all retransmission schemes. Compared to FR, BR+PC scheme guarantees a better uplink performance of drive-thru Internet in various traffic conditions.

Fig. 5 shows the throughput performance vs. BER for all retransmission schemes, where the system parameters are set as follows: $N = 10$, $N_p = 5$, $N_b = 500$ and $L_0 = 4$. We observe that the throughput for all retransmission schemes decreases with the increase of ϵ. However, BR+PC performs much better than FR in serious VANET error-prone environment.

We also evaluate the packet transmission delay for a vehicle, which is defined as the time duration from the epoch that the packet enters the buffer at the MAC layer to the epoch that the packet is successfully received. We set the following system parameters: $\epsilon = 10^{-4.5}$, $N = 10$, $N_p = 5$, $N_b = 500$, $L_0 = 4$. Fig. 6 shows the results for all retransmission schemes. We can observe that BR+PC can effectively reduce transmission delay compared to FR in error-prone VANET environments.

To investigate how the number of cooperative senders influences the uplink throughput of drive-thru Internet, we conduct the analysis with different platoon size N_p (i.e, the number of cooperative senders). We have the following system parameter settings: $N = 15$, $N_b = 500$, $L_0 = 4$ and $\epsilon = 10^{-5}$. The results are illustrated in Fig. 7 (a). We observe that increasing N_p can help to significantly improve S. However, this enhancement becomes less remarkable as the platoon size reaches the half value of N. This fact can be explained by the relationship between N_p and cooperative retransmission probability $p_{\tau c}$, as represented in Fig. 7 (b). $p_{\tau c}$ is monotonically increasing with N_p. When N_p attains to certain threshold (normally half of N), $p_{\tau c}$ will maintain constant.

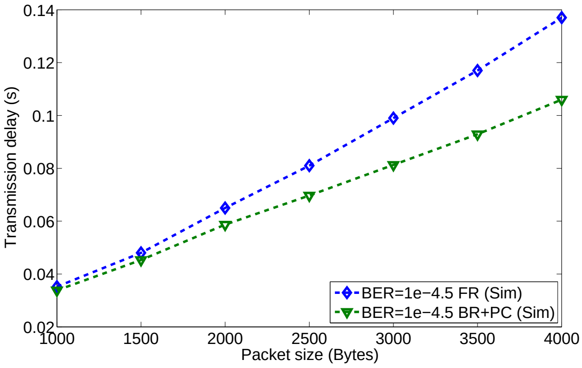
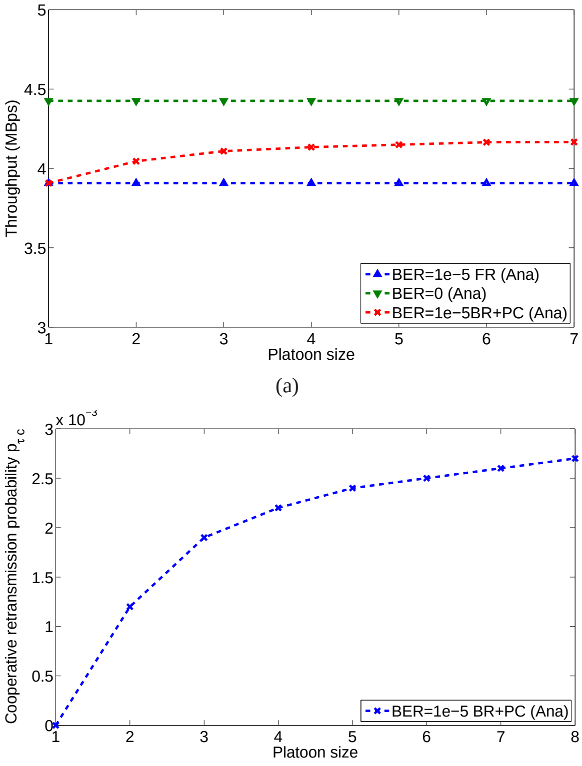


Fig. 6. Transmission delay vs. packet size.



(a)

(b)

Fig. 7. (a) Throughput vs. platoon size (b) cooperative retransmission probability $p_{\tau c}$ vs. platoon size

From all the experiments above, we clearly observe that the proposed platoon-based cooperative retransmission scheme significantly improves the uplink performance of drive-thru Internet, which are verified by both the analytical results and the simulation results.

VI. CONCLUSIONS

In this paper, we have investigated the uplink performance of drive-thru Internet in error-prone environments. By jointly considering traffic mobility and wireless communication, we proposed a novel *platoon-based* cooperative retransmission scheme that can significantly improve the uplink performance of drive-thru Internet. To evaluated the performance of the proposed scheme, we developed a 4-D Markov chain to model the cooperative retransmission behavior in the proposed scheme. Our scheme and analytical model have been validated by extensive simulation in Omnet++. Numerical results show that the proposed platoon-based cooperative retransmission scheme can not only significantly improve uplink throughput of drive-thru Internet, but also considerably decrease the total transmission times for a given quantity of upload data, which can lead to a greener mobile multimedia communications.

REFERENCES

[1] J. Zhao, T. Arnold, Y. Zhang, and G. Cao, "Extending drive-thru data access by vehicle-to-vehicle relay," in *in Proc. ACM VANET, 2008*, New York, USA, 2008, pp. 66–75.

[2] T. H. Luan, X. Ling, and X. S. Shen, "MAC in Motion: Impact of Mobility on the MAC of Drive-Thru Internet," *IEEE Trans. Mobile Computing*, vol. 11, no. 2, pp. 305–319, Feb. 2012.

[3] S. Yang, C. K. Yeo, and B. S. Lee, "MaxCD: Max-Rate Based Cooperative Downloading for Drive-Thru Networks," in *Proc. of ICCCN?12*, Jul. 2012, pp. 1–7.

[4] Y. Zhuang and J. Pan, "On the uplink mac performance of a drive-thru internet," *IEEE Trans. Veh. Technol.*, vol. 61, no. 4, pp. 1925–1935, 2012.

[5] J. Baras, A. Dorsey, and W. Levine, "Estimation of Traffic Platoon Structure from Headway Statistics," *IEEE Trans. Autom. Control*, vol. 24, no. 4, pp. 553–559, 1979.

[6] B. van Arem, C. J. G. van Driel, and R. Visser, "The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 429–436, Dec. 2006.

[7] K. Lu, Y. Qian, and S. Fu, "Enhancing The Performance of Wireless LANs in Error-Prone Environment," *IEEE Globecom 2006*, pp. 1–5, Nov. 2006.

[8] K. Lu, S. Fu, Y. Qian, and H.-H. Chen, "Increasing the Throughput of Wireless LANs Via Cooperative Retransmission," *IEEE Globecom 2007*, pp. 5231–5235, Nov. 2007.

[9] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, 2000.

[10] Z. Hadzi-Velkov and B. Spasenovski, "Saturation throughput-delay analysis of IEEE 802.11 DCF in fading channel," in *ICC '03, IEEE International Conference on*, 2003, pp. 121–126.

[11] E. Ziouva and T. Antonakopoulos, "CSMA/CA performance under high traffic conditions: throughput and delay analysis," *Computer Communications*, vol. 25, no. 3, pp. 313–321, 2002.

[12] I. Tinnirello, G. Bianchi, and Y. Xiao, "Refinements on IEEE 802.11 distributed coordination function modeling approaches," *IEEE Trans. Veh. Technol.*, vol. 59, no. 3, pp. 1055–1067, 2010.

[13] A. Vinel, Y. Koucheryavy, S. Andreev, and D. Staehle, "Estimation of a successful beacon reception probability in vehicular ad-hoc networks," in *Proceedings of the 2009 International Conference on Wireless Communications and Mobile Computing Connecting the World Wirelessly*, New York, USA, 2009, pp. 416–420.

[14] Q. Wang, S. Leng, H. Fu, Y. Zhang, and S. Member, "An IEEE 802 . 11p-Based Multichannel MAC Scheme With Channel Coordination for Vehicular Ad Hoc Networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 2, pp. 449–458, 2012.

[15] S. Wang, A. Song, J. Wei, and A. Hafid, "Maximizing Saturation Throughput of Control Channel in Vehicular Networks," in *2011 Seventh International Conference on Mobile Ad-hoc and Sensor Networks*, Dec. 2011, pp. 297–302.

[16] C. Han and M. Dianati, "Analytical study of the IEEE 802.11 p MAC sublayer in vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 2, pp. 873–886, 2012.

[17] W. Tan, W. Lau, O. Yue, and T. Hui, "Analytical Models and Performance Evaluation of Drive-thru Internet Systems," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 1–16, 2011.

[18] H. Zhu and G. Cao, "r DCF : A Relay-Enabled Medium Access Control Protocol for Wireless Ad Hoc Networks," *IEEE Trans. Mobile Computing*, vol. 5, no. 9, pp. 1201–1214, 2006.

[19] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. Panwar, "CoopMAC: A Cooperative MAC for Wireless LANs," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 340–354, Feb. 2007.

[20] J. Zhang, Q. Zhang, and W. Jia, "VC-MAC: A cooperative MAC protocol in vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 58, no. 3, pp. 1561–1571, 2009.

[21] H. Liang and W. Zhuang, "Double-loop receiver-initiated MAC for cooperative data dissemination via roadside WLANs," *IEEE Trans. Communications*, vol. 60, no. 9, pp. 2644–2656, 2012.

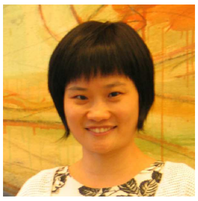
[22] D.-H. Ha, M. Aron, and S. Cohen, "Time headway variable and probabilistic modeling," *Transportation Research Part C: Emerging Technologies*, vol. 25, pp. 181–201, Dec. 2012.

[23] X. Chen, L. Li, and Y. Zhang, "A Markov Model for Headway/Spacing Distribution of Road Traffic," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 4, pp. 773–785, Dec. 2010.

Dongyao Jia received the B.E. degree in automation from Harbin Engineering University, Harbin, China, in 1998, the M.E. degree in automation from Guangdong University of Technology, Guangzhou, China, in 2003. He is currently pursuing the Ph.D. degree in computer science at City University of Hong Kong. He worked as a senior engineer in the telecom field in China from 2003 to 2011. He also took part in the establishment of several national standards for home networks. His current research interests include the cyber-physical systems, vehicular ad hoc networks, and home networking techniques.

Rui Zhang received the B.S. and M.S. degrees from the Department of Mathematics, Imperial College London, London, in 2010 and 2011, respectively. He is currently a Ph.D. student at the Department of Computer Science, City University of Hong Kong, Hong Kong SAR. His research interests include cloud computing, resource management and network security.

Dr. Kejie Lu (S'01-M'04-SM'07) received the BSc and MSc degrees in Telecommunications Engineering from Beijing University of Posts and Telecommunications, Beijing, China, in 1994 and 1997, respectively. He received the PhD degree in Electrical Engineering from the University of Texas at Dallas in 2003. In 2004 and 2005, he was a Postdoctoral Research Associate in the Department of Electrical and Computer Engineering, University of Florida. In July 2005, he joined the Department of Electrical and Computer Engineering, University of Puerto Rico at Mayagüez, where he is currently an Associate Professor. His research interests include architecture and protocols design for computer and communication networks, performance analysis, network security, and wireless communications.



Dr. Jianping Wang is currently an associate professor in the Department of Computer Science at City University of Hong Kong. She received her BSc and MSc degrees from Nankai University in 1996 and 1999 respectively, and her Ph.D. degree from University of Texas at Dallas in 2003. Her research interests include Dependable Networking, Optical Networking, Service Oriented Wireless Sensor/Ad Hoc Networking.

Dr. Zhongqin Bi received his Ph.D. degree in system analysis and integration from East China Normal University, China in 2006. He is currently an Assistant Professor in College of Computer Science and Technology??Shanghai University of Electric Power. Dr. Bi has published more than 30 articles in refereed journals and conference proceedings. His main research interests are cloud computing, data process, and quality control in smart grid.

Dr. Jingsheng Lei is a professor and the Dean of the College of computer science and technology, Shanghai University of Electronic Power. He received his B.S. in Mathematics from Shanxi Normal University in 1987, and MS and Ph.D in Computer Science from Xinjiang University in 2000 and 2003 respectively. He has wide research interests, mainly including machine learning, data mining, pattern recognition and cloud computing. In these areas he has published more than 100 papers in international journals or conferences. He serves as an Editor-in-Chief of the Journal of Computational Information Systems. He is the Members of the Artificial Intelligence and Pattern Recognition Technical Committee of the CCF (China Computer Federation), the member of the Machine Learning Technical Committee of the CAAI (Chinese Association of Artificial Intelligence), and the member of the Academic Committee of ACM Shanghai chapter.