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Hybrid game approach-based channel congestion control for the Internet of Vehicles

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Abstract

Communications between the Internet of Vehicles in smart cities helps increase the awareness and safety among drivers. However, the channel congestion problem is considered as a key challenge for the communication networks due to continuing collection and exchange of traffic information in dense environments. The channel congestion problem degrades the efficiency and reliability of the ad hoc network. Therefore, the adaptation of the data rate and power control is considered as one of the effective solutions to mitigate channel congestion. A new hybrid game transmission rate and power channel congestion control approach on the Internet of Vehicle networks where the nodes play as greedy opponents demanding high information rates with the maximum power level are developed. Furthermore, the existence of a Nash equilibrium, which is the optimal information rate and power transmission for every vehicle, is established. Simulation results demonstrate that the proposed approach enhances the network performance by an overall percentage of 42.27%, 43.94% and 47.66% regarding channel busy time, messages loss and data collision as compared with others. This increases the awareness and performance of the vehicular communication network.

1 | INTRODUCTION

Smart cities have been constructing to improve and facilitate the mobility of vehicles and passengers and provide mobile sources for information sharing. To integrate various electronic devices, smart cities use effective Information and Communication Technologies (ICT) such as the Internet of Things (IoT) and the Internet of Vehicles (IoV). These devices help to collect, investigate and transmit critical information related to the traffic status.

The IoV is a subset of the IoT [1], that prognosticates communication among vehicles and other sensors deployed on the roadside, supporting the traffic data sharing to improve transportation convenience and safety. IoV is an encouraging technology which can provide efficient tools for traffic management systems to observe traffic situations and vehicle routes [2]. IoV includes many communication systems that can sense, collect and transmit traffic information such as Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I). The

transmitting of the traffic information is achieved by periodically sending safety messages via the control channel of the Wireless Access for Vehicular Environment protocol (WAVE) protocol.

The transmission of the traffic information in the IoV is essentially based on IEEE802.11 group protocols. However, the performance verification for most of these protocols does not meet the requirements of the Quality of Service (QoS) in IoV [3]. This is because the safety messages that are related to the traffic situations must be transmitted as fast as possible to reach the surrounding drivers without high packets loss, high delay and jitter. QoSs are vital parameters for many applications in the IoV such as event-driver and public safety messages, traffic coordination, self-parking and comfort applications, infotainment applications and traffic information collection. Therefore, the negative impact of the QoS parameters on the wireless channel congestion problem influences the accuracy of the transmitted traffic information and degrades the IoV performance.

The bandwidth congestion problem in IoV is considered vital due to it influences the disseminated transportation

information and the trustworthiness of the vehicular environments. This dilemma happens when a vehicle propagates a large amount of data over the network or several nodes broadcast duplicated information repeatedly in a crowded vehicular environment. This creates transmission burden and reduces the information transmission rate of the network. Accordingly, QoS such as throughput, delay and packet loss are negatively affected.

Therefore, to control the broadcasted information frequency and power level in IoV, a Hybrid Rate and Power Game Approach (HRPGA) is proposed to formulate the wireless channel congestion problem. This game includes controlling the power level of the data which governs the transmission range at which data are sent and it controls the data rate which constrains the number of messages being transmitted through the network. Adapting the power level and rate of the messages will help to reduce the channel congestion, delay time to receive the traffic information and increases data delivery ratio. This improves smart cities awareness about traffic state conditions. The proposed approach significant contributions:

1. The proposed approach contributes to the development of a novel channel congestion strategy which can enhance the network communication performance and increase the reliability. This means the awareness of smart cities will be increased and the traffic data will be transferred promptly to the drivers. This helps to provide an implementation of practical solutions for enhanced traffic flow and convenience in smart cities.
2. The proposed approach can alleviate congestion on the wireless channel by adjusting the node information frequency and power level by considering the vehicles' sending rate, queueing waiting time, vehicles mobility, power level and distance priorities. These parameters are included in the profit function for each node to provide the desired fairness, a stable transmission protocol and channel overload free.
3. The existence and uniqueness of a unique and stable optimal solution in the IoV congestion game have been proven.
4. The constrained non-linear optimization has been used to formulate the vehicle's utility function of data rate and power level, respectively.
5. An urban-based scenario has been implemented to evaluate the proposed approach and comparisons are presented with the two other recently published approaches.

The study is organized as follows. Section 2 presents a review of the channel congestion problem of the related works. Section 3 addresses the game formulation, utility functions design and the proof of the optimal solution existence and uniqueness. Section 4 provides techniques that are used to find the optimal solution. The performance evaluation is presented in Section 5. Finally, Section 6 provides the conclusion.

2 | RELATED WORKS

Many channel adaptation approaches have been proposed in the literature to tackle the channel congestion problem in the IoV networks such as power transmission, beacon rate, contention window and hybrid adaptation approaches. However, it is mainly focuses on the hybrid adaptation approaches that joint two or more parameters to alleviate the channel congestion problem.

A Joint Power and Rate Control (CPRC) approach have been proposed in Ref. [4]. The CPRC decreases channel congestion by adjusting power transmission and beacon rate based on the available vehicle density on the road segment. The vehicle density has been determined using extra communication of local traffic information and the measurements from the channel busy time. This determines the calculation of new values for both the beacon rate and the power transmission depending on whether the channel busy time is greater than the threshold value and the vehicle number is dense on the road segment. A new beacon propagation frequency and power transmission are considered based on the pre-defined constraint value.

A hybrid strategy that combines the adjustments of power control and beacon rate has been proposed in Ref. [5] to diminish the congestion problem of IoV network wireless channel and reserve the available bandwidth for the emergency messages. This approach operates in three states. In the initial state, a prioritization strategy is used to specify the importance of the generated messages whether it is low-level static traffic information or dynamic parameter related to the emergency cases. At the second state, the congestion detection mechanism is initiated to check the congestion level on the wireless channel. The congestion is detected by measuring the number of beacon collision in the network, messages waiting time and packet delivery ratio. In the last state, the messages generation frequency and power level are adapted based on the number of collisions and available bandwidth. Then, these new values are broadcast to the neighbours' vehicles to use the same calculated values and cope with the wireless channel data bottleneck. However, the further transfer of the additional data causes an overhead and raise of the congestion.

A hybrid adaptation approach that joins the beacon generation rate and transmission power level has been proposed in Ref. [6]. This strategy uses the local traffic data and the tracking error of vehicles as measurements parameters to adapt the beacon rate and power level. The vehicles' tracking accuracy is utilized to adjust the data sending frequency and the power level has been modified based on the vehicle density on the road segments. This approach disseminated the information while the tracking error does not surpass the defined threshold value. The power transmission is tuned based on measuring the channel capacity and the range of the beacon messages is reduced by determining the peak and lowest values of the power level. However, this approach leads to unfairness due to adopt the channel parameters without considered whether the channel is in the saturation conditions or not. This approach

also ignores the priorities of the emergency messages once they are generated.

The authors in Ref. [7] have proposed an approach that combines the transmission power and the size of the contention window has been proposed. The power transmission has been adjusted to modify the packets transmission range by estimating the number of vehicles on the road segments. The size of the contention window has been adjusted using preferences of traffic information messages and local beacon collision average number. Once the channel congestion is detected, every node in the vehicular environment will measure the neighbourhood traffic density from the content of the collected periodic packets to modify the power level. This happens using matching the required transmission range to the identical rate of power transmission in the lookup table. The contention window value regularly adjusted to all access categories by monitoring the state of the wireless channel of the network. Hence, this method does not have an established the contention window size as in the WAVE protocol primary strategy.

In Refs. [8] and [9], hybrid approaches are proposed for controlling the congestion problem in the vehicular network. In Ref. [8], a single objective Tabu optimization algorithm is proposed to overcome the problem of congestion control. In the utilized approach, once the congestion in the channel is detected based on the calculated level of channel usage, the broadcast information frequency and power level are optimized based on the reduction of the single objective function. This approach has been considered the delay parameter as an objective function. In Ref. [9], a multi-objective Tabu search has been introduced to dominate the channel congestion problem in the vehicular network by optimizing the data rate and the transmission power. This approach utilizes the packets loss and the delay parameters as a multi-objective function for the Tabu search. However, this approach has not used the online values of transmission power and information rate. It has utilized the static parameters form the simulation scenarios such as the bit rate and the power level to find the optimal solution. On the other hand, the Tabu search is a heuristic method that does not guarantee to find an optimal solution which in turn leads to local solutions might be an efficient and effects on the QoS parameters of the network.

Recently, the authors in Ref. [10] have proposed a hybrid broadcast approach based on the volunteer's dilemma game. This approach utilizes the contention window and the transmission range parameters as a player payoff function in the formulated game to reduce wireless channel congestion. In formulated approach, every vehicle that receives a broadcast message becomes a player and one vehicle volunteer to retransmit the received messages. Once a vehicle becomes the main transmitter in the game, this vehicle uses the fuzzy logic control to estimate the neighbour density and the transmission probability to adjust the contention window size in the mac layer. However, this approach has not guaranteed an optimal solution to the formulated game which leads to further problems in the vehicular network environments. This approach might lead to higher messages loss and delay, and it

consumes more power due to the higher contention among the vehicles to access the wireless channels.

Many of the above-discussed approaches suffer from common disadvantages. Several of stated approaches only adjust a single channel communication parameter which in turn leads to a decrease in the balance in their adaptation strategies. This significantly influences the awareness of each vehicle driving on the roads network due to decline number of transmitted traffic information. Other approaches suffer from channel overhead due to additional transmission of channel parameter among vehicles. Therefore, different measurements in the utility functions of the transmission rate and power level such as data rate, queueing delay, vehicles mobility, transmission power and vehicles priority to address the channel congestion are considered, and a stable adaptation approach and channel overload free is provided.

3 | SYSTEM DESCRIPTION

3.1 | The formulation of the data rate and transmission power game approach

IoV involves many models of communication systems, as shown in Figure 1. However, the main two components are (i) V2V communication systems which incorporate Wireless Sensor Nodes (WSNs) attached to the body of the vehicle. The WSNs facilitate the vehicles to disseminate and receive the information related to the traffic status [11]. (ii) V2I communication systems that cover road sections sensors, WSNs established at the intersections and cell towers. The V2I provides road elements with the ability to broadcast and collect the information related to the traffic situation.

Sending traffic information in dense environments at a high rate or with the maximum power causes channel congestion and communication overhead. This occurs due to disseminate the traffic information by the vehicles in selfish behaviour and maintain the channel of the wireless network for a long time duration. These vehicles ignored the size of the buffer, the available channel capacity and other vehicles information sending rate. The data congestion in the wireless channel is a severe problem which has vital impacts on traffic information accuracy due to the high delay in delivery time and messages loss. A new hybrid approach is developed to constrain the power level and information stream to mitigate the congestion problem in the IoV wireless channel.

Here, the information rate and power level are adapted using the non-cooperative game approach based on the transmission information rate, queueing messages waiting time, vehicles mobility, power level Signal-to-Noise Ratio (SINR) and distance priorities. In the IoV game, every transmitter node is depicted as a greedy member. The optimal solution or Nash equilibrium [13] of the IoV game is the information rate and power level for which every node cannot increase its earnings by adjusting its transmission rate or power level while the data rate or power level of other nodes remains constant.
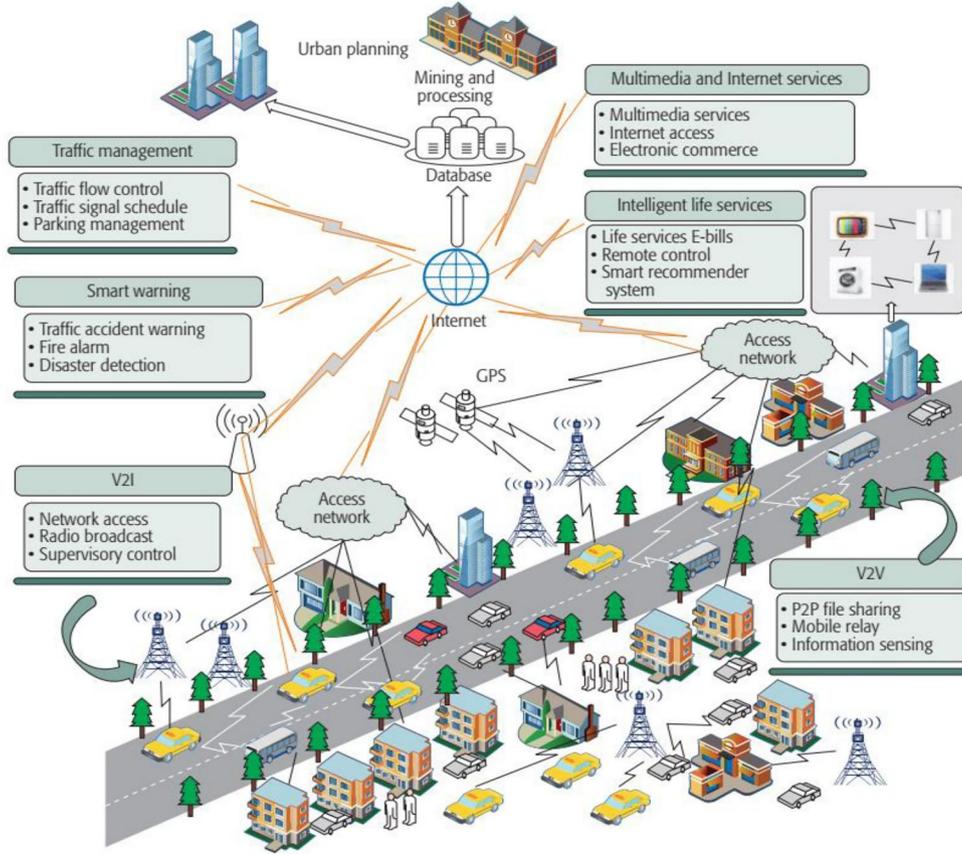
FIGURE 1 IoV applications in smart cities [12]

Here, each vehicle considers a group of m players in its transmission range $M = \{m_1, m_2, \ldots, m_i, \ldots, m_n\}$. These vehicles compete with the other nodes to maintain a wireless channel for itself and send data at high rates actions $a_{rate} = [dr_1, \ldots, dr_i, \ldots, dr_n]$ with the power level of $a_{power} = [pw_1, \ldots, pw_i, \ldots, pw_n]$ to their nearby elements. The dr_i and pw_i acts the data rate and power level of the vehicle m_i, respectively.

The optimization of vehicles sending rate and power level is approached as a non-cooperative game as follows:

$$G1 = (M, (A_{rate})_{i \in M}, (Udr_i)_{i \in M})$$

and

$$G2 = (M, (A_{power})_{i \in M}, (Upw_i)_{i \in M})$$

where the IoV games have the next essential elements:

- *Players*: M has considered as a set of vehicles where n denotes vehicle numbers that are communicated with each other while sharing the same transmission range.
- *Actions profile*: Actions profile represents the available traffic information transmission rate and power level of each vehicle in the IoV. Each competitor or node m_i are

able to broadcast at a maximum and minimum transmitting frequency of dr_i^{max} and 1. Hence, $A_{i_{rate}} = [1, dr_i^{max}]$ is a set of available profiles for the competitor or vehicle i and the Cartesian product of profile range for all competitors is $A_{rate} = \prod_{i=1}^{n} A_{i_{rate}} = [1, dr_1^{max}] \times \cdots \times [1, dr_i^{max}] \times \cdots \times [1, dr_n^{max}]$. $A_{i_{power}} = [0, pw_i^{max}]$ is an action set for the node i and the Cartesian product of action space for all players is $A_{power} = \prod_{i=1}^{n} A_{i_{power}} = [0, pw_1^{max}] \times \cdots \times [1, pw_i^{max}] \times \cdots \times [0, pw_n^{max}]$.
- *Utility function*: The player m_i utility function is defined by Udr_i that represents the data rate function and Upw_i that represents the power level function. They have been used to improve vehicle gain. This can be achieved by optimizing the utility functions concerning dr_i and pw_i.

3.2 | Formulation of the utility function

The utility function Udr_i of the data rate considers three elements which are data rate of the vehicle, the messages queueing that provides the suspension caused when messages are waiting to be sent at the buffer and vehicles mobility cost which reveals the condition of the traffic flow on the road segments. The utility function Upw_i of the power level incorporates two parameters that are the SINR and a preference assigned to every vehicle deciding which vehicles broadcast the

traffic information at maximum power than the surrounding nodes. The profit function Udr_i can be divided into three main elements as follows:

- *Cost function*: The broadcast rate of vehicles traffic information dr_i has been used to evaluate the cost function $CF_i(dr_i)$ of each player or vehicle m_i. The logarithmic function [14] is used to describe the cost function of the data rate. This is because it has a special feature that is rigorously curved on its area. This will help to find the pure strategy Nash equilibrium for each player in the game. Here, the cost function for a vehicle m_i is given by:

$$CF_i(dr_i) = \log(dr_i). \tag{1}$$

- *Queueing delay*: The messages' waiting time in the queue of a node m_i has been indicated by $Q_i(dr_i; q_i)$. Here, the queue delay has been modelled for each player as a $M/M/1/N$ [15]. This function represents the number of messages that are waiting inside each vehicle buffer to be transmitted. According to Ref. [16], the queue delay is calculated as follows:

$$Q_i(dr_i; q_i) = \frac{1}{(dr_{out} - dr_{in})} - \frac{N dr_{in}^N}{dr_{out}(dr_{out}^N - dr_{in}^N)} \tag{2}$$

where $dr_{in} = \sum_{i=1}^{n} dr_i$ is the rate arrival flow of messages in packets per second, N buffer size and n is the number of competitors that are participating in the transmission area. dr_{out} maximum number of packets that can be successfully transmitted per time unit.

- *Mobility function*: The road traffic state has been mathematically expressed by the speed ratio of S_r as follows:

$$S_r = \frac{S_i}{S_f}, \tag{3}$$

where S_i denotes the average speed currently recorded on the road segment and S_f represents the specified speed limit on the road.

The speed of vehicles and density on the roads have a linear relation according to the Green-shield's model [17]. This relationship is represented by the following scheme:

$$S_r = 1 - K_r, \tag{4}$$

where the density ratio is represented by K_r and can be estimated as follows:

$$K_r = \frac{k_i}{k_j}, \tag{5}$$

where k_i in (5) is the road current density of vehicles and k_j depicts the maximum traffic density, which is calculated as follows:

$$k_j = L \frac{d_i}{A_L}. \tag{6}$$

Note, L denotes lanes number on the road, the road distance is represented by d_i and A_L represents the average length of vehicle added to the smallest gap separating pair of vehicles. A_L is used as 6.2 m, similar to Ref. [18].

Using (4) and (5), k_i can be estimated as follows:

$$k_i = k_j(1 - S_r). \tag{7}$$

Therefore, the traffic state can be represented by the speed ratio instead of the density ratio. According to (7), if S_r has a very low value. This leads to an increase in vehicles density and the road becomes under heavy traffic congestion. The proposed hybrid adaptation approach points to enhance network performance by classifying vehicles mobility to a high or low level. Therefore, punishment has to be satisfied by every player m_i with the regards of the communication rate (dr_i) and the traffic flow or mobility situation of vehicles (f_i). A node with a high value of f_i has a high superiority to broadcast data at a high rate. Thus, the competitor or vehicle m_i flow cost function is presented by:

$$F_i(dr_i; f_i) = dr_i f_i, \tag{8}$$

where $f_i = S_r$ is calculated as in (3).

The utility function Upw_i of every vehicle m_i has been formulated as follows:

$$Udr_i(dr_i, r_{-i}) = \alpha_i CF_i(dr_i) - \beta_i Q_i(dr_i; q_i) - \pi_i F_i(dr_i; f_i). \tag{9}$$

where α_i, β_i and π_i are preference weight parameters of utility functions $CF_i(dr_i)$, $Q_i(dr_i; q_i)$ and $F_i(dr_i; f_i)$, respectively. The values of α_i, β_i and $\pi_i > 0$; $\forall i \in M$. Note, dr_{-i} is the sending frequency of all others player except m_i. The utility function Upw_i has the following two main elements:

- *Payoff function*: The power level pw_i of vehicle m_i is used to estimate the payoff function $\lambda_i(pw_i)$. Therefore, the cost function of power level for a vehicle m_i is formulated according to the Shannon-Hartley theorem [19], the capacity (in bits/symbol) of reliable communication using the

Orthogonal Frequency Division Multiplexing (OFDM) channel and is given by:

$$\lambda_i(pw_i) = \sum_{i=1} \log(\frac{1 + pw_i|h_i|^2}{\sigma_i^2}). \tag{10}$$

where pw_i is the specified power to the channel, h_i is the channel gain and σ_i^2 represents additive white Gaussian noise power.

- *Priority function*: The vehicle priority function has been represented by $PV_i(pw_i; pv_i)$ to classify vehicles priorities into high and low levels. Every player m_i has to repay a fine regarding to its communication power (pw_i) and its preference (pv_i). A vehicle with a large pv_i utility has a large preference to send for further distance. Thus, the competitor m_i priority cost function is given by Ref. [20]:

$$PV_i(pw_i; pv_i) = \frac{pw_i}{pv_i}, \tag{11}$$

where pv_i is calculated as follows:

$$pv_i = \frac{G_{tr}}{T_r}. \tag{12}$$

Here, G_{tr} represents the range gap between the transmitter antenna and the transceiver antenna, T_r denotes the communication spectrum of the vehicle m_i or RSU that can covers. Therefore, vehicles that are stand last in the broadcast area zone have a larger probability to transmit traffic information with high power. On the other hand, vehicles near the sender have a lower preference, indicating they are less probable to forward messages at a high power level.

Every vehicle m_i utility function Upw_i has been formulated as follows:

$$Upw_i(pw_i, pw_{-i}) = \gamma_i \lambda_i(pw_i) - \eta_i PV_i(pw_i; pv_i). \tag{13}$$

Here, γ_i and η_i are decision weights that have been selected by the system designer to satisfy system requirements, where γ_i and $\eta_i > 0; \forall i \in M$.

3.3 | The proof of the game Nash equilibrium

Herein, the safety application congestion problem of the wireless channel is formulated as a non-cooperative game approach is represented by $G1 = (M, (A_{i_{rate}})_{i \in M}, (Udr_i)_{i \in M})$ and $G2 = (M, (A_{i_{power}})_{i \in M}, (Upw_i)_{i \in M})$, respectively. The optimal solution (a Nash equilibrium) that is represented by an action (broadcast rate) $a^*_{i_{rate}} \in A_{i_{rate}}$ and (power level)

$a^*_{power} \in A_{i_{power}}$, where $(a^*_{i_{rate}} = [dr^*_1, ..., dr^*_i, ..., dr^*_n])$ and $(a^*_{i_{power}} = [pw^*_1, ..., pw^*_i, ..., pw^*_n])$. The optimal solution (a Nash equilibrium) can be obtained for both G1 and G2 by estimating the optimal data rate and transmission power for each vehicle. Those solution exits where no player can alert its profit (utility function) by modifying its current action while other vehicles actions remain constant.

A Nash equilibrium (optimal solution) for both G1 and G2 is a V-tuple for both data rate $\{dr^*_i\}_{i \in M}$ and power level $\{pw^*_i\}_{i \in M}$ that satisfies:

$$Udr_i(dr^*_i, dr^*_{-i}) \geq Udr_i(dr_i, dr^*_{-i})$$
$$Upw_i(pw^*_i, pw^*_{-i}) \geq Upw_i(pw_i, pw^*_{-i}),$$

$$\forall dr^*_i, dr_i \in A_{i_{rate}}, dr^*_i \neq dr_i, \forall i \in M \quad and \quad pw^*_i,$$
$$pw_i \in A_{i_{power}}, pw^*_i \neq pw_i, \forall i \in M.$$

A sole Nash equilibrium appears for the dilemma G1 and G2 under assumptions that the following hypotheses are proved to be appropriate. This approach has been shown as an accepted factory for the appearance of a single action profile Nash equilibrium for example see Ref. [13] for more details.

Theorem 3.1 *The formed non-cooperative games G1 and G2 are n-person concave, that means every game has at least single Nash Equilibrium (NE).*

Proof Both $A_{i_{rate}}$ and $A_{i_{power}}$ for player m_i are closed and bounded $\forall i \in A_{i_{rate}}$ and $A_{i_{power}}$, respectively. This means that both $A_{i_{rate}}$ and $A_{i_{power}}$ are compact which in turn leads to that both $Udr_i(dr_i, dr_{-i})$ and $Upw_i(pw_i, pw_{-i})$ are strictly concave and continuous on $A_{i_{rate}}$ and $A_{i_{power}}$, respectively.

Let us assume points $x, y \in A_{i_{rate}}, \zeta = [0, 1]$ and $a, b \in A_{i_{power}}$, $\Upsilon = [0, 1]$. The action profiles $A_{i_{rate}}$ and $A_{i_{power}}$ are both convex if and only if for any $x, y \in A_{i_{rate}}$ and any $\zeta = [0, 1]$,

$$1 \leq \zeta x + (1 - \zeta)y \leq dr^{max}_i$$

and $a, b \in A_{i_{power}}$ and any $\Upsilon = [0, 1]$,

$$1 \leq \Upsilon a + (1 - \Upsilon)b \leq pw^{max}_i$$

Here, the points $\zeta a + (1 - \zeta)b \in A_{i_{rate}}$ and $\Upsilon a + (1 - \Upsilon)b \in A_{i_{power}}$, respectively. Therefore, sets profile $A_{i_{rate}}$ and $A_{i_{power}}$ are convex $\forall i \in M$.

Definition The utility functions Udr_i and Upw_i are strictly concave if and only if the Hessian matrix for both of them is Negative Definite (ND) for all

$a_{i_{rate}} \in A_{i_{rate}}$ and $a_{i_{power}} \in A_{i_{power}}$, respectively, and $\frac{\partial^2 Udr_i}{\partial dr_i \partial dr_j} \leq 0 \ \forall i,j \in M$ and $\frac{\partial^2 Upw_i}{\partial pw_i \partial pw_j} \leq 0 \ \forall i,j \in M$.

Let Hessian matrix of the twice continuous differential utility functions Udr_i and Upw_i be represented as $H1$ and $H2$, respectively. Then, $H1$ and $H2$ can be estimated as follows:

$$H1 = \begin{bmatrix} Q''_{11} & Q''_{12} & \cdots & Q''_{1n} \\ Q''_{21} & Q''_{22} & \cdots & Q''_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Q''_{n1} & Q''_{n2} & \cdots & Q''_{nn} \end{bmatrix}, \quad (14)$$

$$H2 = \begin{bmatrix} D''_{11} & D''_{12} & \cdots & D''_{1n} \\ D''_{21} & D''_{22} & \cdots & D''_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ D''_{n1} & D''_{n2} & \cdots & D''_{nn} \end{bmatrix}, \quad (15)$$

where $Q''_{ij} = \frac{\partial^2 Udr_i}{\partial dr_i \partial dr_j} \ \forall i,j \in M$ and $D''_{ij} = \frac{\partial^2 Upw_i}{\partial pw_i \partial pw_j} \ \forall i,j \in M$.

Therefore, for all dr_i such that $\alpha_i, \beta_i, \pi_i > 0; \forall i \in M$ and for all pw_i such that $\gamma_i, \eta_i > 0; \forall i \in M$, Q''_{ij} and $D''_{i,j}$ are given by (16) and (17):

$$Q''_{i,j} = \begin{cases} -\dfrac{\alpha_i}{dr_i^2} - \beta_i\left[\dfrac{2}{(dr_{out} - dr_{in})^3} - \dfrac{N^2 dr_{in}^N dr_{out}^N[(N-1)(dr_{out}^N - dr_{in}^N) + 2Ndr_{in}^N]}{dr_{in}^2 dr_{out}(dr_{out}^N - dr_{in}^N)^3}\right] & \text{if } i = j; \forall i,j \in M \\[4mm] -\beta_i\left[\dfrac{2}{(dr_{out} - dr_{in})^3} - \dfrac{N^2 dr_{in}^N dr_{out}^N[(N-1)(dr_{out}^N - dr_{in}^N) + 2Ndr_{in}^N]}{dr_{in}^2 dr_{out}(dr_{out}^N - dr_{in}^N)^3}\right] & \text{if } i \neq j; \forall i,j \in M \end{cases} \quad (16)$$

$$D''_{i,j} = \begin{cases} -\dfrac{\gamma_i |h_i|^4}{(1 + pw_i|h_i|^2)^2} & \text{if } i = j; \forall i,j \in M \\[4mm] 0 & \text{if } i \neq j; \forall i,j \in M \end{cases} \quad (17)$$

Preposition: Let L be the leading principle minors and if L change in sign with the even-order ones being > 0 and the odd-order ones being < 0 [21]. This means the matrix is a Negative Definite (ND), and it reaches a local maximum for both dr_i and pw_i. Hence, $H1$ and $H2$ leading principal minors are Negative Definite [21, 22]. Thus, the $Udr_i(dr_i, dr_{-i})$ and $Upw_i(pw_i, pw_{-i})$ are both strictly concave on A_{rate} and A_{power}; $\forall i \in M$. Therefore, the above conditions are sufficient to establish that $G1$ and $G2$ games have at least one singular optimal solution or Nash equilibrium [23].

$$\Phi(dr_i, dr_{-i}; z) = \sum_{i=1}^{n} z_i Udr_i(dr_i, dr_{-i}). \quad (18)$$

$$\omega(pw_i, pw_{-i}; z) = \sum_{i=1}^{n} z_i Upw_i(pw_i, pw_{-i}). \quad (19)$$

Theorem 3.2 *According to Ref.* [13], *Let* $z = [z_1, z_2, ..., z_l]$ *be a constant positive vector and if the Diagonal Strict Concavity (DSC) feature has been achieved. Then the modelled games* $G1$ *and* $G2$ *of the data congestion problem of IoV wireless channel has a singular pure-strategy Nash equilibrium* [13].

Proof we define the weighted non-negative sum of $Udr_i(dr_i, dr_{-i})$ and $Upw_i(pw_i, pw_{-i}); \forall i \in M$ as follows:

For each positive constant point z, a relevant mapping $g1(dr_i, dr_{-i}; z)$ and $g2(pw_i, pw_{-i}; z)$ are expressed as gradients of $\nabla Udr_i(dr_i, dr_{(-i)})$ and $\nabla Upw_i(pw_i, pw_{(-i)})$ as follows:

$$g1(dr_i, dr_{-i}; z) = \begin{bmatrix} z_1 \nabla Udr_1(dr_1, dr_{-1}) \\ z_2 \nabla Udr_2(dr_2, dr_{-2}) \\ \vdots \\ z_n \nabla Udr_n(dr_n, dr_{-n}) \end{bmatrix} \quad (20)$$

$$g2(pw_i, pw_{-i}; z) = \begin{bmatrix} z_1 \nabla Upw_1(pw_1, pw_{-1}) \\ z_2 \nabla Upw_2(r_2, pw_{-2}) \\ \vdots \\ z_n \nabla Upw_n(pw_n, pw_{-n}) \end{bmatrix} \quad (21)$$

where $\nabla Udr_i(dr_i, dr_{-i})$ and $\nabla Upw_i(pw_i, pw_{-i})$ are calculated $\forall i \in M$ as in (22 and 23).

$$\nabla Udr_i(dr_i, dr_{-i}) = \frac{\alpha_i}{dr_i} - \beta_i\left[\frac{2}{(dr_{out} - dr_{in})^3}\right. $$
$$\left. - \frac{N^2 dr_i^N dr_{out}^N}{dr_i dr_{out}(dr_{out}^N - dr_{in}^N)^2}\right] - \pi_i S_r \quad (22)$$

$$\nabla Upw_i(pw_i, pw_{-i}) = \frac{\gamma_i |h_i|^2}{1 + pw_i|h_i|^2} - \eta_i \frac{T_r}{G_{tr}} \quad (23)$$

As mentioned in Ref. [13], if the symmetric matrix $[G1(dr_i, dr_{-i}; z) + G1^T(dr_i, dr_{-i}; z)]$ and $[G2(pw_i, pw_{-i}; z) + G2^T(pw_i, pw_{-i}; z)]$ are ND for all $dr_i, dr_{-i} \in A_{rate}$ and $pw_i, pw_{-i} \in A_{power}$ Then, we define the Jacobian matrix $(G1(dr_i, dr_{-i}; z))$ and $(G2(pw_i, pw_{-i}; z))$ with respect to dr_i and pw_i, respectively, of $g1(dr_i, dr_{-i}; z)$ and $g2(pw_i, pw_{-i}; z)$ are given as follows:

$$G1(dr_i, dr_{-i}; z) = \begin{bmatrix} B_{11} & B_{12} & \dots & B_{1n} \\ B_{21} & B_{22} & \dots & B_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ B_{n1} & B_{n2} & \dots & B_{nn} \end{bmatrix} \quad (24)$$

$$G2(pw_i, pw_{-i}; z) = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & \dots & A_{nn} \end{bmatrix} \quad (25)$$

where $B_{i,j} = z_i Q''_{i,j}$ and $A_{i,j} = z_i D''_{i,j}; \forall i, j \in M$.

It is clear that the symmetric matrix $[G1(dr_i, dr_{-i}; z) + G1^T(dr_i, dr_{-i}; z)]$ and $[G2(pw_i, pw_{-i}; z) + G2^T(pw_i, pw_{-i}; z)]$ are both ND for all $dr_i, dr_{-i} \in A_{rate}$ and $pw_i, pw_{-i} \in A_{power}$. Then, the functions $\Phi(dri, dr_{-i}; z)$ and $\omega(pw_i, pw_{-i}; z)$ satisfies the DSC feature. Therefore, this means that there is a single perspicuous action profile Nash equilibrium in every game $G1$ and $G2$ according to (Theorem 2 [13]).

There are different detection measurements methods to identify wireless channel congestion. These methods can detect the congestion by sensing some MAC layer parameters such as channel busy ratio [24], messages queue size [25] and channel busy time [26]. Then these measurements are examined with a threshold value periodically to identify the channel congestion. The threshold value has a vital influence on the production of networks for observing and detecting the channels congestion.

Similarly, the Channel Busy Ration (CBR) MAC layer parameter is used to detect the congestion in the channel by matching the estimated value with a pre-defined threshold value which is considered 70% as in Refs. [24], [27], and [28]. Therefore, channel congestion is detected if the CBR surpasses the threshold value and the application layer is triggered to adapt the transmission rate and power of vehicles based on the proposed approach. The CBR is estimated for the number of transmitted messages by a vehicle in each control channel interval as follows:

$$CBR = \frac{\sum m \, (D_{BUSY} + D_{AFIS} + D_{BACKoff})}{D_{CCH}}. \quad (26)$$

where the D_{BUSY} represents the channel busy period identifies by the Clear Channel Assessment (CCA) function module. D_{AFIS} is the Arbitrary Inter-Frame Space (AIFS) duration of safety application messages. $D_{BACKoff}$ is the back-off time for the safety application messages. D_{CCH} denotes the total busy time of m messages sensed by a node in one control channel period.

4 | IoV GAME OPTIMAL SOLUTION ESTIMATION

The presence and uniqueness of a singular NE have been established in the previous section. This section details the approaches that have been used to find the optimal solution for each vehicle. The data rate optimal solution has been estimated based on the gradient method. This approach is needed due to the additional complexity induced by combining the queueing delay and mobility factor to the cost function introduced herein. The power level optimal solution has been estimated using Lagrangian multipliers method.

4.1 | HRPGA rate implementation

The HRPGA approach is based on optimizing the information frequencies. This is done by determining an action profile that maximises its utility function (9). Hence, the optimization problem can be formulated as follows:

$$\begin{aligned} \underset{dr_i \in A_{i_{rate}}}{\text{maximize}} \quad & Udr_i(dr_i, dr_{-i}) \\ \text{subject to} \quad & dr_i \geq 1 \\ & dr_i \leq dr_i^{max}, \ \forall i \in M. \end{aligned} \quad (27)$$

Applying the gradient ascent method [29] is proposed to optimize the problem presented in (27). This is due to the expressed utility function being inadequate to be determined via Lagrange multiplier and Karush Kuhn Tucker (KKT) conditions. Each vehicle modifies its data rate based on the calculated CBR in every iteration. This helps to avoid the extra transfer of control information among vehicles which in turn helps to decrease the channel overhead. The CBR can be estimated by utilising the CCA function specified in the IEEE 802.11 model [24].Algorithm 1 depicts the steps of estimating the optimal solution of data rate transmission dr_i^* of vehicles in IoV network.

Algorithm 1 Gradient method for updating the data rate

---

1. Each Vehicle Determine the CBR
2. *Initialization*:
    Set variables $\alpha_i, \beta_i, \pi_i, dr_0, dr^{max}, k = 0$
3. Calculate the value dr_i^* of dr_i that increases $Udr_i(dr_{i,k}, dr_{-i,k})$
4. **while** $\|\nabla Udr_i(dr_{i,k}, r_{-i,k})\| \geq \epsilon$
    do
    $dr_{i,k+1} = dr_{i,k} + t_k \nabla Udr_i(dr_{i,k}, dr_{-i,k})$
    $dr_{i,k+1}^* \leftarrow dr_{i,k+1}$
    $k \leftarrow k + 1$
5. **Return** $dr_{i,k+1}^*$

Once the channel congestion is detected based on the MAC layer CBR, the optimization variables are initialized in the application layer of the proposed approach. Then the HRPGA

uses the gradient method for updating the data rate by calculating the optimal safety messages application rates that maximize the formulated data rate utility function (27). Finally, the algorithm finds the optimal solution (data rate) either the iterations are finished or the meeting condition step 4 in Algorithm 1 is satisfied. Then this new rate is assigned to the messages for the next transmission to reduce the channel congestion.

4.2 | HRPGA power implementation

The optimal power level of a vehicle is in range between $[0, pw_i^{max}]$ and every vehicle needs to maximise its utility function to find the NE. Therefore, the power level optimization can be modelled as follows:

$$
\begin{array}{ll}
\underset{pw_i \in A_{i_{power}}}{\text{maximize}} & Upw_i(pw_i, pw_{-i}) \\
\text{subject to} & pw_i \geq 1 \\
& pw_i \leq pw_i^{max}, \ \forall i \in M.
\end{array} \tag{28}
$$

The above non-linear optimization problem can be solved by defining the Lagrangian function $\mathcal{L}_i(pw_i)$ and μ_i and ν_i Lagrangian multipliers of a vehicle i as follows:

$$
\mathcal{L}_i = Upw_i(pw_i, pw_{-i}) + \mu_i pw_i + \nu_i(pw_i^{max} - pw_i). \tag{29}
$$

The KKT conditions of a player m_i to determine the optimal solution are:

$$
\begin{aligned}
\mu_i, \nu_i &\geq 0, \\
pw_i &\geq 1, \\
pw_i^{max} - pw_i &\geq 0, \\
\nabla_{pw_i} Upw_i(pw_i, pw_{-i}) + \mu_i \nabla_{pw_i}(pw_i) & \\
+ \nu_i \nabla_{pw_i}(pw_i^{max} - pw_i) &= 0, \\
\mu_i(pw_i), \nu_i(pw_i^{max} - pw_i) &= 0.
\end{aligned}
$$

Hence, the optimal power level solution (pw_i^*) for a player (vehicle) m_i; $\forall i \in M$

$$
pw_i^* = \begin{cases}
1 & \text{if condition 1} \\
pw_i^{max} & \text{if condition 2} \\
\dfrac{\gamma_i G_{tr}}{\eta_i T_r} - \dfrac{1}{|h_i|^2} & \text{otherwise}
\end{cases} \tag{30}
$$

where condition 1 and condition 2 are given:

$$
\frac{\eta_i T_r}{|h_i|^2 G_{tr}} \geq \gamma_i. \tag{31}
$$

$$
\frac{\eta_i T_r}{G_{tr}} \leq \frac{\gamma_i |h_i|^2}{1 + pw_i^{max}|h_i|^2} \tag{32}
$$

Figure 2 shows a block diagram of the proposed approach. The scenario starts with flowing of vehicles on the road map and every vehicle will initialize system variables (α_i, β_i, π_i, dr_0, dr^{max}). Then vehicles start to send the traffic information at the specified transmission power and data rate. Once the estimated CBR exceeded the specified threshold value, the channel congestion is identified and the optimization variables are initialized in the application layer of the proposed approach. Finally, vehicles start sending messages with the new values of the sending rate and the transmission power.

5 | PERFORMANCE EVALUATION

The proposed transmission protocol has been examined and tested using Veins network simulator [30]. Veins includes Simulator for Urban MObility (SUMO) [31] which manages and observes the vehicles flow on the road maps and OMNet++ network simulator that implements the communication tools of the driving vehicles. Two intersections (650 m × 1000 m) an urban road scenario has been utilized to assess the implemented strategy. The proposed approach has been implemented for a different number of vehicles (50, 100 and 150 vehicles).

Four different parameters have been examined in this simulation evaluation:

- A total channel busy time: Represents the occupation time of the channel by a node within a presented period.
- A total number of collision data: Designates the amount of collision data in the wireless channel through the broadcasting of information.
- A total lost packets: Depicts the cumulative amounts of lost messages through transmission procedure of data in the wireless channel.

The performance of the proposed HRPGA has been compared with the Hybrid Power Contention Window (HPCW) adaptation and Joint Power Rate Control (JPRC) approaches which are performed and implemented in Veins simulator as in Refs. [7] and [32], respectively.

Table 1 displays the attributes that have been applied in the performed simulation example, where the transportation speeds have been defined by the designers based on experience with related dilemma situations and employing the guide of the U.K. road laws.

Herein, the proposed approach has been implemented based on the application and MAC layers in WAVE protocol of the IoV networks. The UDP connectionless protocol has been used in the transport layer and the broadcast has been used as a transmission type of safety messages.

The size of safety application messages has been chosen as 600 bytes as in Ref. [33]. This is because it considered as an efficient payload for the traffic information status. Adding
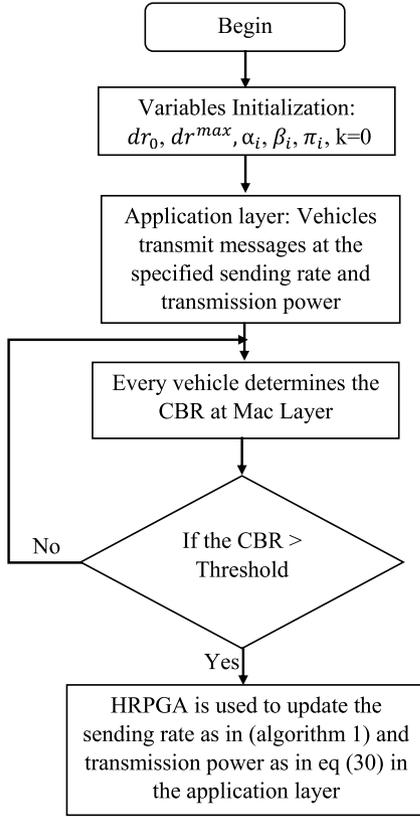
FIGURE 2 A block diagram of the HRPGA

TABLE 1 The implemented simulation scenario configuration parameters

Simulation parameters	Value
Number of vehicles	50, 100, 150
Vehicles speed	13-27 m/s urban scenario
Simulation time	200 s
Wireless protocol	IEEE 802.11p
Power level	1-50 mW
Bite rate	6 Mbps
Size of messages	600 bytes
Information rate	1-10 packets/s
Number of iterations	60
α_i	10
β_i	0.7
π_i	0.3
γ_i	7
η_i	0.5

more bytes to the size of the messages might lead to increase the channel overhead and reducing the size of the messages might lead to inaccurate traffic information being disseminated to the drivers.
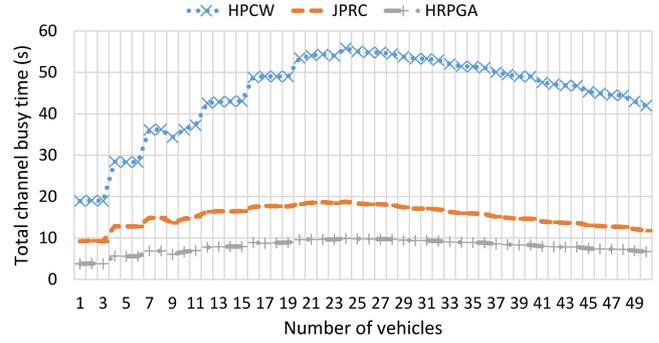
FIGURE 3 Total channel busy time of 50 vehicles
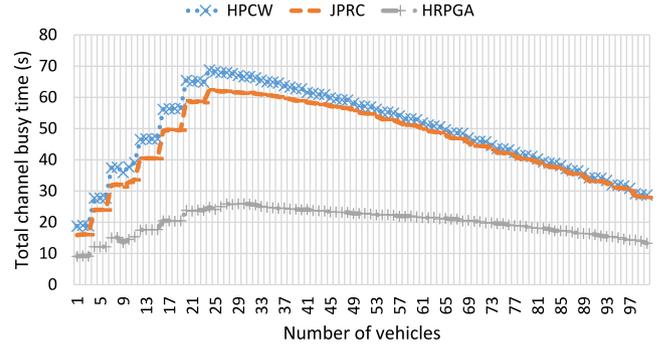
FIGURE 4 Total channel busy time of 100 vehicles

The simulation time is 200 s and is considered to be sufficient for the simulation scenario to assess and verify the performance of the proposed approach as compared with the other implemented approaches from the literature in Veins simulator. Therefore, this simulation time has been chosen similar to many other works in literature such as in Refs. [34] [9], [20], [28] and [34]. All the simulations have been replicated 10 times with different seeds.

The increase of the number of vehicles in the simulation scenario has been done sequentially—vehicle after vehicle. However, there is an incident scenario has been generated at the time 73 s of the simulation time to create a traffic congestion scenario where multiple vehicles start to compete to access the wireless channel. The developed transmission strategy has shown a good achievement as compared with the JPRC and HPCW in terms of all of the tested measurements.

5.1 | Total channel busy time

Figures 3–5 demonstrate the acquired outcomes of total channel busy time reported by the three examined approaches for 50, 100 and 150 vehicles, respectively. These figures confirm that with an increase in the number of vehicles during the simulation time the channel busy time is also increasing. However, the total channel busy time reported by the proposed approach HRPGA approach is the most stationary one contrasted to the HPCW and JPRC approaches. The reported outcomes represent that the proposed approach more reliable
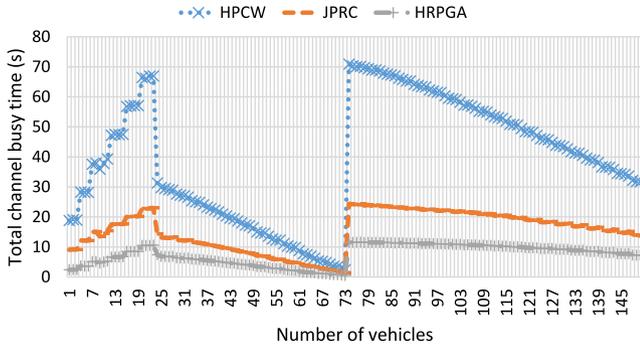
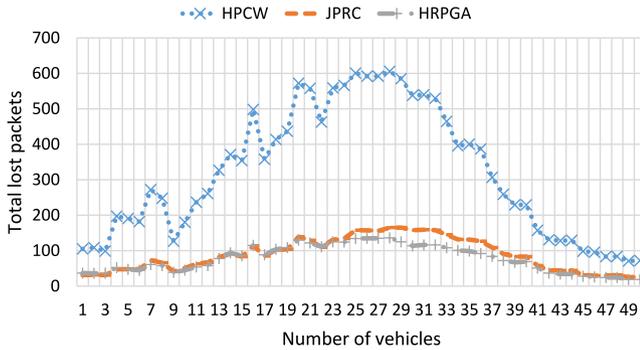**FIGURE 5** Total channel busy time of 150 vehicles

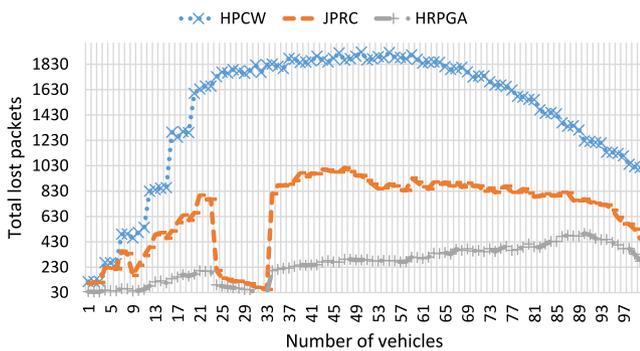**FIGURE 6** Total lost packets of 50 vehicles

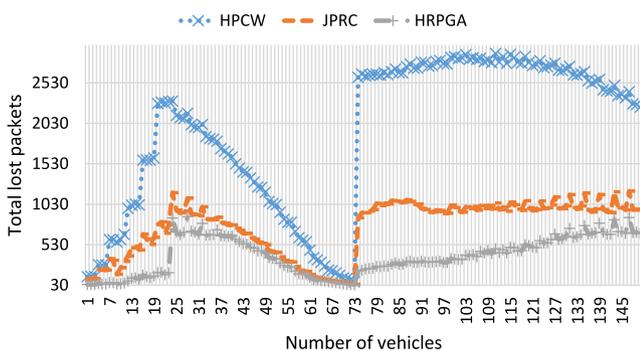**FIGURE 7** Total lost packets of 100 vehicles

FIGURE 8 Total lost packets of 150 vehicles

than the other strategies and it can accomplish a more stable performance in IoV network. This is due to that HRPGA alters the broadcast rate of information and power level of the transmission by determining the optimal value and considering channel queueing delay, vehicle densities and vehicles priorities as cost function penalty when the channel becomes congested.

JPRC optimizes the sending rate and power level using the number of neighbouring vehicles. In this approach, vehicles only choose the lowest power level to transmit the data from the lookup table which might effects channel bandwidth due to the low channel busy ratio. Moreover, sending data with very low transmission power causes a reduction in the burden on the channel but it also reduces vehicles awareness. HPCW has the worst performance among all examined strategies. This is due to it adjusts power level using a single parameter that is the SINR of the Lost Packet. This parameter solely is not enough to be used as a wireless channel requirement calculator because it does not precisely describe the IoV network conditions. In addition, HPCW modifies transmission using only power level. Therefore, its broadcasting performance is not reliable and stable as compared with the proposed HRPGA approach.

Figures 3–5 show different results due to the behaviour of each approach regarding the number of vehicles flying in the simulation scenario. Once the density of vehicles increase in the simulation scenario, the JPRC and HPCW show unstable adaptation of data rate, contention window or power transmission, as in Figure 4, when both decrease the objective parameters that lead to a sharp decrement in the channel busy time. Both JPRC and HPCW cannot guarantee a fair and stable transmission rate or power control in high-density environments as compared with the HRPGA which has a fair data rate and transmission power for safety messages due to finding the optimal solution for each parameter.

5.2 | Total lost packets

Figures 6–8 represent the total number of lost messages for different number of vehicles (50, 100 and 150) that are used in the simulation scenario. These figures show that the proposed approach HRPGA has the lowest number of packets loss when compared with HPCW and JPRC approaches. This dominance over the other approaches has been achieved due to the utilizing an adaptive hybrid rate and power approach in which the optimal data rates and power level have been selected by considering channel condition and parameters in the formulated utility function. This helps to improve the transmission and reduces the debate among the connected nodes to obtain IoV network wireless channel. The proposed approach shows stationary performance in terms of messages loss regardless of the number of connected vehicles being used in the simulation scenario. On the other hand, both HPCW and JPRC have higher lost packets due to optimizing only one single parameter and not considering the channel measurements. This generates additional overhead communication due to the poor
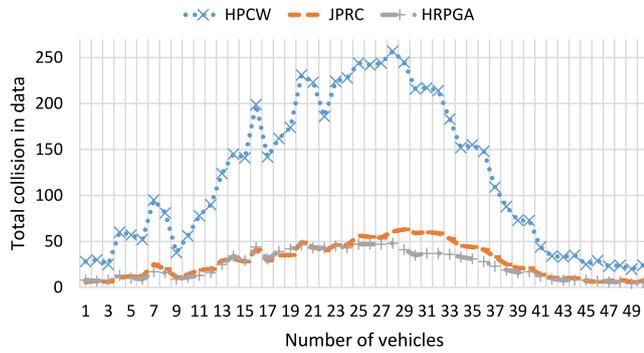
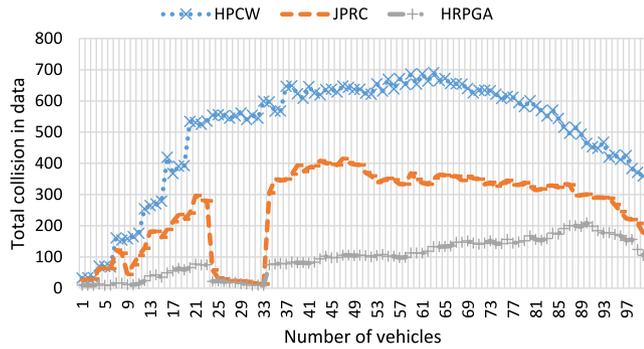**FIGURE 9** Total data collision of 50 vehicles

FIGURE 10 Total data collision of 100 vehicles
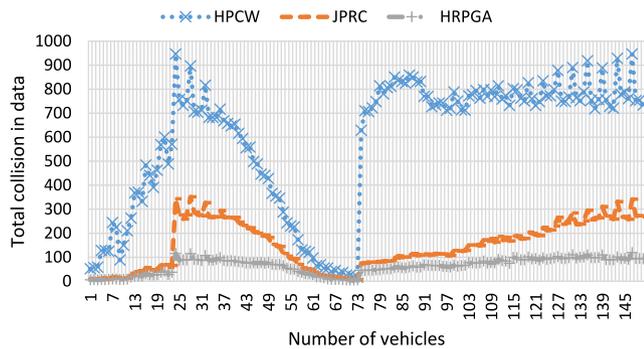

FIGURE 11 Total data collision of 150 vehicles

adaptation procedure that boosts the wireless channel data congestion.

5.3 | Total data collision

Figures 9–11 display the fluctuations of the total data collision with the number of vehicles. These figures have shown that increases in the flowing of vehicles in the simulation scenario, the packets collision increments for HPCW and JPRC strategies. However, the HRPGA has shown significant performance in term of recording a stable data collision results. This is because it recognises channel condition and parameters such as queueing delay, vehicle densities and priorities in the optimized cost functions for data rate and power level, respectively.

HRPGA has provided fairness transmission control protocol for both the data rate and the associated power of each transmitted message which help to reduces the number of contended nodes to reserve the wireless channel. This also helps to reduce the total number of data collision.

6 | CONCLUSION

As vehicle-to-vehicle communications increase in smart cities, the channel overhead also increases due to intensive broadcasting of safety messages through the limited capacity of the wireless channel. This problem reduces the vehicle awareness in such traffic conditions. Therefore, a new hybrid communication protocol based on a game theoretic approach is introduced to mitigate the congestion problem of the wireless channel of IoV. The Nash equilibrium existence and uniqueness have been determined analytically. Then, the gradient ascent and KKT Lagrange multiplier methods have been applied to determine the optimal broadcasting rate and transmission power for every vehicle, respectively. The proposed approach provides a fair and stable transmission protocol for the traffic information which helps to satisfy the safety application requirements which in turn increases the awareness and performance of the vehicular communication network unlike other works in literature that fails to provide fairness among contended nodes. Simulation results reveal that the proposed transmission strategy performance surpasses others compared approaches in terms of total busy time of the channel, packets loss, messages collision.

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