Proceedings Paper:
Amer, H.M., Tsotskas, C., Hawes, M. et al. (2017) A Game Theory Approach for Congestion Control in Vehicular Ad Hoc Networks. In: Sensor Data Fusion: Trends, Solutions, Applications (SDF), 2017. 11th Symposium on Sensor Data Fusion: Trends, Solutions, and Applications, 10.10.2017 - 12.10.2017, Bonn, Germany. IEEE.

https://doi.org/10.1109/SDF.2017.8126359

A Game Theory Approach for Congestion Control in Vehicular Ad Hoc Networks

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***Abstract*—The continuous transfer of messages in vehicular ad hoc networks leads to a heavy network traffic load. This causes congestion in the wireless channel which degrades the reliability of the network and significantly affects the Quality of Service (QoS) parameters such as packet loss, throughput and average delay. Therefore, it is vital to adapt the transmitting data rates in a way that ensure that acceptable performance is achieved and that there is reliable communication of information between vehicles in smart cities. This means the information will be delivered in a timely manner to the drivers, which in turn allows implementation of efficient solutions for improved mobility and comfort in intelligent transportation systems. In this paper, congestion control in the communication channel has been formulated as a non-cooperative game approach and the vehicles act as players in the game to request a high data rate in a selfish way. The solution of the optimal game is presented by using Karush-Kuhn-Tucker conditions and Lagrange multipliers. Simulation results show that the proposed method improves network efficiency in the presence of congestion by an overall average of 50.40%, 49.37%, 58.39% and 36.66% in terms of throughput, average delay, number of lost packets and total channel busy time as compared to Carrier-Sense Multiple Access with Collision Avoidance mechanism.**

***Index Terms*—Vehicular ad hoc networks, non-cooperative game theory, Congestion control, Data rate adaptation, IoV applications.**

I. Introduction

The increasing number of vehicles on road networks has put a great pressure on transportation systems. This leads to serious road traffic problems such as road accidents, increased travel times, fuel consumption and air pollution.

Recently, the appearance of the Internet of Vehicles (IoV) [1], has been considered as an interesting challenge for the traffic research community and it provides a new direction for Intelligent Transportation Systems (ITSs). The IoV foresees future vehicles as being connected, allowing the sharing of safety and non-safety related traffic data to enhance mobility and comfort. The main part of the IoV is the Vehicular Ad hoc Networks (VANETs) that include different systems. Firstly, Vehicle to Vehicle (V2V) communication systems that are on-board Wireless Sensor Networks (WSN) installed inside the vehicles [2]. Secondly, RoadSide Units (RSU) or Vehicle to Infrastructure (V2I) system.

The Dedicated Short Range Communications (DSRC) community has adopted the use of the Wireless Access of Vehicular Environment (WAVE) for supporting V2V and V2I communication systems [3]. WAVE emerged from the IEEE 802.11p and IEEE 609 protocols in the PHYsical layer (PHY) and the Medium Access Control (MAC) layer. This allows the applications in ITS to communicate over short transmission ranges. The European Telecommunication Standards Institute (ETSI) [4] has defined two kinds of safety application messages that can be transmitted through the Control CHannel (CCH) of WAVE protocol: Central Access Messages (CAMs) or beacon messages and Decentralized Environment Notification Messages (DENMs) or event-driven messages.

CAMs are packets sent periodically between V2V or V2I communication systems and they contain traffic data about the status of individual vehicles e.g. speed, position and direction [5]. DENMs are event-driven messages which are generated in emergency cases and are sent periodically until the event or the hazard that caused the emergency has disappeared.

ITSs use these messages to provide the information required to vehicles to allow for efficient mobility and safe journeys for drivers. However, one of the main problems in VANETs is the congestion in the wireless channel that occurs when many vehicles start to periodically transmit many messages at the same time or relay a large volume of data across the network. Hence, each vehicle transmits at a high data rate without considering system resources. This leads to problems such as data collision, buffer overflow and broadcast storm. As a result, the Quality of Service (QoS) parameters is adversely effected, meaning network performance are reduced and accurate information is no longer reaching the drivers in a timely manner.

Numerous strategies have been published on the congestion control problem in VANETs. They include power adaptive strategies, data rate adaptive strategies, Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) parameters adaptive strategies, prioritizing and scheduling approaches, and hybrid strategies. This paper is interested in dynamic data rate adaptation approaches due to the significant influence of data rate adaptation on controlling the channel loads and congestion in the communication network. The adaptation of the data rate is critical because a high data rate causes channel congestion while low data rates result in inaccurate information being communicated between drivers.

Beacon adaptation methods have been proposed in [6] and [7]. In [6] the data rate is reduced when vehicles are roads with multiple lanes. However, this approach has a drawback in that changes the data rate according to the number of lanes only, rather than considering an accurate measure of the actual traffic densities on the roads. Alternatively, in [7] the data rate is adapted based on measures such as traffic density, direction and status of vehicles. The proposed solution has not considered how to combine these measures in an efficient way to obtain the optimized data rates. Moreover, the unfair reduction of beacon rate effects the safety information that should be shared among drivers.

The authors in [8], proposed a cross-layer congestion control approach that increases the data rate of the event-driven packets as compared to the periodic beacon packets. In this approach, the channel occupancy time is estimated and compared with a predefined threshold value to detect the congestion. Once the congestion is detected, the application layer is triggered by the MAC layer to freeze all the beacon messages and the control channel is maintained only for the event-driven messages. Then a notification message is sent by the first blocking vehicle to all its neighbors to inform them to use the MAC blocking and freeze the data rate of beacon messages. Freezing the beacon messages leads to a reduction in the information on positions being shared between vehicles. Moreover, the requirements of safety applications messages have not been considered in this approach.

In [9], the author has proposed an Adaptation Beacon Rate (ABR) approach which is based on fuzzy logic control in order to minimize the beacon rate that flows through the network. In this approach, the percentage of vehicles driving in the same direction and traffic condition of vehicles have been considered as inputs to the fuzzy logic control in order to obtain the optimal data rate. However, this approach has not considered the emergency messages that are generated due to occurrence of events or hazardous situations. This still leads to the congestion in the control channel and adversely affects the QoS of the network.

In [10], the authors have proposed a Fair Adaptive Beaconing Rate for Inter-vehicular Communications (FABRIC) algorithm. The Network Utility Maximization (NUM) problem has been used to model the sending rate of vehicles in the network. Moreover, the scaled gradient projection algorithm has been used to solve the dual of the NUM problem and find the optimal data rate for each vehicle. However, the emergency messages and messages priorities have not been considered in this algorithm.

The methods discussed above have some common drawbacks. These are channel overloading caused by exchanging additional information, unfair reduction of beacon rates and beacon messages being discarded. This effects the quality of the information provided to individual vehicles. Additionally, they have not considered event driven messages that can also contribute to further channel congestion. To overcome these issues, this paper proposes a Game Theory Approach for Congestion Control (GTACC) to control the transmission data rates. In this formulation each vehicle is represented as a selfish player.

The non-cooperative game approach has been implemented in this paper because it involves a number of players having totally or partially conflicting interests in the outcome of a decision process with no extra communication or coordination of strategic choices among the players. On the other hand, the cooperative game approach can not be applied in this scenario because it requires extra information being transferred among vehicles which in turn leads to the overloading of the wireless channel and increases in wireless channel congestion. As a result, some of the improvements offered by the congestion control would be negated by the transfer of this information.

The main contributions of the paper are:

1) A new channel congestion mitigation approach is proposed based on non-cooperative game theory to alleviate the data channel congestion in VANET networks. The vehicle sending data rate is characterised by a utility function and the vehicle priorities are formulated as a priority cost function to achieve the desired fairness among vehicles.
2) A utility function for each vehicle is solved using Karush Kuhn Tucker (KKT) conditions and Lagrange multipliers. This gives the optimal data rate for each individual vehicle, which satisfies congestion mitigation and provides fair allocation of network resources.

The remainder of the paper is structured as follows: Section II provides the game approach formulation for congestion control and calculates the optimal solution for the game. In Section III a performance evaluation is provided. Finally, conclusions are drawn in Section IV.

II. System description

A. The Game Theory Approach Formulation:

VANETs form a part of ITSs which includes two sub-networks, V2V and V2I communication systems. The V2V system consists of on-board units which are installed in the vehicles themselves. The sensors allow the vehicles to send and receive the information such as speed, location and the driving direction [11]. The V2I system is RSU network, which consists of sensors deployed along the road and at the intersections. Vehicles can send information to, and receive information from, the RSUs.

In a VANET system every vehicle sends their data to the nearest vehicle or RSU which in turn broadcast this data (CAMs or DENMs) to other neighbours in its transmission range. The congestion in the wireless channel happens when many vehicles start to periodically send many messages (CAMs and DENMs) at the same time or relay a large volume of data across the network.

To detect the congestion in the wireless channel different measurement methods can be applied. These include calculating the number of packets queuing, estimating channel occupancy and sensing the channel usage levels [12]. In this work, the congestion is detected in the channel by periodically comparing the channel usage with a threshold value as in [10].

Once road traffic congestion occurs, the vehicles begin to broadcast high data rate messages to their neighbours. Each vehicle behaves selfishly and attempts to broadcast messages with a high data rate. This is without taking into consideration the transmitting rate of neighboring vehicles, buffer sizes or the available channel capacity. In this case, a large number of messages are lost either on the wireless channel or in the MAC buffers.

In order to control the transmission rates in VANETs, here non-cooperative game theory is used to solve the problem of optimizing the data rates. Each vehicle is modelled as a selfish player in the game. The Nash equilibrium (optimal solution) is the data rates for which each individual can not improve their individual performance by altering their data rate while the rates of other vehicles remain constant.

Consider each RSU or vehicle has a set of n vehicles (players) in its transmission range $V = \{v_1, v_2, \ldots, v_i, \ldots, v_n\}$ competing to send messages at the data rates (strategies) $s = [r_1, \ldots, r_i, \ldots, r_n]$ to their neighbours. Here, r_i is the sending rate of vehicle v_i. This is given by:

$$r_i = \begin{cases} r_b & \text{if not event driven,} \\ \{w_1 r_e + w_2 r_b\} & \text{if event driven,} \end{cases} \quad (1)$$

where r_b is the data rate of beacon packets or CAMs and r_e is the data rate of DENMs. Here, w_1 and w_2 are weight parameters that are selected by the designer to satisfy the system objectives and requirements.

Each selfish vehicle and their RSU or neighbours sharing the transmission range are modeled as a non-cooperative game $G = (V, (S_i)_{i\in V}, (\chi_i)_{i\in V})$ where:

- Players: A group of vehicles given by V have been considered where n represents number of vehicles which are connected with the RSU or the sharing the transmission range with other vehicles.
- Strategies: That represents the possible data transmission rate for each vehicle. The available strategies for vehicle v_i is denoted by S_i. Each player (vehicle) v_i can broadcast a maximum and minimum data rate of r_i^{max} and zero, respectively. Hence, $S_i = [0, r_i^{max}]$ is the set of available strategies for player or vehicle i and the strategy profile for all players is $S = \prod_{i=1}^{n} S_i = [0, r_1^{max}] \times \cdots \times [0, r_i^{max}] \times \cdots \times [0, r_n^{max}]$.
- Utility function: The utility function of vehicle v_i is given by χ_i and is used to improve its performance. This is achieved by optimising the utility function with respect to r_i.

In this paper, the utility function is formulated to represent each vehicles' desire to send data at a high rate (payoff function) and the priority of the vehicle (priority function). Therefore, the vehicle utility function comprises of two functions:

- Payoff function: The payoff function, $U_i(r_i)$, is modelled so that each vehicle obtains a greater payoff by improving its data rate. There are different kinds of cost functions that are generally utilized. These include linear, logarithmic, sigmoidal and exponential [13]. In this paper, the logarithmic utility function has been used. This is because it is strictly concave on its domain. Hence, the payoff function of all vehicles v_i have been selected as follows:

$$U_i(r_i) = \log(r_i + 1). \quad (2)$$

Note, + 1 has been added in (2) to avoid having the case $U_i(r_i) = -\inf$.
- Priority function: The priority function, $P_i(r_i; p_i)$, is used to reflect the priority of each vehicle to send information. To distinguish between high and low priority vehicles, each vehicle v_i has to be punished based on its transmission rate (r_i) and a measure of its priority to send information. The priority objective function of vehicle v_i can be formulated as follows:

$$P_i(r_i, p_i) = \frac{r_i}{p_i} = \frac{r_i}{\frac{D_{i,j}}{R}}. \quad (3)$$

Here, D_{ij} is the distance between the original sender and the receiver, R is the transmission range of the RSU or vehicle v_i. Therefore, the furtherest vehicles in the transmission range have a higher priority to send data while the vehicles close from the sender transmission range have a lower priority to send messages.

The utility function of vehicle v_i is formulated as follows:

$$\chi_i(r_i, r_{-i}) = \alpha_i \log(r_i + 1) - \frac{\pi_i r_i}{p_i}. \quad (4)$$

Here, α_i and π_i are player preference parameters of functions $U_i(r_i)$ and $P_i(r_i; p_i)$ respectively such that $\alpha_i,\ \pi_i > 0$; $\forall i \in V$. The values of α_i and π_i are selected to satisfy the system requirements and objectives.

The Nash equilibrium gives, the solution to the non-cooperative game. In the VANET congestion control game $G = (V, (S_i)_{i\in V}, (\chi_i)_{i\in V})$, a strategy profile (data rate) $s^* \in S$ is a Nash equilibrium where $s^* = [r_1^*, \ldots, r_i^*, \ldots, r_n^*]$ if no vehicle (player) can improve its performance by altering its strategy, while the other vehicles (players) strategies remain fixed. The Nash equilibrium in this game is V-tuple $\{r_i^*\}_{i\in V}$ that satisfies:

$$\chi(r_i^*, r_{-i}^*) \geq \chi(r_i, r_{-i}^*)$$

$\forall r_i^*, r_i \in S_i, r_i^* \neq r_i, \forall i \in V$. The proof for the existence of the Nash equilibrium can be provided on request.

B. The Proposed Game Theoretic Approach of the VANET

This paper proposes a new channel congestion alleviation approach that is called GTACC which is specially tailored for VANETs. In the previous section the VANET game and the vehicle utility function have been formulated. The optimal game solution (r_i^*) needs to be estimated where the vehicles (players) select a strategy that improves their utility function. The player utility function can be optimized as a constrained non-linear programming model:

$$\begin{aligned}
\underset{r_i \in S_i}{\text{maximize}} \quad & \chi_i(r_i, r_{-i}) \\
\text{subject to} \quad & \sum_{i=1}^{n} r_i \leq C \\
& 0 \leq r_i \leq r_i^{max}, \ \forall i \in V.
\end{aligned} \tag{5}$$

Here, C is the Maximum Data Load (MDL), that avoids channel congestion.

To solve the problem (5), let $\mathcal{L}_i(r_i, \lambda_i, \xi_i)$ represent the Lagrangian function of player i as follows:

$$\mathcal{L}_i = \chi_i(r_i, r_{-i}) + \lambda_i(C - \sum_{i=1}^{n} r_i) + \xi_i(r_i^{max} - r_i). \tag{6}$$

Here, λ_i and ξ_i are the Lagrange multipliers. The KKT conditions of vehicle (player) v_i to obtain optimal solution are as follows:

$$\lambda_i, \xi_i \geq 0$$

$$r_i \geq 0$$

$$r_i^{max} - r_i \geq 0$$

$$\nabla_{r_i}\chi_i(r_i, r_{-i}) + \lambda_i \nabla_{r_i}(C - \sum_{i=1}^{n} r_i) + \xi_i \nabla_{r_i}(r_i^{max} - r_i) = 0$$

$$\lambda_i(C - \sum_{i=1}^{n} r_i), \xi_i(r_i^{max} - r_i) = 0.$$

The problem in (6) has three unknowns (r_i, λ_i and ξ_i). In order to solve the problem, three cases are considered based on complementarity conditions:

Case 1: $r_i = 0$ and $\xi_i = 0$:

$$\alpha_i - \frac{\pi_i}{p_i} + \lambda_i = 0$$

$$\lambda_i = \frac{\pi_i}{p_i} - \alpha_i$$

The solution $r_i = 0$ is feasible, if the condition ($\lambda_i > 0$) holds and it is as follows:

$$\frac{\pi_i}{p_i} \geq \alpha_i \qquad \text{... condition 1}$$

Case 2: $r_i = r_i^{max}$ and $\lambda_i = 0$:

$$\frac{\alpha_i}{r_i^{max} + 1} - \frac{\pi_i}{p_i} - \xi_i = 0$$

$$\xi_i = \frac{\alpha_i}{r_i^{max} + 1} - \frac{\pi_i}{p_i}$$

The solution $r_i = r_i^{max}$ is feasible, if the condition ($\xi_i > 0$) holds and it is as follows:

$$\frac{\pi_i}{p_i} \leq \frac{\alpha_i}{r_i^{max} + 1} \qquad \text{... condition 2}$$

Case 3: $\lambda_i = 0$, $\xi_i = 0$ and ($0 < r_i < r_i^{max}$)

$$\frac{\alpha_i}{r_i + 1} - \frac{\pi_i}{p_i} = 0$$

$$r_i = \frac{\alpha_i p_i}{\pi_i} - 1.$$

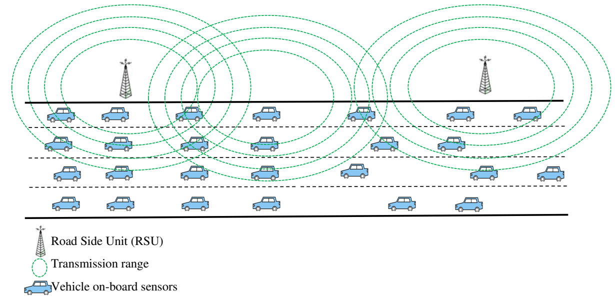

Fig. 1: A Example scenario considered in SUMO.

Hence, the optimal data rate (r_i^*) for player v_i; $\forall i \in V$

$$r_i^* = \begin{cases} \frac{\alpha_i p_i}{\pi_i} - 1 & \text{otherwise} \\ r_i^{max} & \text{if condition 1} \\ 0 & \text{if condition 2} \end{cases} \tag{7}$$

where condition 1 and condition 2 are as follows:

$$\frac{\pi_i}{p_i} \leq \frac{\alpha_i}{r_i^{max} + 1} \tag{8}$$

$$\frac{\pi_i}{p_i} \geq \alpha_i. \tag{9}$$

III. Performance Evaluation

The proposed method has been tested and evaluated through the vehicular network simulator Veins [14] which integrates the Simulator for Urban MObility (SUMO) [15] with the network simulator OMNeT++ [16] to manage the mobility of vehicles and the communication between V2V or V2I communication systems. A four lane road with traffic flowing in one direction has been implemented in SUMO to evaluate and test the proposed method as shown in Figure 1.

The proposed algorithm has been implemented for differing numbers of vehicles, with the transmission data rate being optimized in each scenario. The GTACC has been compared with the CSMA/CA that is originally implemented in the WAVE protocol [17]. The GTACC approach has been implemented based on CCH of MAC layer in WAVE protocol. This is in order to mitigate the congestion generated due to the continuous transfer of safety messages. In this work, initial results have been provided based on a single stretch of road as a proof of concept. Therefore, free space path loss has been used and effects such as shadow fading and scattering have not yet been considered. Such effect could be included in future work.

Long Term Evolution-Vehicle (LTE-V) sidelink is another VANET protocol for supporting V2V and V2I communication systems. However, it has a different mechanism to transmit the safety messages as compared to WAVE protocol. Studies exist which have addressed the performance comparison between these two protocols. For example, [18] shows that when transmissions of periodic cooperative awareness messages are performed by LTE, the capacity of the network is limited by the downlink data channel. In turn, [19] argues that the

TABLE I: Configuration parameters for the implemented example

Simulation parameters	Value
Map dimension	1.0 km
Vehicles speed	2.5-34 m/s
Number of vehicles	50, 70, 90, 110, 130, 150
Simulation time	200 s
MAC/PHY	IEEE 802.11p
Transmission range	300-1000 m
Transmission rate	3-27 Mbps
Safety messages data rate	10 packet/s
α_i	20
π_i	2
w_1	0.7
w_2	0.3

uplink data channel is a bottleneck of the LTE network for the intelligent transport systems use cases. These two studies have shown that the wireless channel congestion problem is generated when there is a large number of vehicles inside the base station transmission range. Thus, the GTACC approach can equally be applied to LTE-V side-link network to alleviate the channel congestion as a future work and similar performance patterns are expected to be obtained.

Four different performance measures have been considered in this performance evaluation:

- **Average throughput (mbps)**: The total number of received packets at all vehicles.
- **Average delay (ms)**: The time needed to deliver a packet between the sender and receiver.
- **Packet loss (Number of packets)**: The number of packets are lost in channel or MAC buffer.
- **Channel busy time (s)**: Indicates the wireless channel busy time within a given interval.

Table I shows the parameters that have been used in the simulation, where the vehicles speed have been chosen by the designer based on the the authors' experience of the problem and using U.K. road laws as a guide.

Figure 2 shows the total average throughput obtained by GTACC and CSMA/CA, respectively. It is obvious that the average throughput increases with increasing numbers of vehicles. It is also clear that the GTACC method has significantly improved the average throughput as compared to the CSMA/CA. The reason is that the GTACC adapts the sending rate of vehicles based on their chosen optimal value as well as considering message and vehicle priorities once the congestion occurs. On the other hand, the CSMA/CA does not have data rate adaptation mechanism when the congestion in the wireless channel occurs. This leads to many messages being sent through the network at a high data rate, which in turn leads to collision and congestion in wireless channel causing packet loss and thus reduced throughput.

Figure 3 depicts the variation of the average delay with the number of vehicles. It is clear when the number of vehicles increases the average delay increases. The results show that the delay in GTACC method is significantly less than the CSMA/CA and there is also not a sharp increase in the average delay when there is an increase in the number of vehicles. This is because the data rate has been tuned to obtain the optimal sending value, which in turn minimizes the delay in receiving the packets.

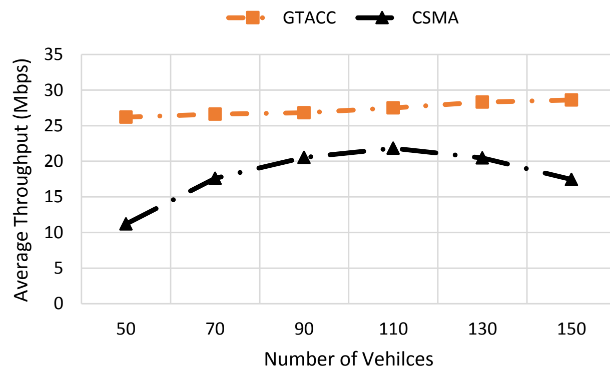

Fig. 2: Total average throughput

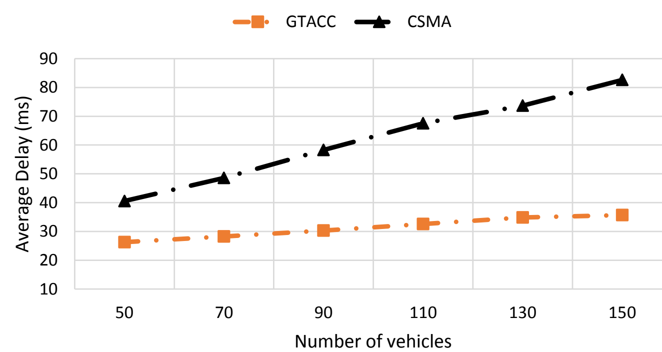

Fig. 3: Total average delay

Figure 4 illustrates the total number of lost packets in the network due to the congestion in the wireless channel. It is obvious that the number of lost packets in GTACC is less than the CSMA/CA. This is due to using an adaptive sending rate which helps to mitigate the congestion in the wireless channel. This decreases the number of lost packets, regardless of the number of vehicles being considered. However, the CSMA/CA has many lost packets due to sending messages at a high unoptimized data rate which leads to a collision in the transmitted data and congestion in the wireless channel.

Figure 5 depicts the total channel busy time from GTACC and CSMA/CA, respectively. The effect of sending at a high data rate on channel occupancy time is evident. It is clear that the CSAM/CA has a higher channel busy time. This is due to the contention between vehicles trying to send messages at a high data rate without considering the available resources. On the other hand, the GTACC has better channel busy time as compared to CSMA/CA. This is due to tuning the data rate to obtain the optimal sending rate for each vehicle individually.

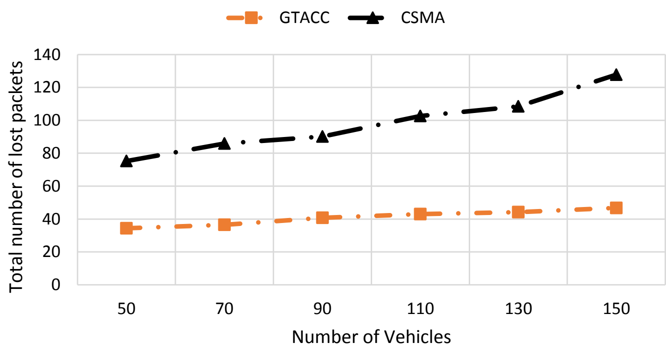

Fig. 4: Total number of lost packets

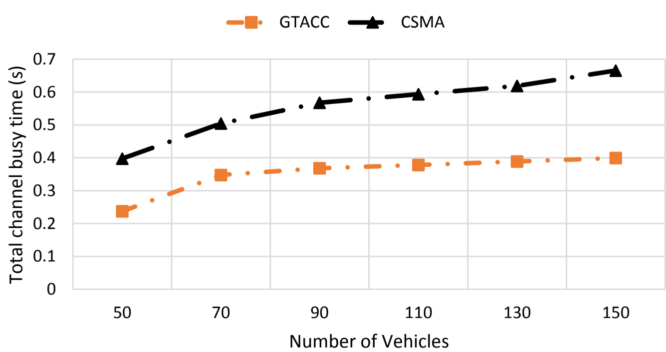

Fig. 5: Total channel busy time

IV. CONCLUSIONS

As the number of connected vehicles on a road network increase so does the number of transmitted messages which leads to congestion in the wireless communication channel. This degrades the network performance and the QoS parameters. In this paper, congestion control in the communication channel has been formulated as a non-cooperative game. Each vehicle acts as a player in the game and requests a high data rate in a selfish way. Simulation results show that the GTACC has a better performance as compared to the Carrier-Sense Multiple Access with Collision Avoidance mechanism of the Wireless Access for Vehicular Environment protocol. As reported from the highway street scenario, it is shown that the proposed approach improves the QoS parameters such as throughput, average delay, number of lost packets and total channel busy time by an overall average of 50.40%, 49.37%, 58.39% and 36.66% respectively, as compared to Carrier-Sense Multiple Access with Collision Avoidance mechanism.

ACKNOWLEDGMENT

The authors are grateful to the Iraqi Government, especially the Ministry of Higher Eduction and the Higher Committee for Education Development (HCED) in Iraq. The authors also appreciate the support of the Transport Systems Catapult (TSC) University Partner Programme (UPP) and the support of the SETA project funded from the European Unions Horizon 2020 research and innovation program under grant agreement no. 688082.

REFERENCES

[1] Y. Fangchun, W. Shangguang, L. Jinglin, L. Zhihan, and S. Qibo, "An overview of internet of vehicles," *China Communications*, vol. 11, no. 10, pp. 1–15, 2014.
[2] M. Boban, R. Meireles, J. Barros, P. Steenkiste, and O. K. Tonguz, "TVRTall vehicle relaying in vehicular networks," *IEEE Transactions on Mobile Computing*, vol. 13, no. 5, pp. 1118–1131, 2014.
[3] Y. Yao, L. Rao, and X. Liu, "Performance and reliability analysis of IEEE 802.11 p safety communication in a highway environment," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 9, pp. 4198–4212, 2013.
[4] R. A. Uzcátegui, A. J. De Sucre, and G. Acosta-Marum, "Wave: A tutorial," *IEEE Communications magazine*, vol. 47, no. 5, 2009.
[5] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, and T. Weil, "Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions," *IEEE communications surveys & tutorials*, vol. 13, no. 4, pp. 584–616, 2011.
[6] R. Fukui, H. Koike, and H. Okada, "Dynamic integrated transmission control DITRAC over inter-vehicle communications in ITS," in *Proceedings of the 55th IEEE Vehicular Technology Conference, Birmingham, 2002*, vol. 1. IEEE, 2002, pp. 483–487.
[7] R. K. Schmidt, T. Leinmuller, E. Schoch, F. Kargl, and G. Schafer, "Exploration of adaptive beaconing for efficient intervehicle safety communication," *IEEE network*, vol. 24, no. 1, 2010.
[8] J. He, H.-H. Chen, T. M. Chen, and W. Cheng, "Adaptive congestion control for DSRC vehicle networks," *IEEE Communications Letters*, vol. 14, no. 2, pp. 127–129, 2010.
[9] K. Zrar Ghafoor, K. Abu Bakar, M. van Eenennaam, R. H. Khokhar, and A. J. Gonzalez, "A fuzzy logic approach to beaconing for vehicular ad hoc networks," *Telecommunication Systems*, pp. 1–11, 2013.
[10] E. Egea-Lopez and P. Pavon-Marino, "Distributed and fair beaconing rate adaptation for congestion control in vehicular networks," *IEEE Transactions on Mobile Computing*, vol. 15, no. 12, pp. 3028–3041, 2016.
[11] F. Cunha, L. Villas, A. Boukerche, G. Maia, A. Viana, R. A. Mini, and A. A. Loureiro, "Data communication in VANETs: Protocols, applications and challenges," *Ad Hoc Networks*, vol. 44, pp. 90–103, 2016.
[12] K. Z. Ghafoor, J. Lloret, K. A. Bakar, A. S. Sadiq, and S. A. B. Mussa, "Beaconing approaches in vehicular ad hoc networks: a survey," *Wireless Personal Communications*, vol. 73, no. 3, pp. 885–912, 2013.
[13] L. Wang and G.-S. G. Kuo, "Mathematical modeling for network selection in heterogeneous wireless networksa tutorial," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 271–292, 2013.
[14] C. Sommer, R. German, and F. Dressler, "Bidirectionally coupled network and road traffic simulation for improved IVC analysis," *IEEE Transactions on Mobile Computing*, vol. 10, no. 1, pp. 3–15, 2011.
[15] M. Behrisch, L. Bieker, J. Erdmann, and D. Krajzewicz, "Sumo–Simulation of Urban MObility," in *Proc. of the Third International Conf. on Advances in System Simulation, Barcelona, Spain*, 2011.
[16] "What is OMNeT++?., OMNet++discrete event simulator, opensimltd. web," https://omnetpp.org/, accessed: 2015-10-23.
[17] V. D. Khairnar and K. Kotecha, "Performance of vehicle-to-vehicle communication using IEEE 802.11p in vehicular ad-hoc network environment," *arXiv preprint arXiv:1304.3357*, 2013.
[18] M.-A. Phan, R. Rembarz, and S. Sories, "A capacity analysis for the transmission of event and cooperative awareness messages in lte networks," in *Proceedings of the 18th ITS world congress*, 2011.
[19] J. Hu, S. Chen, L. Zhao, Y. Li, J. Fang, B. Li, and Y. Shi, "Link level performance comparison between LTE V2X and DSRC," *Journal of Communications and Information Networks*, vol. 2, no. 2, pp. 101–112, 2017.