Research Article

A Proximity-Based Concurrent Access Strategy to Improve Throughput in VANETs

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Abstract

Intervehicle communication gives vehicles opportunities to exchange packets within limited transmission ranges and self-organize with ad hoc manner into VANETs (vehicular ad hoc networks). However, due to shared spectrum and present collisions’ resolution mechanism which reject new admissions when wireless medium is busy, communications between vehicles have experienced severe throughput degradation and been restrained for concurrent transmissions. In this paper, a PCM (proximity-based concurrent transmission MAC) protocol has been proposed to permit concurrent access in shared channel for improving goodput in VANETs. By introducing game theory to the concurrent transmission opportunities determination process, PCM could provide extra access chances between active nodes or vehicles based on our defined proximity. To make PCM practical, we further give a detailed implementation method on NS2 to evaluate its performance. Numerical results show that PCM is not only feasible and reasonable in theory, but also has great improvement on average transmission delay, delivery ratio, and throughput performance in test.

1. Introduction

1.1. Introduction of VANET. Vehicular ad hoc networks [1–3] (VANETs) are distributed, self-organizing communication networks built up by moving vehicles and RSUs (roadside units), and are thus characterized by very high node mobility and limited degrees of freedom in the mobility patterns. The discussed IEEE 1609 Wireless Access in Vehicular Environments [4] (WAVE) draft is being developed for VANETs applications including mainly safety-related scenarios, such as cooperative forward collision warning [5] (CCW), traffic signal violation warning [6], lane change warning [7], and some information applications [8]. The success of these critical applications all greatly depend on the effective information exchange between different vehicles or vehicles and RSUs. Unfortunately, current standard or draft does not well support the rigor requirements for these applications and has some drawbacks on throughput improvement strategies.

1.2. Motivation. In VANETs, applications, especially those safety-related, extremely rely on the successful receiving of packets on road. For instance, an emergent broadcasting for accident notification should be reliably delivered to destinations to avoid crash. In bad weather, detected sloppy or frozen road surface condition needs to be rapidly notified to following vehicles by wireless signals. In highway ramp merge case, wireless packets should be received by the possible collided vehicles to prompt the mutual existence accurately. Even in non-safety-related scenarios, effective information receiving also impacts greatly on experience for trip comfortableness and convenience. When the traffic light is red, vehicles are assembling around intersections, and it is a good chance for them to exchange their local collected information within limited time. When intervehicle media sharing or video game has been established, high packets throughput means fluent playback and few frames skipping. In general, effective information exchange is curial to services in VANETs.
However, the present popular protocol stacks, such as IEEE 802.11p which has been referenced as a de facto standard for next generation vehicular networks, is suffering a great throughput degradation which may severely decrease information exchanging efficiency. In MAC layer description in IEEE 802.11p, EDCA (enhanced distribution coordinate access) still serves as the mechanism for multiuser access. Although differentiated service is introduced, the throughput could not be greatly increased due to the CSMA/CA-based collision resolution strategy. For instance, when using RTS/CTS handshakes as contention resolution solution, all neighbors should be silent during the period indicated by the network allocation vector (NAV) in RTS or CTS packets. In other words, an ongoing transmitting under CSMA/CA mechanism inevitably affects others due to the shared spectrum. In fact, even small wireless devices can cause strong interferences for others, thus severely decreasing the overall throughput. Therefore, a well designed strategy should be presented to overcome this inborn drawback of CSMA/CA and increase the achievable network throughput by permitting concurrent ongoing transmissions. In our work, to increase the precious access opportunity, we designed a new MAC layer protocol which permits concurrent ongoing transmissions existence based on IEEE 802.11p draft. We proposed a metric “proximity” to help to determine the requirement for concurrent transmission and also gave the implementation details to carry out our protocol in VANETs.

The rest of this paper is organized as follows. In Section 2, we outline previous related works. In Section 3, the proposed proximity-based concurrent transmission game is introduced. The implementation details are issued in Section 4. Numerical results and discussions are given in Section 4 followed by conclusion in Section 5 and acknowledgment section.

2. Related Works

In VANETs, which in general lack fixed communication infrastructure, a wise and intelligent decision is hard to be made in a distributed manner. However, RSUs, which are introduced to enhance network performance, can make this work easy. After enough information is collected on RSUs, an intelligent decision could be made with fairness and effectiveness. However, although RSUs can act as the decision-making center, they also readily become the bottleneck of its covered area especially when multiple packets are possibly transmitted to it simultaneously. Therefore, how to handle the concurrent transmitting and make full use of the provided broad bandwidth is very crucial to the up-to-datedness of information and driving safety.

To reach this goal, a distributed algorithm on each node is necessary to make its own decision whether to transmit to the RSUs or not. If choosing to send, the concurrent transmitted signals on the fly could together output a feasible SINR for each participated node and not make the network load saturation. For this distributed decision making problem, one of the best candidates is the game theory which has been largely applied to the wireless resource allocation scenarios [9–12]. The main advantage of a game-theory-based scheme is that, by turning nodes into selfish players for pursuing high payoff, an otherwise complex system can reach efficient outcomes in a lightweight and distributed manner. To apply game theory to our discussed problem, the difficulty lies in obtaining complete information of nodes under dynamic network state variation and high mobility, where information broadcasting is also useless to reflect the exact and real-time distributed global situations. Although there were some topics on wireless resource allocation [13], attacks classification [14], transmission selection [15], and others in ad hoc network based on incomplete information game, to our best knowledge, for our later described “proximity”-based concurrent transmission strategy which relies on incomplete information game, there are few related works.

For concurrent transmission strategy research, there mainly exist two categories of schemes: game-theory-based and TPC-(transmission power control-) based concurrent transmission proposals. The former can be further classified into three classes: NE-based backoff time adaptation [9], NE-based power control [16, 17], and NE-based transmission schemes depending on channel conditions [18]. For NE-based determination scheme used in wireless networks especially in ad hoc networks, most works have been done around wireless resources allocation such as radio frequency, available bandwidth, and transmitting power. Generally speaking, any resource-limited allocation or assignment problems are candidates for NE determination. Usually, since concurrent transmission opportunity is decided by SINR, the most relevant resources for this determination problem are NE-based power control. Saraydar et al. [19] proposed a game-theory-based power control algorithm for data transmissions in cellular networks to increase capacity and extend lifecycle. Although the paper was not putting focus on concurrent transmission, the work has been recognized as the base of followed concurrent transmission research papers because capacity growing is common to concurrent transmission opportunities increasing. Wang et al. [20] proposed G-MAC with adaptive power control to make nodes plan their transmissions simultaneously in an ad hoc manner. Their work’s frame the concurrent transmission problem as a complete information noncooperative power control game to find the transmitting power threshold meeting SINR need. Adlakha et al. [21] proposed a Bayesian game with incomplete interference information about opponents. The game is static, say simultaneous move between nodes, for selecting a power profile over the entire available bandwidth to maximize Shannon’s capacity. Lee et al. [17] developed a channel access game, which considered concurrent transmissions with different access points, under the influence of intercluster interferences. After successfully finding the Bayesian Nash equilibrium, they further presented a simple dynamic implementation procedure for nodes to efficiently find a Nash Equilibrium without knowing the number of total active nodes.

For TPC-based concurrent transmission schemes, their objectives mainly focus on either energy conservation [22, 23] or throughput improvement [24–26]. In PCMA [26], a flexible “variable bounded power” collision suppression
model was introduced. Each receiver advertises its calculated interference margin by sending busy tone pulses over a separate control channel. The PCDC protocol [25] uses two channels for data and control packets, respectively. They do not use the RTS/CTS exchange to silence the neighboring nodes. Instead, collision avoidance information is inserted into the CTS packets and is sent over the control channel. The information is used to dynamically bound the transmitting power of potentially interfering nodes in the vicinity of a receiver to allow for interference-limited simultaneous transmissions. Being different from the above two multichannel concurrent transmission schemes, POWMAC [24] uses a single channel for both data and control packets. The scheme adjusts the transmitting power of data packets to allow for some interference margin at the receiver. Therefore, multiple interference-limited transmissions near a receiver are allowed to overlap in time, provided their multiaccess interference (MAI) effects do not lead to collisions at nearby receivers. Although there were some works focusing on concurrent transmission solutions in VANETs, such as those of Sun et al. [27] and Nittel et al. [28], there are design schemes under multi-channel or enabling cognitive radio, which is much different from our work only requiring single channel.

In summary, our work has mainly two contributions as follows. First, we have given a simple but efficient way to determine the concurrent transmission occasion in our discussed scenario in VANETs; second, we implemented this scheme on NS2 platform and evaluated the output performance.

3. Model Description

3.1. Discussed Scenario and Assumptions. The discussed scenario is demonstrated in Figure 1.

There are two kinds of vehicles, that is, high-speed cars numbered from 1 to N and the low-speed buses which have access points installed with large radio coverage. The buses here serve for the packets exchange between different cars or cars and internet. For information exchange between cars, the buses act as store-carry-forward nodes to provide indirect connections between sources and destinations. In this way, the packets or bursts can be stored temporarily when target is not reachable and forwarded later with movement. Another important capability of buses is serving as the mobile RSUs, which are necessary equipments in VANETs to provide broad access bandwidth and large communication range.

Before giving our proposed model, we first present the definition of “proximity” and some assumptions.

Definition 1. Proximity is defined as the intimacy level between cars and buses and expressed by

$$e_i = \frac{1}{d_i}$$  \hspace{1cm} (1)

for car $i$, where $d_i$ is the distance between $i$ and its affiliated bus.

The affiliate relation indicates whether the given car is within the radio range of the investigated bus. If there is more than one bus covering the same car, the affiliated bus is the one with the maximum proximity to $i$. To make our model practical, the following assumptions are given.

Assumption 2. The total amount of active nodes can be obtained by some estimation methods [29, 30].

Assumption 3. Transmission power is fixed to 1 for simplicity and adaptive power control (APC) is disabled considering hardware complexity.

Assumption 4. The packets to be sent are delay tolerant and could be buffered for future transmission. This assumption is reasonable for the low-duty cycle periodical applications such as road condition report and congestion notification.

Assumption 5. The distances between sources and destinations can be readily obtained by the receive signal strength indicator (RSSI) under LOS (line of sight) environment or hybrid TOA/AOA [31] algorithms under NLOS (non-line-of-sight) circumstance.

3.2. Transmission Model. Now we describe the proposed transmission model and propagation model. We discuss the scenario in which all vehicles communicate on the same channel. Thus, for a given transmitter, any other signal at the intended receiver is regarded as the interference to this transmission. We assume that packets from a particular vehicle can be transmitted to its intended receiver at a rate not exceeding C bps, provided that the SINR at the receiver does not fall below a threshold SINRth. In general, SINRth depends on the modulation technique, the desired bit error rate, the required transmission rate, and the coding strategy employed. Here, according to Figure 1, we define the SINR for the successful transmission of any given vehicle $i$ as

$$\gamma_i = \frac{h_i P_i}{\sum_{j \in \chi_i} h_j P_j + \sigma^2} \geq \text{SINR}_{th},$$  \hspace{1cm} (2)

where $P_i$ is the power of vehicle $i$ and $h_i$ is the channel gain between $i$ and its receiver. $\alpha$ is the crosstalk interference ratio to adjust the influence from signal interferences. $\chi_i$ is the set of all interfering nodes for $i$ and $\sigma^2$ is the variance of...
AWGN with mean 0. Then, for any given propagation model in wireless communications, we have the following equation:

\[ P_r(t) = P(t) h(d(t)) \]

(3)

where \( P(t) \), \( P_r(t) \) indicate the transmitting power at sender and the signal strength at receiver, respectively, at moment \( t \). \( h(d) \) denotes the channel gain as a function of the distances between sources and destinations. In most of the previous studies [32, 33], \( h(d) \) is expressed as \( (d)^{-\beta} \), where \( \beta \) is the path loss factor with an empirical value of \( \beta = 1.6 \sim 6 \). Nevertheless, this relation becomes invalid when the distance \( d \) between transmitter and receiver drops below 1, where \( P_r(t) \) will exceed \( P(t) \) based on (3) and \( P_r(t) \) will have arbitrarily large value as \( d \) becomes sufficiently small. This problem was also noticed in aforementioned works [26, 27], and some measurements have been given to handle it. In our work, to obtain reasonable results when \( d \) is less than 1 and at the same time keep the relationship when \( d \) is greater than or equal to 1, the following channel gain expression was presented:

\[ h(d) = (1 + d)^{-\beta}, \quad d > 0. \]

(4)

Now, with (1) and (4), we have

\[ h_i = \left(1 + \frac{1}{e_i}\right)^{-\beta}. \]

(5)

3.3. Proposed Proximity-Based Concurrent Transmission Game (PCM). Based on the above transmission model and the proximity concept, we could define a channel access strategy by introducing incomplete information game theory. The definitions of utility function for reflecting award and price are expressed as follows.

**Definition 6** (static channel access game). We formulate an interference-aware channel access game as follows.

(i) **Players:** there are a bus and \( N \) players, with each player \( i \in \{1, 2, \ldots, N\} \) having a distance \( d_i \) from the bus, where \( d_i \geq 0 \).

(ii) **Actions:** \( a_i \in \{T, W\} \); that is, transmit or wait for all players.

(iii) **Payoff function:**

\[ u_i(a_i, a_{-i}; e_i) = \begin{cases} \prod_{i=1}^{n} (W, a_{-i}) = 0, & a_i = W, \\ \prod_{i=1}^{n} (T, a_{-i}) = R_i(a_{-i}) - c(P)_i, & a_i = T. \end{cases} \]

(6)

\( R_i(a_{-i}) \) is the network throughput, which is expressed by

\[ R_i(a_{-i}) = \begin{cases} \log(1 + y_i) & y_i \geq \text{SINR}_{\text{th}}, \\ 0 & \text{else,} \end{cases} \]

\[ y_i = \frac{(1 + (1/e_i))^{-\beta}}{\alpha \sum_{j \in X_i} (1 + (1/e_j))^{-\beta} + \sigma^2}, \quad \chi_i = \{j \neq i: a_j = T\}. \]

(7)

\( c(P_i) = \mu(P_i/h_t) = \mu/(1 + (1/e_i))^{-\beta} \) is the price formula denoting the cost for transmission. The definition for price function has twofold meanings: one for pricing each transmitting attempt indicated by \( \mu \) and the other for denoting the relation that channel gain is in inverse proportion to the transmitting cost or price. That is, the larger the channel gain is, the less the cost is needed for nodes to transmit. The definition also presents the potential meaning for the proximity variable, that is, \( e_i \). That is, a bigger \( e_i \) will make node \( i \) more intimate with the bus, thus paying less effort to contact with the bus. In other words, a larger proximity or a shorter distance between a given node and the bus indicates the smaller probability for severe channel fading or gain degradation.

**Definition 7.** \( a_i^*(e_i) \) is a Bayesian Nash equilibrium if and only if

\[ a_i^*(e_i) = \arg \max_{a_i} \sum_{e_i} P_i(e_i | e_i) \cdot u_i(a_i, a_{-i}^*(e_i) | e_i) \]

\[ = \arg \max_{a_i} E \left[ \prod_{i=1}^{n} (a_i, a_{-i}^*(e_i) | e_i) \right]. \]

(8)

**Definition 8.** In a Bayesian Nash equilibrium, player \( i \) will play Transmit if and only if

\[ E \left[ \prod_{i=1}^{n} (T, a_{-i}^*(e_i) | e_i) \right] \geq E \left[ \prod_{i=1}^{n} (W, a_{-i}^*(e_i) | e_i) \right]. \]

(9)

3.4. Proof for the Existence and Uniqueness of NE

**Lemma 9.** The NE for our proposed game is existent. To prove this proposition, the nonemptiness of strategy space and convex/quasiconvex property of utility function is needed to be verified.

**Proof.** (a) Obviously, the strategy space of our game is nonempty.

(b) The payment function is continuous and quasiconvex due to

\[ \frac{\partial^2 u_i}{\partial e_i^2} = -\frac{1}{\left((1 + (1/e_i))^{-\beta} + \alpha \sum_{j \in X_i} (1 + (1/e_j))^{-\beta} + \sigma^2\right)^2} \]

\[ -\frac{2\mu}{(1 + (1/e_i))^{-3\beta}} < 0. \]

(10)

**Lemma 10.** The NE for our proposed game is unique. To prove this proposition, the positive definiteness and monotonicity of our game are needed to be verified.

(a) Positive definiteness: that is, prove

\[ E \left[ \prod_{i=1}^{n} (T, a_{-i}^*(e_i) | e_i) \right] > 0. \]

(11)
Proof.

\[ \frac{\partial E}{\partial e_i} \left[ \prod_{i=1}^{n} (T, a_i (e_i) \mid e_i) \right] > 0. \quad (12) \]

The BNE about \( e \) satisfies

\[ E \left[ \prod_{i=1}^{n} (T, a_i (e_i) \mid e_i) \right] = 0. \quad (13) \]

So, with (12) and (13), one has

\[ E \left[ \prod_{i=1}^{n} (T, a_i (e_i) \mid e_i) \mid e_i > e_i, \right] > 0. \quad (14) \]

(b) Monotonicity: that is, prove that for all \( e \) and \( e_i > e_i \),

\[ E \left[ \prod_{i=1}^{n} (T, a_i (e_i) \mid e_i + e) \right] \geq E \left[ \prod_{i=1}^{n} (T, a_i (e_i) \mid e_i) \right]. \quad (15) \]

Proof.

\[ E \left[ \prod_{i=1}^{n} (T, a_i (e_i) \mid e_i) \right] = \sum_{\chi \cup \chi_i \neq \{1, \ldots, n\}} \left[ \log \left( \frac{1 + (1/(e_i + e_i))^{\beta}}{\alpha \sum_{j \in \chi} (1 + (1/e_j))^{\beta} + \sigma^2} \right) \right. \]

\[ - \frac{\mu}{(1 + (1/e_i))^{\beta}} \cdot p (e_i) \, de_i. \quad (16) \]

where

\[ \psi = \left\{ e_i \mid \sum_{j \in \chi} \left( 1 + \frac{1}{e_j} \right)^{-\beta} \leq \frac{1}{\alpha} \left( \frac{1 + (1/(e_i))^{\beta}}{\text{SINR}_{th}} - \sigma^2 \right), \right\} \]

\[ a_i (e_i) = T, \forall j \in \chi_i; a_i (e_i) = W, \forall j \in \bar{\chi}_i \}\right\} \in \chi \]

\[ \bar{\psi} = \left\{ e_i \mid \sum_{j \in \chi} \left( 1 + \frac{1}{e_j} \right)^{-\beta} \leq \frac{1}{\alpha} \left( \frac{1 + (1/(e_i + e_i))^{\beta}}{\text{SINR}_{th}} - \sigma^2 \right), \right\} \]

\[ a_i (e_i) = T, \forall j \in \chi_i; a_i (e_i) = W, \forall j \in \bar{\chi}_i \}\right\} \in \bar{\psi} \]

Because

\[ \int_{\psi} \left( \log \left( \frac{1 + \left( \frac{1}{(e_i + e_i)} \right)^{\beta}}{\alpha \sum_{j \in \chi} (1 + (1/e_j))^{\beta} + \sigma^2} \right) \right. \]

\[ - \frac{\mu}{(1 + (1/e_i))^{\beta}} \cdot p (e_i) \, de_i \]

\[ \geq \int_{\bar{\psi}} \left( \log \left( \frac{1 + \left( \frac{1}{(e_i + e_i)} \right)^{\beta}}{\alpha \sum_{j \in \chi} (1 + (1/e_j))^{\beta} + \sigma^2} \right) \right. \]

\[ - \frac{\mu}{(1 + (1/e_i))^{\beta}} \cdot p (e_i) \, de_i \]

thus, we have

\[ E \left[ \prod_{i=1}^{n} (T, a_i (e_i) \mid e_i + e) \right] \geq E \left[ \prod_{i=1}^{n} (T, a_i (e_i) \mid e_i) \right]. \quad (19) \]

So, conditions (a) and (b) are both satisfied.

\[ \square \]

3.5. NE Analysis. Section 3.2 verifies the existence and uniqueness of NE for our proposed game. To further explain the working mechanism of our proximity-based access model, we then give a detailed illustration to our scheme under different number of active vehicles.

To verify the feasibility of our game by instance, we first introduce 2 vehicles and then extend this case to more nodes (\( n > 2 \)) later.

(i) \( n = 2 \). It means that both vehicles \( i, j \) are considered as interferences for each other. We then calculate the BNE about proximity \( e \) as the concurrent transmission threshold for both vehicles. If action \( a_i = T \), there are two cases.

(ii) While \( e_i \leq e_{th} \), \( a_i = W \), this means that only node \( i \) could transmit. In addition, if \( e_j = (e_i/(e_i+1))^{\beta}/\sigma^2 \geq \text{SINR}_{th} \), the sent packets from node \( i \) will be received successfully. As a result, the payoff function is

\[ u_{i_{th}} = \log \left( 1 + \left( \frac{e_j/(e_i + 1)}{\sigma^2} \right)^{\beta} \right) - \mu \times \left( \frac{e_j + 1}{e_i} \right)^{\beta}. \quad (20) \]

(ii) While \( e_j \geq e_{th} \), there are also two cases. One case is that node \( i \) transmitted and is received successfully; that is, \( y_2 = (e_j/(e_i + 1))^{\beta}/((e_j/(e_i + 1))^{\beta} + \sigma^2) \geq \text{SINR}_{th} \). We define
\((e'_{th}/(e'_{th} + 1))^\beta = ((e_i/(e_i + 1))^\beta/\text{SINR}_{th}) - \sigma^2\); it means that the payoff function is

\[
u_{ts2} = \log \left(1 + \frac{(e_i/(e_i + 1))^\beta}{(e_i/(e_i + 1))^\beta + \sigma^2}\right) - \mu \times \left(\frac{e_i + 1}{e_i}\right)^\beta,
\]

while \(e_i \geq e'_{th}\).

With (21)–(25), we have the following.

When \(e_j < e_{th}\),

\[
u_{ts1} = \log \left(1 + \frac{(e_j/(e_j + 1))^\beta}{\sigma^2}\right) - \mu \times \left(\frac{e_j + 1}{e_j}\right)^\beta.
\]

When \(e_j \geq e_{th}\), if \(e_j \leq e'_{th}\),

\[
u_{ts2} = \log \left(1 + \frac{(e_j/(e_j + 1))^\beta}{(e_j/(e_j + 1))^\beta + \sigma^2}\right) - \mu \times \left(\frac{e_j + 1}{e_j}\right)^\beta.
\]

Or \(e_j > e'_{th}\), \(\nu_{tf} = 0 - \mu \times \left(\frac{e_j + 1}{e_j}\right)^\beta\) \quad (24).

We define the cumulative distribution function of random variable \(x\) as \(F_x(x)\), and \(\overline{F}_x(x) = 1 - F_x(x)\). With the aforementioned discussion, both nodes could optimally respond to maximize their expected utilities. For instance, if node \(i\) transmits, there exists

\[
E\left(\prod_t (T, a_j(e_j))\mid e_i\right) = p(e_j < e_{th}) \left[\log (1 + y_1) - \mu \times \left(\frac{e_j + 1}{e_j}\right)^\beta\right] + p(e_j \geq e_{th}) \times \left[\prod\left(\nu_2 \geq \text{SINR}_{th}\mid e_j \geq e_{th}\right) \cdot E\left(\log (1 + y_1) - \mu \times \left(\frac{e_j + 1}{e_j}\right)^\beta\mid e_{th} \leq e_j \leq e'_{th}\right)\right.
\]

\[+ P(\nu_2 < \text{SINR}_{th}\mid e_j \geq e_{th}) \left(0 - \mu \times \left(\frac{e_j + 1}{e_j}\right)^\beta\right)\]
Finally, we could calculate the Bayesian Nash equilibrium regarding the distance as the transmission threshold between vehicles, that is,

\[ E\left( \prod_i \left( T, a_i (e_{-i}) \mid e_{th} \right) \right) = 0. \]  

(30)

4. Model Implementation and Performance Evaluation

In this section, we will first give the PCM implementation details on NS2 and then evaluate its performance with different parameters settings.

4.1. PCM Implementation on NS2. For typical IEEE802.11x CSMA scheme, the packets will be collided and dropped when they arrive at the physical interface of the receiver at the same time. The reason is that there are lots of hidden nodes which cannot sense the sender’s ongoing transmission and at last result in collisions. Although there are some vendors implementing the “capture effect” on hardware, this mechanism actually works with very strict limitation. For instance, on NS2 platform, the “capture effect” will only be triggered when the strength difference between received signals from various senders is larger than 10 times. Even though the “capture effect” could work well, it only permits the successful reception of the most powerful packets which has captured the channel. In other words, concurrent reception is still not permitted. Besides, in IEEE802.11x protocols, the “duration” field in MAC header, as shown in Figure 2, sets a NAV (network allocation vector) value to restrain the transmitting attempts from neighboring nodes of transmitters, which will further reduce the channel utilization ratio especially when concurrent transmissions are possible. Our proposed PCM scheme tries to explore the simultaneous transmission opportunities between nodes and made the following revisions to the original CSMA mechanism.

(a) First, we set the higher priority for concurrent transmission when it is available than for NAV indication. In other words, if concurrent transmission is available currently, the NAV field will be useless.

(b) Second, we revised the collision processing module in IEEE802.11x CSMA protocol to allow the interferences computing for all incoming packets whereby the successfully decoded packets can be queued in the physical interface buffer. In this way, because the delimiter in the preamble could certainly distinguish the incoming packets, a dropped packet will only occur when physical decoding fails.

We also revised the standard IEEE 802.11 module in NS2 and coded our PCM model on it. The reason is that NS2 focuses on protocol simulation and optimization which is not expert in iteration computation. Therefore, we implemented the game-theory-based NE searching with MATLAB toolkits on Linux platform. In this way, by releasing our MATLAB codes in Linux executable binary format, NS2 could readily invoke the complex computation part and concentrate on protocol performance evaluation. The numerical analyses of our proposed proximity-based concurrent transmission strategy involve two parts: one for algorithm correctness verification and the other for network performance inspection in VANETs simulation environment with real settings.

4.2. Algorithm Correctness Verification. The simulation parameters for algorithm correctness evaluation are listed in Table 1. The relationship between calculated proximity \( e \) and number of active nodes is depicted in Table 2, and the corresponding curve is plotted in Figure 3.

The proximity, which indicates the affinity between normal vehicles and buses, increases dramatically with the growing of the number of active vehicles as shown in Figure 3.
From the approximately linear relationship, we could conclude that our proposed scheme is also fair among vehicles where more active vehicles need more “loves” from buses. On the other hand, larger proximity corresponds to lower distance between normal vehicles and buses, for instance, 106.6 meters for 2 active vehicles and 76.2 meters for 21 active vehicles. It means that for a given transmitting power for all vehicles, a larger number of active vehicles require short distances from buses which may make successful concurrent receptions at buses possible due to bigger SINR and less frequent channel gain changing. The word “possible” here denotes the possibility of reception failure due to channel gain changing during the process of concurrent transmission.

In Figure 4, the performance evaluations by the other possible influences are simulated involving mutual interference ratio, SINR\textsubscript{th}, variance of AWGN, and coefficient of transmitting cost. The proximity increases as the mutual interference ratio and the number of active vehicles grow as shown in Figure 4(a). The reason is that larger mutual interference ratio introduces more interference among vehicles resulting in more needs for proximity from buses to anti-interferences. Figure 4(b) shows that the growing of SINR\textsubscript{th} also makes the proximity increase due to lower interferences bearing capability. Figure 4(c) indicates that the rise of variance of noise also causes the increase of final proximity with the number of active vehicles augmenting. The reason is almost the same with the impact of SINR\textsubscript{th} on proximity performance. The effect of the coefficient of transmitting cost on proximity is plotted in Figure 4(d), where the resulted proximity is increasing with the growing of the coefficient, which expresses the price brought by transmitting attempts. It could be observed that the more the vehicles need to pay for the transmitting, the less the proximity will be.

4.3. Network Performance Inspection. In this section, we will evaluate the performance of our proposed scheme on NS2. The used parameters of our PCM model are the same as listed in Table 1. The general parameters for our network performance evaluation are listed in Table 3. The Queue model used in our simulation is just DropTail strategy due to the simplified setting for routing scheme, that is, DumbAgent, which implies that no routing is actually required. The simulation topology, which is a snapshot of the NS2 NAM (Network Animator), is plotted in Figure 5 in a 1000 m*1000 m circular field where 50 vehicles are uniformly distributed in 4 lanes and move following the freeway [34] mobility model. The other parameters of freeway model are listed in Table 4. The acceleration speed is set as Acceleration\textsubscript{speed} = 10\% * Maximum velocity according to [34]. There are 8 buses circled by red color taken as the mobile access points/gateways, which are placed to approximately cover all the vehicles within their radio ranges. Other vehicles choose to access the nearest mobile bus to finish messages exchanging. The following simulation scenarios will increase the number of vehicles according to the uniform distribution on the simulation area, but the number of buses will never change.

Figure 6 has shown the performance comparisons between IEEE802.11x CSMA scheme and PCM. Note that although the simulation period is set to 300 seconds, the tests will be actually ended before it due to queues overflow, too many packets drops, or out-of-radio range. By Figures 6(a) and 6(c), we could notice that the average transmission delay has clear relation with the number of active nodes and data rate. However, for average speed, which follows a uniform (min. velocity, max. velocity) distribution, it shows uncertain relevance with average transmission delay as shown in Figure 6(e). The reason is that a higher average driving speed make the topology more dynamic thereby lots of sent packets could not be received due to mobility, which will trigger the retransmission procedure to retry to the limit. Therefore, the average transmission delay will become larger and jittering.

As shown in Figure 6(a), where 1 Mbps data rate is configured, our PCM mechanism always has better average transmission delay performance than IEEE802.11x CSMA. The number of active nodes is the total number of vehicles attempting to transmit to buses within our measurement period, that is, 0.1s in our simulation. However, the concurrent transmission proximity for each bus is computed based on the number of active nodes around it. The average transmission delay is an arithmetical average of delays for all received packets at all buses. It can be noticed that when the number of active nodes is less than 80, PCM shows better performance than CSMA because there are lots of concurrent transmission opportunities for vehicles around each bus.

| Parameters | values |
|------------|--------|
| Lane number | 4 |
| Lane distance (m) | 5 |
| Max. velocity (m/s) | 30 |
| Direction | 2 |
| Min. velocity (m/s) | 20 |
| Rate (packets/s) | 10 |

Table 3: Scenario settings.
In fact, for a given calculated concurrent transmission proximity $e$, any node or vehicle with proximity larger than $e$ could attempt to transmit. In Figure 6(c), we increase the data rate, which indicate the provided bandwidth by physical layer, to investigate the output performance. The number of active nodes for Figure 6(c) is 100 involving the buses. Note that the average transmission delay decreases dramatically for CSMA when data rate increases, whereas our PCM scheme, although still has lower average delay than CSMA before 5 Mbps, shows a relatively slow falling compared with CSMA and finally has a higher average transmission delay than CSMA at 6 Mbps. The reason is that, for a large data rate, CSMA could greatly reduce the collision possibility due to smaller air flying time for packets. However, for our PCM mechanism, although increase of data rate could further reduce the needed period for either concurrent/nonconcurrent transmissions, the concurrent transmission opportunities are still the same with cases under lower data rate. Figure 6(e) denotes that there is no apparent relationship between average vehicles' speed and average transmission delay where the number of deployed vehicles is still 100 with 1 Mbps data rate.
with various data rates. The relation between delivery ratio and average speed is also obscure as shown in Figure 6(f). However, we can conclude from Figure 6(f) that our PCM is not suitable for high dynamic vehicular networks.

Figures 6(g), 6(h), and 6(i) show the throughput performance comparisons between our PCM and CSMA. Here, \((xN), (xs), (xR)\) in these figures indicate the number of active nodes, the average speed, and the data rate, respectively. The other unspecific parameters are the same as shown in Tables 3 and 4. In Figure 6(g), we can conclude that our PCM always has better throughput performance than CSMA in lower dynamic network when the number of vehicles changes. However, when the average speed is continuously increasing, PCM begins to show poorer performance than CSMA especially when average speed is beyond 25 m/s as shown in Figure 6(h). As for throughput performance under different data rate, the results from Figure 6(i) are consistent with Figure 6(d), where more data rate has little effect on final throughput for our PCM scheme due to no more concurrent transmission opportunities increasing. However, for CSMA mechanism, growing of data rate has greatly improved the final throughput regarding less collisions and retransmissions.

To verify PCM in real application scenario, we also implemented it on our vehicular communication testbed composed of 8 cars as shown in Figure 7. The red circled car here is taken as the BUS node, and the other cars try to access the bus. The small car is equipped with a wireless radio device which consists of an ATME Atmega128L MCU (microprogrammed control unit), a Chipcon 2420 SmartRF, a Maxim IC MAX3232 transceiver, and some other chips for storage and debug. The PCM protocol is coded on the embedded Linux platform on this device. Our cars can move autonomously with predefined routes or be controlled through infrared. The size of the car is 20 cm (length) × 7.5 cm (width) and the area of the test field is 100 m (length) × 3.5 m (width). The speeds of the 8 cars are uniformly chosen from [100 cm, 3 m] per second and the radio range of the transceiver is 8 meters. We run an 80 seconds test and repeat it 20 times to output the arithmetic average. The other settings like SINR threshold, packet size, data rate, packets generation period, and so forth are the same as in Table 4. Here, we just show the throughput performance compared with the typical IEEE 802.11a protocol. Due to the different PHY and MAC layer mechanisms, we use a USB WLAN adapter for testing which can be connected to the peripheral board of the wireless communication device.

The throughput results are plotted in Figure 8. Note that the throughput performance in real environment is more fluctuant than in simulation. The reason is that the wireless signal is much susceptible to interferences and influences in practice such as unstable transmitting power, other wireless devices’ disturbance, nonideal propagation channel, and statistical errors. But for all this, the trend in Figure 8 is still clear and shows that our proposed PCM always outperforms IEEE 802.11a on throughput. The reason is simple and the same as previous simulation results; say there are lots of concurrent transmission opportunities for vehicles running with our PCM. However, with typical WLAN protocol, the throughput...
Figure 6: Continued.
will degrade due to CSMA/CA-based collision release mechanism.

5. Conclusion

In this paper, we have proposed a proximity-based incomplete information game to solve the concurrent transmission problem between vehicles and mobile RSUs. By detailed analysis and simulations, the correctness and effectiveness have been proofed for our proposed PCM scheme. Besides, we also give the implementation procedure of our PCM on NS2 simulation platform to verify its practicality. Although PCM could better work under lower dynamic networks, it shows poor performance when topology changes frequently. Our future work will focus on reducing the computation and time complexity of PCM and increasing its scalability and adaptability in high mobility networks.
Figure 7: Testbed with programmable autonomous cars.

Figure 8: Throughput performance on real testbed.

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