IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 21, 2017, accepted August 12, 2017, date of publication August 21, 2017, date of current version September 19, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2742864

Non-Cooperative Beacon Rate and Awareness Control for VANETs

FOROUGH GOUDARZI[1], (Student Member, IEEE), AND HAMID ASGARI[2,3], (Senior Member, IEEE)
[1]Transport Research Group, University of Southampton, Southampton SO16 7QF, U.K.
[2]Thales Research, Technology and Innovation, U.K., Reading RG2 6GF, U.K.
[3]King's College London, London WC2R 2LS, U.K.

Corresponding author: Forough Goudarzi (f.goudarzi@soton.ac.uk)

ABSTRACT In vehicular ad hoc networks (VANETs), vehicles broadcast their status information in beacons periodically to make the surrounding vehicles aware of their presence. To maximize the level of awareness, a congestion control mechanism is necessary to avoid loss of beacons due to collision in dense traffic environments. In addition to congestion control, it is desirable that vehicles share network bandwidth in a manner proportional to their dynamics or safety application requirements. Current congestion control mechanisms have a number of issues including control information overheads, fairness, and awareness. In this paper, a beacon rate and awareness control mechanism based on non-cooperative game theory called non-cooperative beacon rate and awareness control (NORAC), is proposed. The existence and uniqueness of the Nash equilibrium of the game is proved mathematically and an algorithm is proposed to find the equilibrium point in a distributed manner. The proposed algorithm is used to assign a beacon rate to every vehicle proportional to its requirements, while ensuring fairness between vehicles with the same requirement. NORAC is compared with the two other known congestion control mechanisms. The simulation results show the efficiency and stability of the proposed NORAC algorithm in several high-density traffic scenarios. The results indicate its advantages in terms of fairness and congestion and awareness control over the other two algorithms, while not requiring excessive information to be included in beacons.

INDEX TERMS Awareness control, beacon rate control, non-cooperative game, VANETs.

I. INTRODUCTION

The primary motive for using Vehicular Ad hoc Networks (VANETs) is to enhance safety in transportation. This goal is achieved by messages exchanged among vehicles. One of the most important messages is the Basic Safety Message (BSM), also called beacons, which includes vehicle status data such as position, speed, and acceleration. Frequent broadcast of BSM provides awareness about nearby vehicles. Thus, beaconing with the highest rate (10 Hz) is desirable from the viewpoint of providing fresh information and ensuring that vehicles have high levels of awareness. However, in dense traffic environments, a high beaconing rate increases packet collision, which reduces the number of received beacons, and thus, reduces vehicles' awareness of surrounding vehicles. In addition, channel congestion reduces the network good-put owing to high collision rate. The maximum beacons are received when the Channel Busy Ratio (CBR) is around 0.65 for different transmission rates or ranges [1]. Therefore, considerable efforts have been dedicated toward designing congestion control mechanisms in order to limit the channel load around 0.65 for VANETs by controlling either beacon rate or transmission range or both [2]–[11]. In this paper, we consider beacon rate control.

Congestion control is an important issue in computer networks because congestion degrades network performance. The key characteristics that have traditionally been used to evaluate congestion control mechanisms include efficiency in keeping channel load under a desired level, fairness among network users, convergence time of the mechanism, and oscillation size [12]. Given the special features of VANETs, the requirements in terms of these characteristics are distinctive; sometimes, even new requirements emerge. Congestion control in VANETs should work in a distributed manner without involving any infrastructure. The overhead due to the control mechanism should be as minimal as possible. Owing to the highly dynamic nature of VANETs, convergence time of the congestion control mechanism should be short.

In networks, assigning fair share of limited network bandwidth is an important issue. Fairness as a metric is generally measured to determine whether users are receiving a fair share of network utilization. Obtaining fairness between network users and, at the same time, assuring the control of network load and efficient network utilization, is a source of non-trivial network problems. Regarding fairness in VANETs, in many works, fairness simply has been considered the condition in which all vehicles in a congested condition should use the same beacon rate apart from their dynamics. Even with this simple definition, several protocols fail to achieve fairness [5]. Moreover, such fairness cannot meet awareness and safety application requirements in VANETs [13], [14]. A scenario in which there is congestion on one direction of a highway and free flow on the other direction exemplifies that vehicles have different beaconing requirements. Vehicles on both sides of the highway might experience the same CBR, but those running at higher speeds should have higher beaconing rates than standstill vehicles to create a high level of awareness. Actually, in a congested scenario, when the overall bandwidth is inadequate to allow vehicles to transmit beacons with the highest allowed beaconing rate, the bandwidth should be shared among vehicles proportional to their dynamics or requirements, while maintaining the CBR below the desired level.

Generally, approaches in resolving the unfairness of congestion control mechanisms are based on piggybacking excess information in beacons (such as current beacon rate or experienced CBR) and propagating it over one or two hops [2]–[6]. Broadcasting such information creates overhead and makes the mechanism error-prone due to channel fading and loss of information. In addition, when the size of a congested area is larger than the range that this information is shared, the unfairness problem appears again.

In this paper, a beacon rate and awareness control mechanism based on non-cooperative game theory [15] is proposed. Non-cooperative game theory deals with interactions among several entities that might have conflicting preferences. Every entity selects a strategy individually to increase its payoff selfishly, while its pay-off is affected by other entities' strategies. This theory matches the problem we face with congestion control in VANETs. Every vehicle tries to work with the highest beaconing rate to make the surrounding vehicles aware of its presence. However, in situations with dense traffic, when every vehicle works with the highest rate, the level of awareness decreases due to loss of beacons. Interestingly, non-cooperative games do not rely on communication between nodes. Every node decides individually, and the whole network ends up at an equilibrium point. In a wireless network, this is a desirable characteristic because it results in scarce bandwidth saving. In our proposed congestion control mechanism, a price function [16] is used to limit bandwidth usage by each network node and reduce the beaconing rate in congested situations. The existence and uniqueness of the Nash Equilibrium (NE) is proved, and the condition for the stability of NE is derived mathematically. A distributed method is used to find the equilibrium point of the congestion control mechanism.

Two features make this work distinctive from other congestion control mechanisms for VANETs. Firstly, the proposed mechanism does not need to share control information between vehicles for the operation or to achieve fairness. In other words, it is fully distributed and non-cooperative. This leads to saving of valuable network bandwidth and enhances robustness to error because it avoids control information exchanges over a wireless channel. The proposed mechanism achieves fairness based on the fairness concept of the NE. If there is no fairness at the equilibrium point, some vehicles can change their strategy unilaterally to obtain higher payoff, and this is in contradiction with the NE point concept. Secondly, it provides an efficient congestion control mechanism that can satisfy safety application requirements [13], [14]. Bandwidth is shared among vehicles in proportion to their requirements, while fairness is achieved among vehicles with the same requirements. The proposed mechanism uses parameters that every vehicle can set individually without communicating with the other vehicles, and the entire system ends up being in the desired condition.

The remainder of this paper is organized as follows. In Section II, the related work is reviewed. Section III introduces the non-cooperative beacon rate and awareness control game in mathematical terms. In Section IV, existence, uniqueness, and stability of NE is investigated and its mathematical proof is provided. A distributed algorithm for finding the NE point based on the gradient method is presented in Section V. Selection of the parameters for the proposed mechanism and their effects on its outcome are discussed in Section VI. The simulation results, and an evaluation and comparison of the results against two other protocols are presented in Section VII. Finally, some concluding remarks are given in Section VIII.

II. RELATED WORK

LIMERIC [10] is a beacon rate control algorithm in which, each vehicle measures CBR and then updates its rate proportional to the error between the desired CBR and the measured value. To ensure the convergence of the algorithm in dense traffic situations, a gain saturation approach is introduced; if the magnitude of the updates exceeds a specified threshold, the updates will be limited to the magnitude of that threshold. The algorithm does not require exchange of control information between vehicles. It assumes that all the vehicles measure the same CBR which can be unrealistic, even when all the vehicles are in the communication range of each other, due to channel fading.

PULSAR protocol [4] uses Additive Increase Multiplicative Decrease (AIMD) technique to adapt the beacon rate of vehicles. Vehicles communicate the measured CBR within a two-hop distance. If the maximum reported CBR is higher than a threshold level, the rate is decreased by a multiplicative factor; otherwise it is increased by an additive factor.

Both LIMERIC and PULSAR suffer unfairness in rate allocation [5].

To solve the unfairness problem in beacon rate control, a technique is proposed in [5] which relies on piggybacking the excess information on beacons. Every vehicle includes its current beacon rate in its beacons. Before applying any change to the rate, a vehicle compares its rate to the average rate of its immediate neighboring vehicles to avoid too much difference between the rates of neighboring vehicles. A similar mechanism is used in [6] in which vehicles exchange their state information instead of beacon rate. Three different states are defined and, in each state, vehicles use different transmitter power levels, beaconing rates, receiver sensitivities, and physical layer bit rates. Numerical values of 0, 1, and 2 are assigned to the states. Each vehicle piggybacks its current state number on its beacons. The average value of states of neighboring vehicles is used as a criteria for changing state.

In INTERN protocol [3], the safety application sets the minimum and maximum rate and required power for transmission of beacons. Then every vehicle adjusts its beacon rate within the specified interval. In order to achieve fairness, vehicles exchange information on the measured CBR and their excess rate with respect to the minimum they use, over two hops. This is similar to the approach used in PULSAR. Since each vehicle sets a minimum beacon rate that is required by an application, the aggregated channel utilization may violate the maximum desired level of CBR.

In [8], a protocol for adaptive beaconing rate and power based on the dynamics of a vehicular network is proposed. A vehicle increases its beacon rate when it suspects the estimated tracking error of neighboring vehicles towards its position has increased. For this purpose in every defined time step, vehicles compute transmission probability based on suspected tracking error on neighboring vehicles towards its own position in a Euclidean sense. If the suspected error is smaller than a threshold, there will be no transmission. Otherwise, if the suspected error is larger than this threshold, the transmission in that time step occurs with a probability proportional to the magnitude of the suspected error. For the power control, two levels of CBR are defined; CBR_{max} and CBR_{min}. If the CBR measured by each vehicle is greater than CBR_{max}, minimum transmission power is used; if it is lower than CBR_{min}, maximum transmission power is used; otherwise, the transmission power is selected between the maximum and minimum values using a linear function. In this work, fairness was not studied.

FABRIC algorithm [2] is based on network utility maximization in which every vehicle piggybacks information on the computed Lagrange multipliers and its current beaconing rate in its beacons. Vehicles use this information from their immediate neighbors to update their rates and the Lagrange multipliers. The speed of convergence of the algorithm is dependent on the initial values of the Lagrange multipliers which are not controllable in practice because over time, vehicles change these parameters. Although it has been stated that the algorithm can meet the application requirements, there are no experimental results given in the paper to verify it. Actually, an algorithm should have parameters per vehicle to be able to present this feature, while such parameters do not exist in the algorithm.

In FABRIC-P algorithm [17], it is assumed that a vehicle can transmit its beacons with a discrete set of power levels. An individual beaconing rate for each power level is determined by the algorithm to control the CBR. In addition to the excessive information that is included in beacons in FABRIC, vehicles also piggyback the power level that they use to transmit a beacon, in their beacons.

There are a number of adaptive beaconing algorithms that are aimed at reducing the tracking error of vehicles [18], [19] or addressing the required beaconing rate for specific applications [20]. Our work provides a more inclusive solution as there are situations where, although tracking error of vehicles is low, vehicles require high beaconing rates. An example for this is the situations when vehicles are close to a junction even if they are stationary [3]. As far as we know, the issues related to the work stated in this section, and generally in the literature, can be summarized as follows:

- Most of these mechanisms rely on the exchange of extra information in beacons over one or two hops to obtain fairness. Such mechanisms:
  - consume the network bandwidth and are error-prone due to the loss of information.
  - might lose fairness if the scenario is extended to more than the range that the information is exchanged.
  - might reduce the beacon rate of vehicles that have no contribution to the congestion [2].
- The safety application requirement has not been addressed or if it has been stated, two processes of congestion control and application requirements work separately and thus, there is no guarantee that the channel occupancy remains below the desired level.

These problems have been addressed in the proposed NORAC mechanism.

III. NON-COOPERATIVE BEACON RATE AND AWARENESS CONTROL GAME

This section explains the non-cooperative beacon rate and awareness control in mathematical terms. Let $\mathcal{G} = \{\mathcal{N}, \{\mathcal{R}_i\}_{i\in\mathcal{N}}, \{\varphi_i\}_{i\in\mathcal{N}}\}$ denotes the Non-cooperative beacon Rate and Awareness Control (NORAC) game, where $\mathcal{N} = \{1, 2, \ldots, N\}$ is the set of players (vehicles), and $\mathcal{R}_i$ is the set of possible beacon rates for player i and is called the strategy set of player i. φ_i is the pay-off function of player i. The beacon rate $r_i \in \mathcal{R}_i$ is referred to as the strategy of player i. Each player i selects a strategy independently. The vector $\mathbf{r} = (r_1, r_2, \ldots, r_N) \in \mathbf{R}$ denotes the selected beacon rates of all players, where $\mathbf{R} = \prod_{i=1}^{N} \mathcal{R}_i$. The resulting pay-off function for the ith player is given as $\varphi_i(\mathbf{r}) = \varphi_i(r_i, \mathbf{r}_{-i})$, where $\mathbf{r}_{-i}$ represents the vector consisting of the beacon rates of all players except the ith player.

Every player creates a beacon with a rate between 1 and 10 Hz [21]. Thus, the strategy set of player i is $\mathcal{R}_i = [1, 10]$. The players create beacons to make aware other players of their presence. Higher awareness about a player enhances that player's safety. Thus, it should result in higher pay-off. As explained in Section I, a higher beacon rate is desirable because it creates higher awareness under normal conditions, but it has a negative effect on awareness in congested situations. Then, the desirable pay-off function would yield lower pay-off with the same beacon rate in situations with high levels of congestion. To achieve this objective, the pay-off function is modeled as the difference between a utility and a price function. Accordingly, the pay-off function for user i is introduced as follows:

$$\begin{aligned}\varphi_i(r_i, \mathbf{r}_{-i}) &= U_i(r_i) - P_i(r_i, \mathbf{r}_{-i})\\ &= u_i \ln(r_i+1) - \frac{p_i}{1 - CBR_i(r_i, \mathbf{r}_{-i})}\end{aligned} \tag{1}$$

where u_i and p_i are positive parameters, and $CBR_i(r_i, \mathbf{r}_{-i})$ is the channel busy ratio that player i senses, and it is a function of all players' beacon rates.

The first term $(u_i \ln(r_i+1))$ in (1) is called utility, and it increases with increasing beacon rate and indicates the preference of players to have a higher rate. In addition, this utility function leads to proportional fairness in data rates [22]. The second term $(p_i/(1 - CBR_i(r_i, \mathbf{r}_{-i})))$ in (1) is the price function. Pricing [16] in computer networks is a way to motivate efficient use of network resources. When there is congestion in a network, an efficient pricing mechanism discourages excessive resource usage by competing nodes. This term is a function of CBR because CBR is a good indicator of successful information dissemination [1]; high CBR results in poor inter-vehicle awareness. The price function becomes larger in scenarios with higher levels of congestion, resulting in a lower pay-off. Furthermore, it increases more rapidly at higher CBR values than at lower values, which leads to a faster decrease of rate in higher CBRs.

The marginal pay-off of player i is $\nabla_i\varphi_i(\mathbf{r}) = \partial\varphi_i(\mathbf{r})/\partial r_i$ and the vector of marginal pay-offs of all players is given as $\nabla\varphi(\mathbf{r}) = (\nabla_1\varphi_1(\mathbf{r}), \nabla_2\varphi_2(\mathbf{r}), \ldots, \nabla_N\varphi_N(\mathbf{r}))^T$ and its Jacobian as $G(\mathbf{r})$.

The mathematical model used for $CBR_i(\mathbf{r})$, is fully described in the Appendix. As the result the experience CBR by node i is:

$$CBR_i(\mathbf{r}) = \sum_{j=1}^{N} h_{ij} r_j \tag{2}$$

where

$$h_{ij} = T_{frame} \times \frac{\Gamma\left(m, \frac{mC_{Tt}}{\Omega}\right)}{\Gamma(m)}, \tag{3}$$

and

$$\Omega = \frac{P_t\lambda^2}{(4\pi)^2 d_{ij}^{\gamma}}, \tag{4}$$

In the above equations, $\Gamma(.)$ is the gamma function, $\Gamma(.,.)$ is the upper incomplete gamma function, C_{Tt} is the threshold power level of carrier sense, P_t is transmitter power, d_{ij} is the distance between jth and ith players, m is the Nakagami fading parameter, λ is the wavelength, γ is the path loss exponent, and T_{frame} is the time required to send a beacon message.

IV. NASH EQUILIBRIUM (NE)

In this section, we prove the proposed NORAC game has a unique NE point and then derive a sufficient condition for stability of the NE.

A. EXISTENCE AND UNIQUENESS OF THE NE

The game $\mathcal{G}$ has twice differentiable pay-off functions and according to [23] it is a submodular game if, and only if:

$$\forall i, j \in \mathcal{N}, \quad i \neq j, \ \frac{\partial^2\varphi_i}{\partial r_i \partial r_j} \leq 0 \tag{5}$$

For NORAC we have:

$$\frac{\partial^2\varphi_i}{\partial r_i \partial r_j} = -\frac{2\, p_i h_{ii} h_{ij}}{(1 - CBR_i(\mathbf{r}))^3} < 0 \tag{6}$$

thus, it is a submodular game. In addition, according to Theorem 3.1 in [23] the set of equilibrium points of such a game is not empty and a least and a greatest equilibrium point exist. Therefore, NORAC has at least one NE and we require to prove that the NE is unique. Equilibrium uniqueness is a desirable property in non-cooperative games because, in such games, players make their decisions independently, and in the case of several equilibriums, the game might end up at a non-equilibrium point [24].

Assume the greatest equilibrium point is $\mathbf{r}_1 = (r_{11}, r_{12}, \ldots, r_{1N})$ and the least is $\mathbf{r}_2 = (r_{21}, r_{22}, \ldots, r_{2N})$ thus,

$$\forall i \in \mathcal{N}, \quad r_{1i} \geq r_{2i} \tag{7}$$

At equilibrium points:

$$\frac{\partial\varphi_i}{\partial r_i} = \frac{u_i}{r_i+1} - \frac{c_i h_{ii}}{(1 - CBR_i(\mathbf{r}))^2} = 0 \tag{8}$$

thus,

$$\forall i \in \mathcal{N}, \quad r_{1i} + 1 = \frac{u_i\ (1 - CBR_i(\mathbf{r}_1))^2}{c_i h_{ii}} \tag{9}$$

and similarly for $\mathbf{r}_2$:

$$\forall i \in \mathcal{N}, \quad r_{2i} + 1 = \frac{u_i\ (1 - CBR_i(\mathbf{r}_2))^2}{c_i h_{ii}} \tag{10}$$

regarding (7),

$$\forall i \in \mathcal{N}, \quad \frac{u_i\ (1 - CBR_i(\mathbf{r}_1))^2}{c_i h_{ii}} \geq \frac{u_i\ (1 - CBR_i(\mathbf{r}_2))^2}{c_i h_{ii}} \tag{11}$$

therefore,

$$CBR_i(\mathbf{r}_1) \leq CBR_i(\mathbf{r}_2) \tag{12}$$

Because $CBR_i(\mathbf{r})$ is an increasing function of $\mathbf{r}$, (12) contradicts (7) and therefore, $\mathbf{r}_1 = \mathbf{r}_2$, which means the equilibrium point is unique.

B. STABILITY OF THE NE

In this section, we try to derive a sufficient condition for the stability of the NE. In NORAC, $-G(\mathbf{r})$ is an $N \times N$ matrix with elements of:

$$g_{ii} = \frac{u_i}{(r_i+1)^2} + \frac{2\,p_i h_{ii}^2}{(1-CBR_i(\mathbf{r}))^3} \tag{13}$$

and

$$g_{ij} = \frac{2\,p_i h_{ii} h_{ij}}{(1-CBR_i(\mathbf{r}))^3} \quad i \neq j \tag{14}$$

An equilibrium point is gradient stable if the corresponding Jacobian is a stable matrix at that point (see Fact 1 in [25]). At equilibrium, $\nabla\varphi(\mathbf{r}) = 0$, which gives

$$\frac{u_i}{r_i+1} = \frac{p_i h_{ii}}{(1-CBR_i(\mathbf{r}))^2} \tag{15}$$

Thus,

$$1 - CBR_i(\mathbf{r}) = \left(\frac{(r_i+1)\,p_i h_{ii}}{u_i}\right)^{1/2} \tag{16}$$

so the elements of the matrix can be written as

$$g_{ii} = \frac{u_i}{(r_i+1)^2} + \frac{2h_{ii}u_i^{3/2}}{(r_i+1)^{3/2}(p_i h_{ii})^{1/2}} \tag{17}$$

and

$$g_{ij} = \frac{2h_{ij}u_i^{3/2}}{(r_i+1)^{3/2}(p_i h_{ii})^{1/2}} \quad i \neq j \tag{18}$$

A matrix with positive row averages and all off-diagonal elements bounded above by their corresponding row averages has a positive determinant [26]. Such a matrix is called a B-matrix, and it is positive definite [27]. The matrix $-G(\mathbf{r})$ at equilibrium is a B-matrix if:

$$\forall i \quad \frac{1}{N} \times \left(\frac{u_i}{(r_i+1)^2} + \sum_{j=1}^{N} \frac{2h_{ij}u_i^{3/2}}{(r_i+1)^{3/2}(p_i h_{ii})^{1/2}}\right) > \max_{i\neq j}\left(\frac{2h_{ij}u_i^{3/2}}{(r_i+1)^{3/2}(p_i h_{ii})^{1/2}}\right) \tag{19}$$

Then

$$\forall i \quad \left(\frac{p_i h_{ii}}{u_i(r_i+1)}\right)^{1/2} > 2 \times \left(N \times \max_{i\neq j} h_{ij} - \sum_{j=1}^{N} h_{ij}\right) \tag{20}$$

The maximum of h_{ij} is when $j = i$ ($d_{ij} = 0$ in (2)), thus $Nh_{ii} - \sum_{j=1}^{N} h_{ij}$ is considered the upper bound of the right-hand side of (20). Then,

$$\forall i \quad \frac{u_i}{p_i h_{ii}} < \frac{1}{4(r_i+1)\left(Nh_{ii} - \sum_{j=1}^{N} h_{ij}\right)^2} \tag{21}$$

Most congestion control mechanisms have been tested in a network with a bit rate of 6 Mbps, since this bit rate provides a good trade off between channel load and signal to noise requirements [28]. For VANETs, with a bit rate of 6 Mbps and a maximum beacon size of 500 bytes [2], h_{ii} is equal to 6.6×10^{-4}. Both terms Nh_{ii} and $\sum_{i=1}^{N} h_{ij}$ grow with increasing numbers of vehicles (N). Therefore, it is expected that the term $\left(Nh_{ii} - \sum_{i=1}^{N} h_{ij}\right)^2$ would be a small number considering the value of h_{ii} and the term's power two. Thus, with the maximum r_i=10 Hz, the unique NE is stable for a broad range of $u_i/p_i h_{ii}$, as shown in the simulation results. Moreover, it is worth noting that the condition specified in (21) is a sufficient condition for the stability of the NE, not a required one.

V. CONGESTION CONTROL PROCESS IN NORAC

As it has been indicated in Section IV-B, the NE is gradient-stable under sufficient conditions (21). In NORAC, every vehicle updates its beacon rate according to the gradient method as follows.

$$\frac{\partial r_i}{\partial t} = \frac{\partial \varphi_i}{\partial r_i} = \frac{u_i}{r_i+1} - \frac{p_i h_{ii}}{(1-CBR_i(\mathbf{r}))^2} \tag{22}$$

From now on, $p_i h_{ii}$ is considered as a single parameter pc_i for simplicity. Algorithm 1, given below, represents the NORAC mechanism, where r_{max} and r_{min} are 10 Hz and 1 Hz respectively. In Algorithm 1, given below, every vehicle updates its BSM rate according to the locally measured CBR in each iteration, and vehicles do not require to exchange control information. It is worth noting that CBR can be measured using the Clear Channel Assessment (CCA) function defined in IEEE 802.11 standard [29].

Algorithm 1 Beacon Rate Update Based on Gradient Method

1: Every vehicle measures CBR
2: Every vehicle updates the beacon rate according to:

$$r_i = \left[r_i + \frac{u_i}{r_i+1} - \frac{pc_i}{(1-CBR_i(\mathbf{r}))^2}\right]_{r_{min}}^{r_{max}}$$

VI. SELECTION OF NORAC PARAMETERS

To evaluate the effect of u_i and pc_i on the CBR and beacon rate, the results of simulation performed for a track measuring 400 m in length and with N = 159 vehicles are shown in Figures 1 and 2. All vehicles have the same pc_i and u_i. Figure 1a shows the results when u_i is constant and equal to 5, and pc_i has values of 0.1, 0.3, 0.7, and 1. As expected, an increase in pc_i increases the price of using bandwidth; then, players use lower beacon rates, so CBR is controlled to a lower level. In Figure 1b, pc_i is constant and equal to 0.2 and u_i has values of 1, 3, 5, and 20. By increasing u_i, the algorithm ends up with higher CBR and beacon rates because the players' pay-off is increased according to equation (1). Figure 1b, also shows that for $pc_i = 0.2$ and u_i between 5.0 and 20,

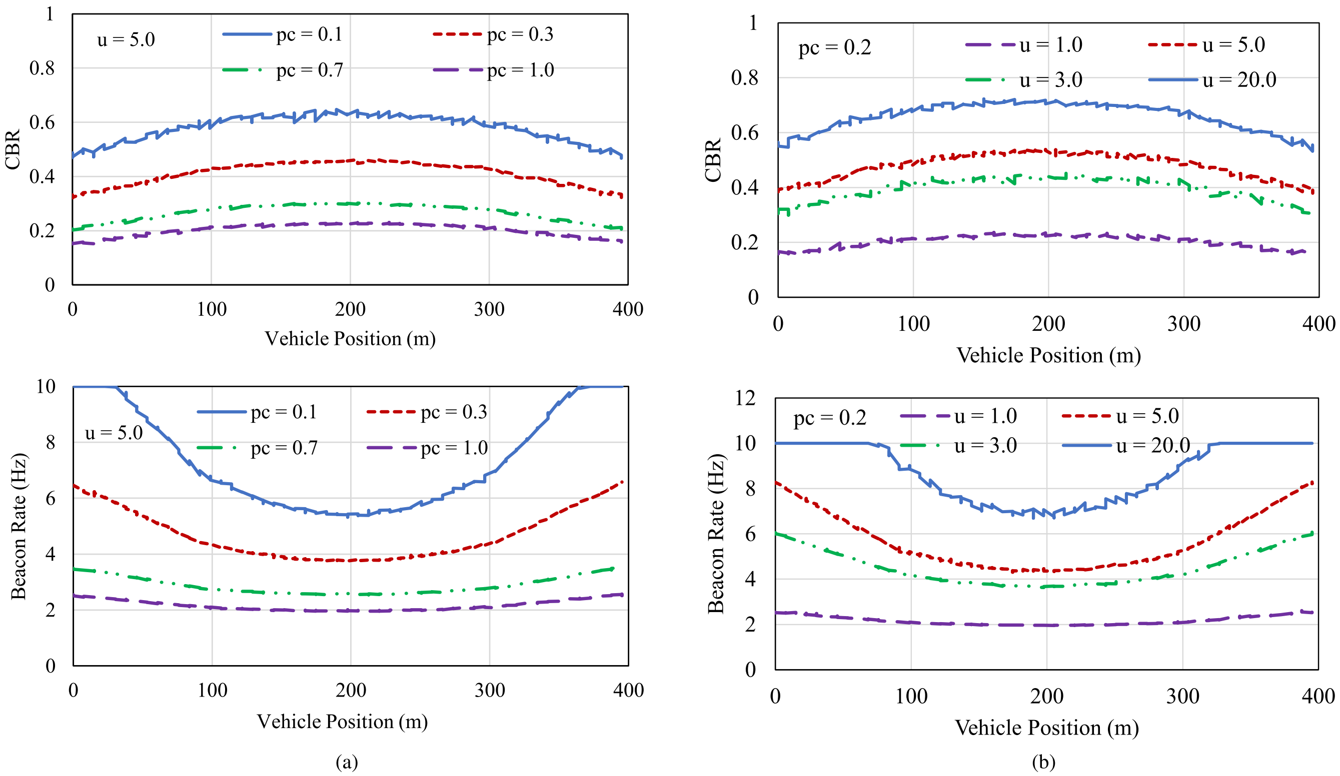

FIGURE 1. Beacon rate and CBR for a track measuring 400 m in length with N = 159 vehicles. (a) Effect of changes in price when utility parameter is constant and equal to 5. (b) Effect of changes in utility when price parameter is constant and equal to 0.2.

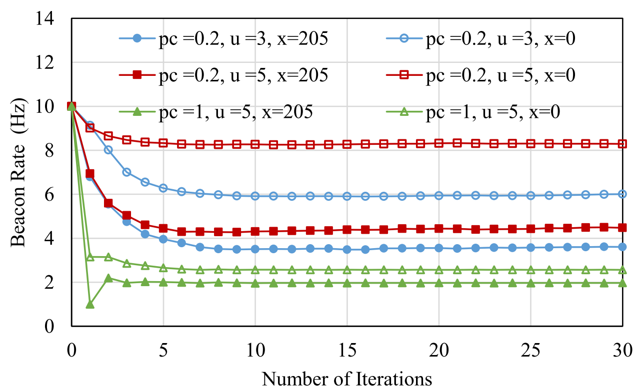

FIGURE 2. Beacon rate updates for vehicles at x = 0 m and x = 205 m for different values of pc and u.

CBR is controlled within the desired range. These are the values that are used in the simulation runs reported in the next section.

Figure 2 shows the beacon rate in every iteration of NORAC when all vehicles have a beacon rate of 10 Hz at the start of the simulation. For every pair of u_i and pc_i, changes in the beacon rate are shown for two vehicles; one at the middle of the track (x = 205) and one at the edge (x = 0). For larger values of u_i and pc_i, the algorithm converges faster, for example, with $pc_i = 0.2$ and $u_i = 5$, it converges in fewer than 10 iterations.

In formulation of the mechanism, it was never assumed that u_i and pc_i are equal for all players. Thus, every vehicle can select its parameters individually according to its safety application and awareness requirements and yet congestion is controlled. This is demonstrated in the simulation results reported in the next section.

VII. PERFORMANCE EVALUATIONS AND COMPARISONS

The performance of NORAC is evaluated in several high-density scenarios using OMNeT++ [30] as a network simulator and SUMO [31] for generating traffic mobility. The scenarios have been selected to demonstrate the functionality of NORAC in different traffic conditions: 1) when just stationary vehicles exist in the scenario. 2) when both stationary and moving vehicles exist. 3) when just moving vehicles exist. The number of stationary vehicles in each scenario is the maximum number of vehicles that the simulators allow by default for each length of the track. The simulation parameters are summarized in Table 1. LIMERIC and FABRIC are chosen for comparison. Similar to NORAC, LIMERIC does not rely on exchange of excess information in beacons and FABRIC is one the newest rate control mechanisms. The parameters of LIMERIC and FABRIC are the same as those suggested in [10] and [2]. u_i and pc_i parameters have been selected so that the congestion level is controlled between 0.4 and 0.8 [1]. As indicated in Section VII vehicles can change both u_i and pc_i, however changing one of them is

TABLE 1. Simulation parameters.

Parameter	Value
Carrier Frequency	5.89 GHz
Communication Range	300 meters
MAC Protocol	IEEE 802.11p
Bit Rate	6 Mbps
Beacon Size	500 Bytes
Sampling Time	500 ms
Propagation Model	Nakagami m = 2.0
pc_i	0.2
u_i	5 unless specified
α (FABRIC)	1, 2
β (FABRIC)	2.8×10^{-5}
π_i^0 (FABRIC)	1.252×10^{-3}
Maximum Channel Capacity (FABRIC)	781.25 beacons/s
Anti-flapping Parameter (FABRIC)	0.022
α (LIMERIC)	0.1
β (LIMERIC)	1/150
Gain Saturation Parameter (LIMERIC)	0.005

sufficient to address safety application requirements. In all simulation runs, pc of all vehicles is considered constant, equal to 0.2 and all vehicles change their u parameter, only.

In VANETs, devices should be synchronized as recommended in IEEE Std 1609.0-2013 [32] and IEEE Std 1609.4-2016 [33]. This synchronization is necessary for multi-channel operation and security purposes, and it can be achieved by GPS, as has been mentioned in the above standards. NORAC works in both conditions of synchronous and asynchronous rate adaptation. In the next section, we assume that vehicles adapt their rates asynchronously because the algorithms that have been selected for comparison were tested in asynchronous condition too and working in this condition can show the strength of the mechanism. An asynchronous update simply increases the convergence time of NORAC, but it is still faster than the other state-of-the-art mechanisms selected for comparison as the simulation results indicate.

A. STATIONARY VEHICLES IN IMMEDIATE NEIGHBORHOOD OF EACH OTHER

In this experiment, the geographical size of the network is equal to one communication range (300 m). Thus, all the vehicles are immediate neighbors of each other and are not moving. Here, 120 vehicles on a 3-lane track measuring 300 m in length are distributed homogeneously. Figure 3 shows the beacon rate and CBR of the vehicles after convergence. While all congestion control algorithms control CBR well, LIMERIC is not fair in beacon rate allocation and vehicles have different beacons ranging from 4 to 10 Hz. In FABRIC, with both $\alpha = 1$ and 2, all vehicles converge to the same rate, but convergence is faster with $\alpha = 1$. All the vehicles are within the range of each other and they can receive beacons and consequently FABRIC's control information of all other vehicles; thus, they converge to the same beacon rate, as shown in Figure 3. NORAC has good

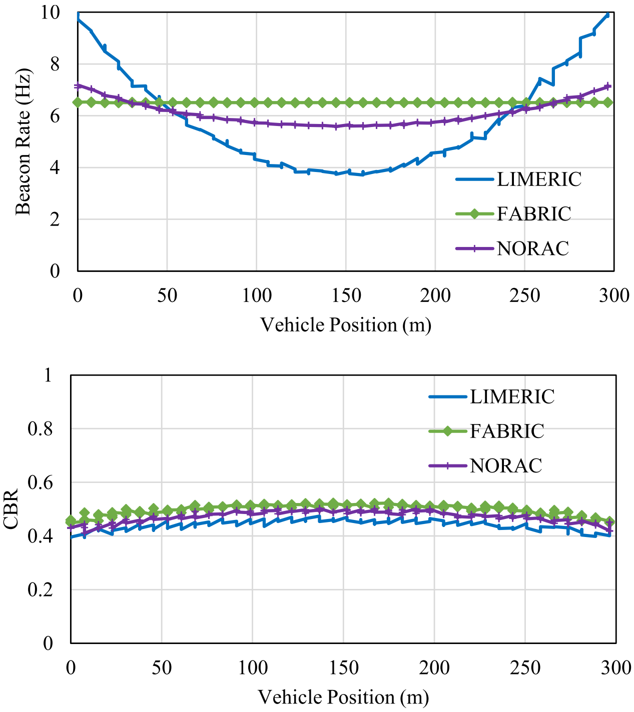

FIGURE 3. Beacon rate and CBR for N = 120 stationary vehicles in immediate neighborhood of each other.

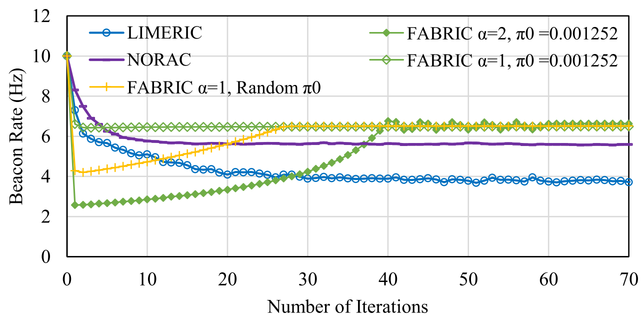

FIGURE 4. Beacon rate against number of iterations of the algorithms for a vehicle at x = 152 m on a track measuring 300 m in length.

fairness, too, with beacon rates between 5.5 and 6.5 Hz all over the track.

Figure 4 shows the beacon rate updates of a vehicle at position x = 152 m (almost the middle of the track). LIMERIC converges in 20 iterations and NORAC converges in fewer than 15 iterations. With iteration intervals of 500 ms (see Table 1) 15 iterations take 7.5 s. Actually, after the first few steps of the algorithm, the beacon rate is very close to the final value, which signifies the congestion level is controlled rapidly. This makes NORAC suitable for congestion control in dynamic VANET scenarios. There is a jump in beacon rate in the first iteration of FABRIC because it is updated in every iteration as:

$$r_i = \frac{1}{\left(\sum_N \pi_i\right)^{1/\alpha}} \tag{23}$$

Thus, the size of this jump depends on the initial values of π_i (π_i^0), α, and the number of vehicles. The recommended

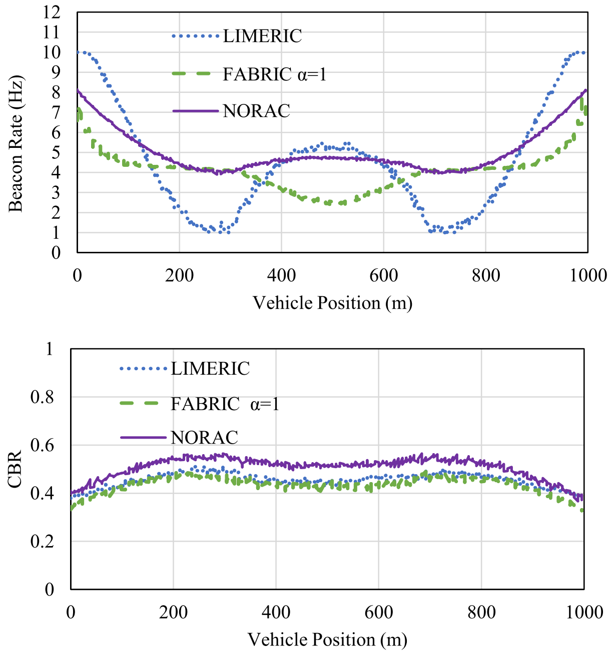

FIGURE 5. Beacon rate and CBR for N = 399 stationary vehicles on a track of length 1000 m with three lanes.

value of π_i^0 in [2] is given in Table 1. Using this value, at the first step, the algorithm for $\alpha = 1$ jumps to a point close to the final rate for this scenario and converges fast. To assume that all vehicles have equal π_i^0 is not realistic because vehicles change their π_i over time, and when they contribute to a congestion control scenario, they might have a different π_i than the recommended value.

For FABRIC, the beacon rate updates with $\alpha = 1$ when every vehicle i has a random value of π_i^0 between 0.001252 and 2×0.001252, is shown in Figure 4 for comparison. It is observed that the convergence time is much longer in this case. At every iteration of FABRIC, π_i is increased or decreased by β, which is a very small number (2.8×10^{-5}), and this generally results in a high number of iterations before convergence, and the convergence speed becomes heavily dependent on π_i^0. In subsequent simulation runs, it is still assumed that π_i^0 values are identical and equal to the recommended value, which seems to result in the best convergence time for FABRIC.

B. STATIONARY VEHICLES IN HIGHWAY SCENARIOS

In these experiments, the length of the tracks is more than one communication range, thus vehicles cannot receive beacons of all the other vehicles as beacons are one-hop broadcast messages. The first experiment comprises a track measuring 1000 m in length with 3 lanes and N = 399 vehicles distributed homogeneously along the track. Figure 5 shows beacon rates and CBRs for the algorithms, and Figure 6 shows changes in the beacon rate of a vehicle at the middle of the track at position x = 501 m. The LIMERIC unfairness is worse in this experiment, but it controls congestion efficiently and converges in about 30 iterations.

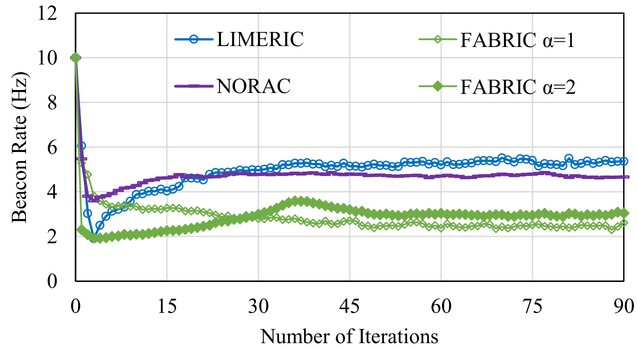

FIGURE 6. Beacon rate against number of iterations for the three algorithms for a vehicle at x = 501 m on a track of length 1000 m.

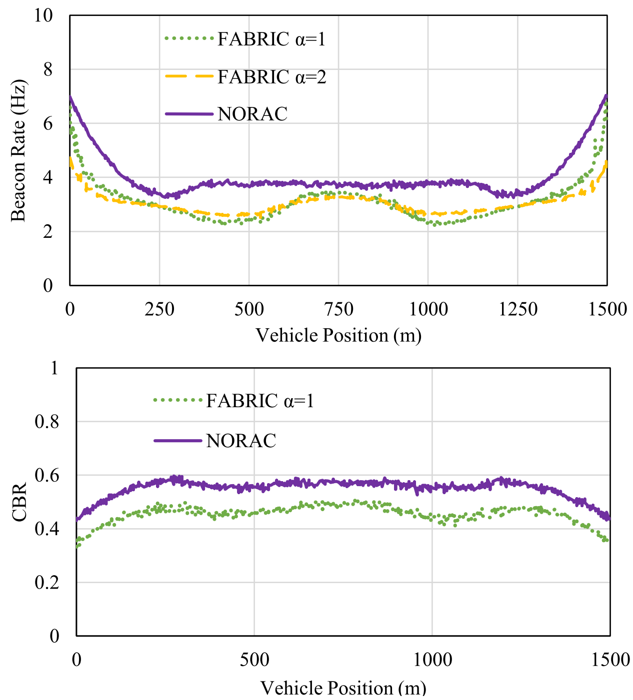

FIGURE 7. Beacon rate and CBR for N = 792 vehicles on a track of length 1500 m with four lanes.

With both $\alpha = 1$ and $\alpha = 2$, FABRIC almost converges to the same beacon rate and CBR after an adequate number of iterations. Hence, to keep the figures tidy, only the results for $\alpha = 1$ are shown. In FABRIC, vehicles communicate their parameters with their immediate neighbors. Thus, when the scenario is larger than one communication range, the algorithm loses its fairness. Similar to the experiment presented in Section VII-A, FABRIC with $\alpha = 1$ is faster than with $\alpha = 2$.

In NORAC, vehicles all over the track converge to a rate between 4 and 8 Hz. Vehicles which are far enough from the ends of the track, experience almost the same CBR and have rates between 4 and 5 Hz. Moreover, NORAC converges faster than the other alternatives considered herein.

Figures 7 and 8 show the same results for N = 792 vehicles on a track of length 1500 m with 4 lanes. Again, for vehicles

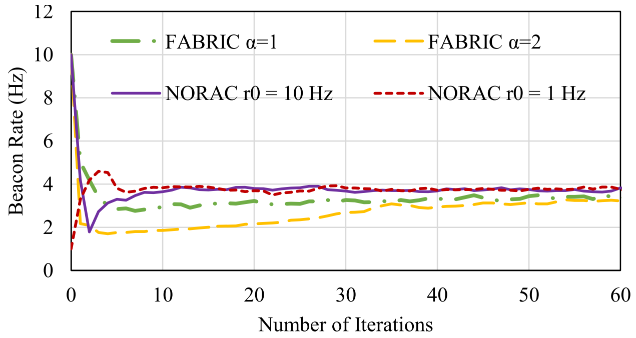

FIGURE 8. **Beacon rate against number of iterations for NORAC and FABRIC for a vehicle at x = 752 m on a track of length 1500 m with four lanes and N = 792 vehicles.**

far from the ends of the track, NORAC is fairer in terms of beacon rate. Both FABRIC and NORAC are quite efficient in controlling congestion. Figure 8 shows the beacon rate updates of the algorithms when the initial beacon rate is 10 Hz. It also shows the result for NORAC when the initial rate is 1 Hz. In both conditions, NORAC converges in about 5 iterations. The results for LIMERIC are not shown because it failed to provide fairness.

C. SCENARIOS WITH MOVING AND STATIONARY VEHICLES

In this experiment, both stationary and moving vehicles exist. In a dynamic scenario, it is desirable that vehicles with a higher speed use a higher beaconing rate to create a higher level of awareness. Thus far, u_i has been assumed to have the same constant value for all vehicles. However, this parameter (and pc_i) can be set per vehicle to meet the safety application and awareness requirements of that vehicle, which might be different from others. Vehicles moving at a speed of 10 m/s change their positions twice as fast as vehicles moving at a speed of 5 m/s. Then, in a congested scenario while the congestion level should be maintained under a desired level, vehicles moving at a higher speed should have a higher beaconing rate. In this section, it is shown that NORAC has awareness control property too. To this end, the following function is used instead of constant u_i:

$$u_i = [v_i]_4 \tag{24}$$

where v_i is the speed of vehicle i. In this way, every vehicle sets its utility parameter equal to its speed, and the minimum value of the utility parameter is 4. The minimum value is selected based on the experiments reported in Section VI and to prevent vehicles with very low speed from always using the minimum beaconing rate (1 Hz). Two points are worth noting. First, u_i can be selected as a function of speed, acceleration, or even vehicle position (for example, at junctions, when a higher beacon rate is desirable). It is not assumed that vehicle speed directly indicates the required awareness. The utility in (24) is selected to show, as an example, that every vehicle can control its bandwidth share with per vehicle

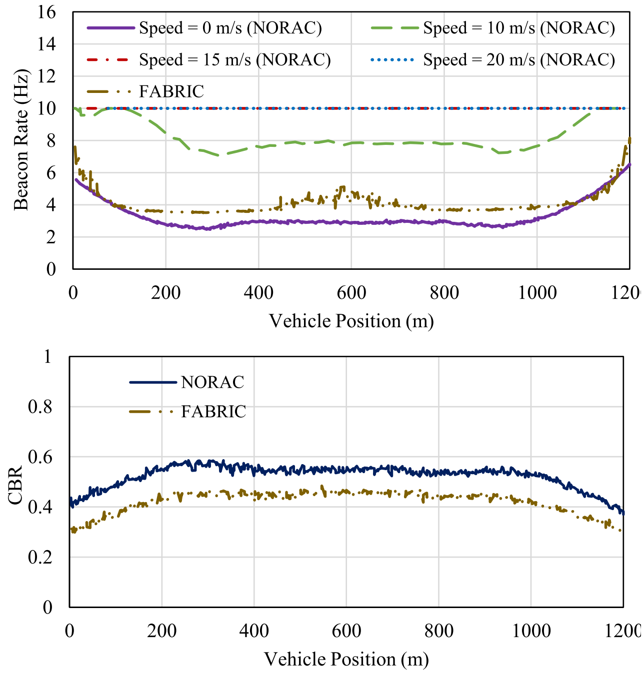

FIGURE 9. **Beacon rate and CBR for a track of length 1200 m with two lanes of stationary vehicles – Moving vehicles have speeds of 10, 15, and 20 m/s and $u_i = [v_i]_4$.**

parameter (u_i) and it is not necessarily equal to the speed. The utility in (24) is selected to show, as an example, how the algorithm functions. The design of u_i and pc_i can be based on safety requirements and is out of the scope of this paper. Second, every vehicle can set its u_i and pc_i parameters individually and does not need to communicate it with other vehicles.

Three experiments are conducted to show how NORAC can control awareness. All experiments comprise a track of length 1200 m with vehicles having speeds of 0, 10, 15, and 20 m/s. The first experiment has two lanes with stationary vehicles (316 stationary vehicles) and three lanes with vehicles moving at speeds of 10, 15, and 20 m/s; the vehicles set their u_i according to (24). In the second experiment, there are twelve lines, 6 of them are with stationary vehicles (3 × 316 stationary vehicles). The vehicles use the same u_i as in the first experiment. The third experiment has the same number of vehicles as in the first experiment but with $u_i = \left[v_{i/2}\right]_4$. The beacon rates and CBRs are shown in Figures 9-11, respectively.

In the three aforementioned experiments, congestion is controlled efficiently while, in each of them, vehicles with higher utilities (speeds) achieved higher beacon rates. Moreover, fairness in beaconing rate is maintained among vehicles with the same utility. In the first experiment, vehicles with speeds of 15 and 20 m/s do not contribute to congestion control because their utility is higher than those of the others, and congestion is not so high as to warrant their contribution.

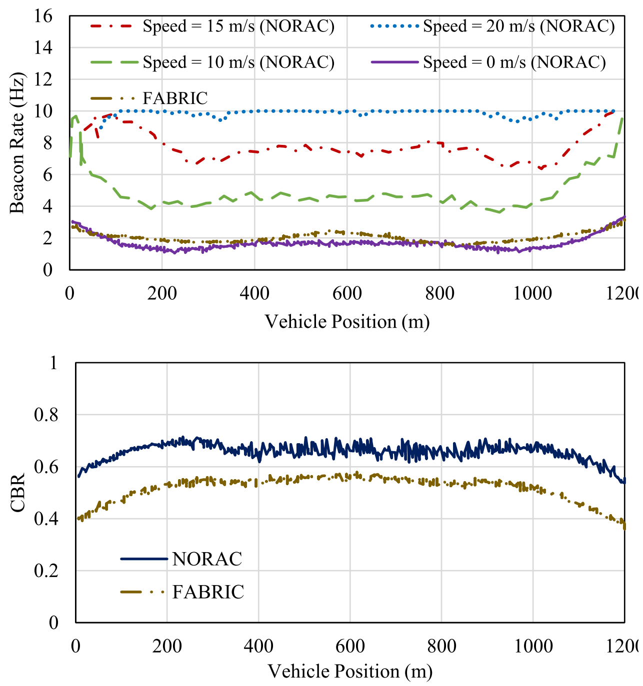

FIGURE 10. Beacon rate and CBR for a track of length 1200 m with 12 lanes – vehicles have different speeds of 0, 10, 15, and 20 m/s and $u_i = [v_i]_4$.

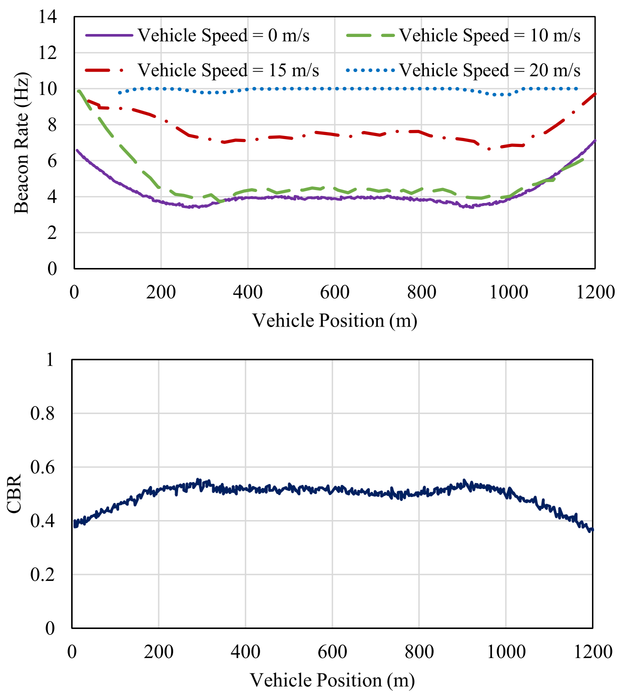

FIGURE 11. Beacon rate and CBR for a track of length 1200 m – vehicles have different speeds of 0, 10, 15, and 20 m/s and $u_i = [v_i/2]_4$.

The rate that vehicles obtained can be explained as follows: at the NE point for every vehicle, $\partial\varphi_i/\partial r_i = 0$ thus,

$$r_i + 1 = \frac{u_i\,(1 - CBR_i\,(\mathbf{r}))^2}{pc_i} \tag{25}$$

So for vehicles i and j with the same measured CBR (the same x-position),

$$\frac{r_i}{r_j} \approx \frac{u_i\,pc_j}{u_j\,pc_i} \tag{26}$$

For these experiments, the same pc_i is used for all vehicles. Therefore, the relation

$$\frac{r_i}{r_j} \approx \frac{u_i}{u_j} = \frac{[v_i]_4}{[v_j]_4} \tag{27}$$

is expected between the beacon rates of the vehicles at the same x-position because those vehicles sense the same CBR. In the first experiment, relation (27) is true for vehicles with speeds of 0 and 10 m/s. For example, at position x = 600 m, these vehicles have beacon rates of almost 3 and 8 Hz, respectively. For vehicles moving at higher speeds, the beacon rate is constrained by the maximum allowed rate (10 Hz).

In the second experiment with a larger number of vehicles, the beacon rates of stationary vehicles is almost the minimum rate, and vehicles moving at the speed of 15 m/s contribute to congestion control by reducing their beacon rates. The relation in (27) is observable among the beacon rates of vehicles with speeds of 0, 10, 15 m/s. For the vehicles far enough from ends of the track and with the same u_i, there is good fairness, with a difference of about 1 Hz in their beacon rates. In the third experiment, where vehicles have a smaller utility than those in experiments one and two, they contribute to congestion control with smaller CBRs. In Figure 11, the relation $r_i/r_j \approx u_i/u_j = [v_i/2]_4/\left[v_j/2\right]_4$ is observed among the rates of vehicles with speeds of 0, 10, 15 m/s and CBR is controlled around 0.5.

These experiments show that with NORAC, vehicles can share bandwidth based on their requirements, while congestion controlled to a desired level and fairness is ensured among the vehicles with the same requirements (utility).

The results for FABRIC are indicated in Figure 9 and Figure 10 too. FABRIC has parameter α, but experiments in Sections VII-A and VII-B showed that for different values of α, vehicles converged to the same beacon rate with different convergence speeds. Moreover, for larger α such as $\alpha = 6$, even for the experiments with only stationary vehicles, in Sections VII-A and VII-B, the beacon rate oscillates; thus, FABRIC assigns the same rate to all the vehicles apart from their speed. In LIMERIC, the parameters α and β can be set per vehicle [34], so vehicles with different parameters converge to different rates. However, in this situation, fairness is worse than that in the case where all vehicles have the same parameters, and the results are not comparable to those of NORAC.

D. CLUSTERS OF MOVING VEHICLES

In this experiment, two clusters of vehicles with N = 63 and 80 at speeds of 15 m/s and 10 m/s, respectively, move toward each other on a highway of length 1200 m. The utility introduced in (24) is used for this experiment for NORAC. Figure 12 shows the beacon rate and CBR at

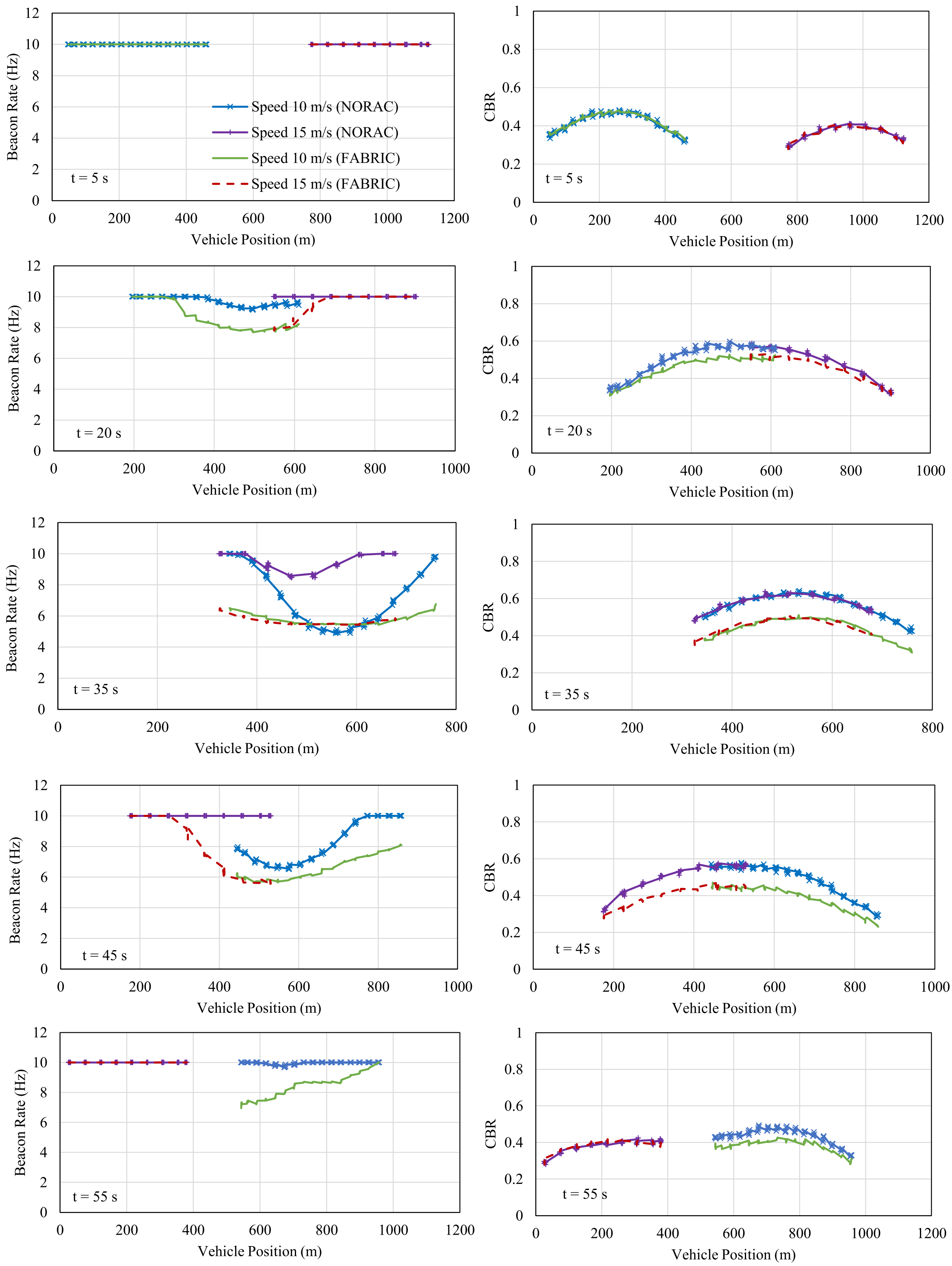

FIGURE 12. Beacon rate and CBR for two clusters of vehicles with speeds of 10 and 15 m/s and $u_i = [v_i]_4$. Note: the legend in the top graph applies to the all other graphs in this figure.

different times for FABRIC and NORAC. With NORAC, at t = 5 s, the vehicles in both the clusters use their maximum beaconing rate. At this time, the two clusters are far enough to not have any effect on each other's CBR and the number of vehicles in each cluster is not so large that they require to reduce their beacon rates.

As the two clusters move closer, first, the vehicles in the cluster with the lower utility start to reduce their rate as it is indicated in Figure 12 at t = 20 s. At t = 35 s, where the clusters have the maximum overlap, the relation (27) can be observed for the vehicles in the middle of the clusters. When the clusters move farther apart, the vehicles with the higher utility increase their rate earlier than those with the lower utility. While bandwidth is shared between two clusters in a manner proportional to their utilities, CBR is maintained below 0.65 level. This experiment indicates that NORAC is fast enough to be suitable for dynamic scenarios in VANETs.

With FABRIC, at t = 5 s vehicles work with their highest rate; hence, CBR and rate curves overlap completely those of NORAC. The figures at t = 45 s and t = 55 s show, vehicles return to the maximum rate slower with FABRIC than they do with NORAC. At t = 55 s vehicles are again far enough and CBR is almost around 0.4 in both clusters and vehicles in the larger cluster have not obtained their maximum rate yet. Equation (23) shows the beacon rate updates in FABRIC depend on the number of vehicles so the cluster with the lower number of vehicles returns to 10 Hz faster.

VIII. CONCLUSION

In this paper, a beacon rate and awareness control algorithm called NORAC, based on non-cooperative game theory, was proposed. A pay-off function for the game was presented and the existence and uniqueness of NE was proved. A sufficient condition for the stability of NE was derived mathematically. The gradient method was used to find NE in a distributed way. The presented algorithm was evaluated in several scenarios with stationary and moving vehicles and compared to state-of-the-art rate control algorithms. In the comparison, characteristics such as fairness, efficiency in controlling congestion, and processes speed were considered. The two compared algorithms can control congestion to below a desired level, although NORAC is considerably better in terms of fairness than the other two. NORAC demonstrated a short convergence time both in scenarios with stationary and moving vehicles. In the experiments, generally, NORAC converged in less than 20 iterations. In very rare cases, FABRIC can be faster than NORAC (for example in the scenario described in Section VII-A in which all the vehicles have the same initial Lagrange multipliers at the beginning of the process).

In addition to the above criteria used for comparison, NORAC is principally much better in its design than those congestion control mechanisms which achieve fairness by exchanging control information between nodes. Information exchange creates overhead and makes the system error-prone. Moreover, it cannot always solve the problem. As the simulation results showed, when the size of a congested area was larger than the range over which information can be shared, the unfairness problem appeared in FABRIC. Furthermore, in algorithms that exchange control information over more than one hop, the rate or range of vehicles that do not contribute to congestion might be reduced unnecessarily [2].

NORAC can also meet safety application requirements and assign a rate based on the requirement to every single vehicle, while controlling CBR and ensuring fairness among vehicles with the same requirement. This feature was evaluated in a number of dynamic scenarios where utility was a function of speed, so vehicles with higher speeds could achieve higher beacon rates.

APPENDIX
MATHEMATICAL MODEL FOR CBR

In this Appendix, the mathematical modeling of channel load presented in [35] is used to derive CBR. If there are $\mathcal{N}$ transmitters then the Channel load sensed by node i at position x is the sum of the load created by each one of those transmitters at point x; so we can write:

$$\begin{aligned} load_i(x) &= \sum_{n\in\mathcal{N}} load_n(x) \\ &= \sum_{n\in\mathcal{N}} sensible\ transmissions\ at\ x\ \times T_{frame} \end{aligned} \tag{28}$$

Where $T_f rame$ is the duration of received packets and $load_n(x)$ is the load created by node n at x and can be written:

$$load_n(x) = r_n\, Prob(d_n)\, T_{frame} \tag{29}$$

$Prob(d_n)$ is the probability of reception of the transmitted packet at distance d_n and r_n is packet rate of node n. By considering a Nakagami distribution for the received power p, we have:

$$PDF(p) = \left(\frac{m}{\Omega_n}\right)^m \left(\frac{p^{m-1}}{\Gamma(m)}\right) e^{-\frac{m}{\Omega_n}p} \tag{30}$$

where

$$\Omega_n = \frac{p_t \lambda^2}{(4\pi)^2 d_n^{\gamma}} \tag{31}$$

p_t is transmitted power, m is shape factor, d_n is the distance between sender and receiver and λ is the wavelength. Thus we can write:

$$prob(d_n) = \int_{C_{th}}^{\infty} PDF(p)\, dp = \tag{32}$$

By considering $t = \frac{m}{\Omega_n} p$ and $dp = \frac{\Omega_n}{m} dt$:

$$\begin{aligned} prob(d_n) &= \left(\frac{1}{\Gamma(m)}\right) \int_{\frac{mC_{th}}{\Omega_n}}^{\infty} t^{m-1} e^{-t} dt \\ &= \frac{\Gamma\left(m, \frac{mC_{th}}{\Omega_n}\right)}{\Gamma(m)} \end{aligned} \tag{33}$$

Therefore:

$$load_n(x) = r_n\, T_{frame} \frac{\Gamma\left(m, \frac{mC_{th}}{\Omega_n}\right)}{\Gamma(m)} \tag{34}$$

and the experienced CBR by node i is:

$$CBR_i(\mathbf{r}) = load_i(x) = \sum_{n\in\mathcal{N}} r_n\, T_{frame}\, \frac{\Gamma\left(m, \frac{mC_{th}}{\Omega_n}\right)}{\Gamma(m)} \quad (35)$$

Where $\mathbf{r}$ is vector of all the nodes' beacon rate.

REFERENCES

[1] Y. P. Fallah, C.-L. Huang, R. Sengupta, and H. Krishnan, "Analysis of information dissemination in vehicular ad-hoc networks with application to cooperative vehicle safety systems," *IEEE Trans. Veh. Technol.*, vol. 60, no. 1, pp. 233–247, Jan. 2011.

[2] E. Egea-Lopez and P. Pavon-Mariño, "Distributed and fair beaconing rate adaptation for congestion control in vehicular networks," *IEEE Trans. Mobile Comput.*, vol. 15, no. 12, pp. 3028–3041, Dec. 2016.

[3] M. Sepulcre, J. Gozalvez, O. Altintas, and H. Kremo, "Adaptive beaconing for congestion and awareness control in vehicular networks," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2014, pp. 81–88.

[4] T. Tielert, D. Jiang, Q. Chen, L. Delgrossi, and H. Hartenstein, "Design methodology and evaluation of rate adaptation based congestion control for vehicle safety communications," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Nov. 2011, pp. 116–123.

[5] B. Kim, I. Kang, and H. Kim, "Resolving the unfairness of distributed rate control in the IEEE WAVE safety messaging," *IEEE Trans. Veh. Technol.*, vol. 63, no. 5, pp. 2284–2297, Jun. 2014.

[6] S. Kuk and H. Kim, "Preventing unfairness in the ETSI distributed congestion control," *IEEE Commun. Lett.*, vol. 18, no. 7, pp. 1222–1225, Jul. 2014.

[7] R. K. Schmidt, T. Leinmuller, E. Schoch, F. Kargl, and G. Schafer, "Exploration of adaptive beaconing for efficient intervehicle safety communication," *IEEE Netw.*, vol. 24, no. 1, pp. 14–19, Jan./Feb. 2010.

[8] C.-L. Huang, Y. P. Fallah, R. Sengupta, and H. Krishnan, "Adaptive intervehicle communication control for cooperative safety systems," *IEEE Netw.*, vol. 24, no. 1, pp. 6–13, Jan./Feb. 2010.

[9] Y. P. Fallah, N. Nasiriani, and H. Krishnan, "Stable and fair power control in vehicle safety networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 3, pp. 1662–1675, Mar. 2016.

[10] G. Bansal, J. B. Kenney, and C. E. Rohrs, "LIMERIC: A linear adaptive message rate algorithm for DSRC congestion control," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4182–4197, Nov. 2013.

[11] E. Egea-Lopez, J. J. Alcaraz, J. Vales-Alonso, A. Festag, and J. Garcia-Haro, "Statistical beaconing congestion control for vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4162–4181, Nov. 2013.

[12] D.-M. Chiu and R. Jain, "Analysis of the increase and decrease algorithms for congestion avoidance in computer networks," *Comput. Netw. ISDN Syst.*, vol. 17, no. 1, pp. 1–14, 1989.

[13] M. Sepulcre, J. Mittag, P. Santi, H. Hartenstein, and J. Gozalvez, "Congestion and awareness control in cooperative vehicular systems," *Proc. IEEE*, vol. 99, no. 7, pp. 1260–1279, Jul. 2011.

[14] M. Sepulcre, J. Gozalvez, J. Harri, and H. Hartenstein, "Application-based congestion control policy for the communication channel in VANETs," *IEEE Commun. Lett.*, vol. 14, no. 10, pp. 951–953, Oct. 2010.

[15] S. Lasaulce and H. Tembine, *Game Theory and Learning for Wireless Networks: Fundamentals and Applications*. New York, NY, USA: Academic, 2011.

[16] J. K. MacKie-Mason and H. R. Varian, "Pricing congestible network resources," *IEEE J. Sel. Areas Commun.*, vol. 13, no. 7, pp. 1141–1149, Sep. 1995.

[17] E. Egea-Lopez and P. Pavon-Mariño, "Fair congestion control in vehicular networks with beaconing rate adaptation at multiple transmit powers," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 3888–3903, Jun. 2016.

[18] H.-H. Nguyen and H.-Y. Jeong, "Crosslayer beaconing design toward guaranteed cooperative awareness with contending traffic," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2015, pp. 131–134.

[19] G. Bansal, H. Lu, J. B. Kenney, and C. Poellabauer, "EMBARC: Error model based adaptive rate control for vehicle-to-vehicle communications," in *Proc. 10th ACM Int. Workshop Veh. Inter-Netw., Syst., Appl.*, 2013, pp. 41–50.

[20] M. A. Javed and J. Y. Khan, "Performance analysis of a time headway based rate control algorithm for VANET safety applications," in *Proc. IEEE 7th Int. Conf. Signal Process. Commun. Syst. (ICSPCS)*, Dec. 2013, pp. 1–6.

[21] H. Hartenstein and K. Laberteaux, *VANET Vehicular Applications and Inter-Networking Technologies*. New York, NY, USA: Wiley, 2009.

[22] F. Kelly, "Charging and rate control for elastic traffic," *Eur. Trans. Telecommun.*, vol. 8, no. 1, pp. 33–37, Jan./Feb. 1997.

[23] D. M. Topkis, "Equilibrium points in nonzero-sum n-person submodular games," *SIAM J. Control Optim.*, vol. 17, no. 6, pp. 773–787, 1979.

[24] T. Basar and G. J. Olsder, *Dynamic Noncooperative Game Theory*, vol. 23. Philadelphia, PA, USA: SIAM, 1999.

[25] A. Hefti, "On the relationship between uniqueness and stability in sum-aggregative, symmetric and general differentiable games," *Math. Soc. Sci.*, vol. 80, pp. 83–96, Mar. 2016.

[26] J. M. Carnicer, T. N. T. Goodman, and J. M. Peña, "Linear conditions for positive determinants," *Linear Algebra Appl.*, vol. 292, nos. 1–3, pp. 39–59, 1999.

[27] J. M. Peña, "A class of p-matrices with applications to the localization of the eigenvalues of a real matrix," *SIAM J. Matrix Anal. Appl.*, vol. 22, no. 4, pp. 1027–1037, 2001.

[28] J. B. Kenney, "Dedicated short-range communications (DSRC) standards in the United States," *Proc. IEEE*, vol. 99, no. 7, pp. 1162–1182, Jul. 2011.

[29] *IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Standard 802.11-1997, 2012.

[30] *OMNeT++ Discrete Event Simulator*. Accessed on Jun. 1, 2016. [Online]. Available: http://www.omnetpp.org/

[31] *Simulation of Urban MObility (SUMO)*. Accessed on Jun. 1, 2016. [Online]. Available: http://sumo.sourceforge.net/

[32] *IEEE Guide for Wireless Access in Vehicular Environments (WAVE)—Architecture*, IEEE Standard 1609.0-2013, 2013.

[33] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE)—Multi-Channel Operation*, IEEE Standard 1609.4-2016, 2016.

[34] G. Bansal and J. B. Kenney, "Achieving weighted-fairnessin message rate-based congestion control for DSRC systems," in *Proc. IEEE 5th Int. Symp. Wireless Veh. Commun. (WiVeC)*, Jun. 2013, pp. 1–5.

[35] Q. Chen, D. Jiang, T. Tielert, and L. Delgrossi, "Mathematical modeling of channel load in vehicle safety communications," in *Proc. IEEE Veh. Technol. Conf. (VTC Fall)*, Sep. 2011, pp. 1–5.

FOROUGH GOUDARZI received the M.Sc. degree in electrical engineering from the Sharif University of Technology, Tehran, Iran. She is currently pursuing the Ph.D. degree in electrical engineering with Brunel University London. She is also a Senior Research Assistant with the Transport Research Group, University of Southampton, U.K. Her research interests include VANETs and applications of game theory in wireless networks.

HAMID ASGARI (SM'03) received the Ph.D. degree in electrical and electronics engineering from the University of Wales, Swansea, U.K., in 1997. He has been with Thales Research, Technology and Innovation, U.K., since 1996, where he has been a Chief Technical Consultant. He is also a Visiting Professor with King's College London. He is highly experienced and skilled professional in leading large Research and Development teams, a technical expert in data communication networks, and security subjects. He has been leading the Research and Development teams and participating in collaborative European Commission projects since the year 2000. He is the Network Technical Lead working in Advanced and Future Networking and Security Concepts including Information and Cyber Security, Multi-Level Security, Wired/Wireless Networks Architectures and Technologies, Network, Service and Quality of Service Management. He has a proven track record and published 60 book chapters and papers in the most respected scientific journals and peer-reviewed conferences. He is an IET Fellow and Senior member of the ACM.