



Fair and stable joint beacon frequency and power control for connected vehicles

Forough Goudarzi¹ · Hamid Asgari² · Hamed Safa Al-Raweshidy³

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Abstract

In vehicular communications, periodic one-hop broadcast of beacons allows cooperative awareness for vehicles. To avoid congestion in the shared channel used for transmission of beacons, a joint beacon frequency and power control protocol based on game theory is presented in this paper. The existence, uniqueness and stability of the Nash Equilibrium (NE) of the game is proved mathematically. An algorithm is devised to find the equilibrium point in a distributed manner and its stability and convergence has been validated using simulation. The algorithm converges to the NE from any initial frequency and power and it can provide both fairness in power and weighted fairness in frequency. The protocol has per vehicle parameters, hence, every vehicle can control its share of the bandwidth according to its dynamics or safety application requirements while the whole usage of bandwidth is controlled at a desired level.

Keywords Beacon frequency and power adjustment · Channel congestion control · Fairness · Stability · VANETs

1 Introduction

In Vehicular Ad hoc Networks (VANETs), vehicles periodically broadcast their kinematic information in Basic Safety Messages (BSMs), also called beacons. The message broadcast enables vehicles cooperative awareness to support the safety applications in VANETs. In dense vehicular environments, uncontrolled broadcast of beacons results in channel congestion and consequently beacon loss, which degrades cooperative awareness and the accuracy of safety applications. The maximum level of awareness is obtained when the channel load is controlled around 0.65 [1]. Therefore controlling channel load around 0.65 was the main purpose for design of many congestion control mechanisms for VANETs [2–9].

There are other important factors that should be considered in the design of congestion control mechanisms. Fair access to the wireless channel for vehicles creates

awareness with respect to surrounding vehicles in a fair manner, which is necessary to make the safety applications of VANETs reliable. Fairness has significant impact on the performance of safety applications of VANETs. If some vehicles are assigned lower power or frequency, nearby vehicles would not be notified of them early enough and this might result in danger. Besides, a beaconing strategy should be able to assign more bandwidth to vehicles that are in more dangerous situations and require to create higher level of awareness; for example, those that have higher speed or are changing lane. The other important requirement of a congestion control mechanism is stability. This guarantees that vehicles can obtain and maintain the required transmission parameters for the application that they are running.

To address the problem of channel congestion, several solutions based on adaption of beacon transmission parameters such as transmission frequency, power and bit rate have been proposed [2–21]. Many of these approaches just adapt one of the beacon transmission parameters, however, it is very likely that approaches that adapt more than one parameter are used in the future VANETs. In this paper, a fair and stable joint BSM frequency and power control algorithm called BFPC based on non-cooperative game theory is proposed. The joint beacon power

✉ Forough Goudarzi
Forough.Goudarzi@ieee.org

¹ Nottingham Trent University, Nottingham, UK

² Thales Research Technology and Innovation, Reading, UK

³ Brunel University London, London, UK

and frequency control mechanism is modeled as a non-cooperative game in which the strategy spaces of the players (vehicles) are two dimensional (frequency and power). The existence, uniqueness and stability of the Nash Equilibrium (NE) of the game is proved mathematically. The algorithm converges to a stable beacon frequency and power from any initial point and it can provide both fairness in power and weighted fairness in frequency. The weighted fairness is useful in a congested situation where different vehicles require different beaconing frequencies. The algorithm has per vehicle parameters, therefore, every vehicle can control its share of the bandwidth (its beaconing frequency), while the whole usage of bandwidth is controlled at a desired level. The purpose of this paper is not to suggest any criteria (such as accuracy in tracking error) for adaption of beaconing frequency, however, the proposed algorithm has such capability without high computational burden, just by adapting the algorithm parameters. An advantage of the proposed approach is that it is overhead free, while most of the previous approaches rely on the exchange of extra information in beacons over one or two hops to obtain fairness.

The contributions of this paper are as follows.

- The mechanism of beaconing congestion control has been modeled as a non-cooperative game.
- The proposed BFPC protocol can provide fairness in beacon power and weighted fairness in frequency.
- BFPC has per vehicle parameters that can address individual vehicle beaconing requirements.
- The protocol is stable, overhead free and computationally inexpensive.

This paper is the extension of our previous works [2] and [22]. In [2] and [22] vehicles adapt just one of their beacon frequency or power. In this work vehicles adapt both their frequency and power. The remainder of the paper is organized as follows. Section 2 presents a brief background on non-cooperative games then reviews congestion control mechanisms that adapt more than one BSM transmission parameters. Section 3 introduces the problem of beaconing congestion control as a non-cooperative game. Then, the proof of existence, uniqueness and stability of the NE and a stable algorithm to find the NE are presented. In Sect. 4, the performance of the proposed congestion control algorithm is evaluated and finally, Sect. 5 concludes the paper.

2 Background and related work

2.1 Non-cooperative game

A situation is referred to as a game when several entities are involved in the situation and the outcome of the

situation for an entity depends not only on what the entity does but also what the other entities do. The entities are referred to as decision-makers or players of the game. Game theory is a mathematical study of the interactions between the players who might have conflicting or common interests. Game theory deals with designing interaction models, studying the conditions that some outcome can be achieved and designing strategies to reach desired outcomes [23]. A non-cooperative game is a game in which players take their actions without any agreement with other players.

A game can be represented in different types. In this paper, a non-cooperative game in the strategic or normal form [24] has been used, then just these games are introduced. A strategic form game is a triplet $\mathcal{G} = \{\mathcal{N}, \{\mathcal{S}_i\}_{i \in \mathcal{N}}, \{Q_i\}_{i \in \mathcal{N}}\}$ where $\mathcal{N} = \{1, 2, \dots, N\}$ is the set of players, \mathcal{S}_i is the set of strategies of player i and Q_i is the payoff function of player i that gives the player i the value $Q_i(s)$ for each strategy profile $s = \{s_1, s_2, \dots, s_n\} \in \prod_{i=1}^N \mathcal{S}_i$. Nash Equilibrium (NE) is a key concept in game theory. It is the profile of strategies such that each player's strategy is an optimal response to the other players' strategy [24]. In mathematical terms, the vector \mathbf{s}^* is an NE if:

$$\forall i \in \mathcal{N}, \forall s_i \in \mathcal{S}_i, Q_i(s_i^*, \mathbf{s}_{-i}^*) \geq Q_i(s_i, \mathbf{s}_{-i}^*) \quad (1)$$

where \mathbf{s}_{-i} is a vector of strategies of all the players except player i . In other words, an NE is the point that no player has incentive to change its strategy unilaterally and it is the solution of the non-cooperative game involving rational players.

2.2 Related work

In [14] a vehicle computes a target distance within that, beacons should be received. Then, the required power to cover the target distance is found using a lookup table. The beacon frequency is adapted in an allowed range to keep channel load under a maximum allowed level. The protocol lacks details for implementation and the performance of the approach was not evaluated. In [13] vehicles first decrease their beacon frequency until the minimum frequency is reached then reduce their power until collision rate and channel load are lower than some threshold levels. The frequency and power adaptation approach used in [13] results in unfair beaconing transmission frequency and power [8, 9].

ETSI proposed several techniques for DCC which are: (1) transmit frequency control, (2) transmit power control, (3) receiver sensitivity control, (4) transmit data rate control, and (5) transmit access control [25]. ETSI DCC can be implemented by applying one or a combination of several of these techniques. To implement ETSI DCC using the

mentioned techniques, ETSI defines a State Machine (SM) that has three states: RELAXED, RESTRICTIVE and ACTIVE [12]. The ACTIVE state can have multiple sub-states. In each state, vehicles use different transmission or receiver parameters. The transition between the states happens based on measured channel load. Channel load is represented by Channel Busy Ratio (CBR), which is the ratio of the time that the channel is busy to the sampling time. Figure 1 shows the SM with one ACTIVE state in which CBR_{max} and CBR_{min} are threshold channel loads for changing states. If channel load passes a threshold and this condition continues for a specific time (1 second or 5 seconds as indicated in Fig. 1) the state changes.

Several studies have revealed that ETSI DCC suffers unfairness and oscillation [26–28]. In [26] a DCC that used methods (1) to (4) simultaneously was evaluated and it indicated that ETSI DCC is unstable and unfair. In [28] by adapting just transmit frequency control, the instability of the method was demonstrated. In [27] DCC techniques (1), (2) and (4) individually and also where the three techniques are simultaneously active, were evaluated. In all of them, instability in the state of vehicles was observed.

An algorithm for joint beacon frequency and power control, which is called algorithm X, is being adopted as standard in the US [29, 30]. This method was first proposed in [10]. In algorithm X, a vehicle increases its frequency when it suspects that the estimated Position Tracking Error (PTE) of neighboring vehicles towards its position has increased. For this purpose, in every defined time step, vehicles compute beacon transmission probability based on the suspected PTE on neighboring vehicles toward its own position. If the suspected error is smaller than a threshold, there is 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 measured CBR by a 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 mapping.

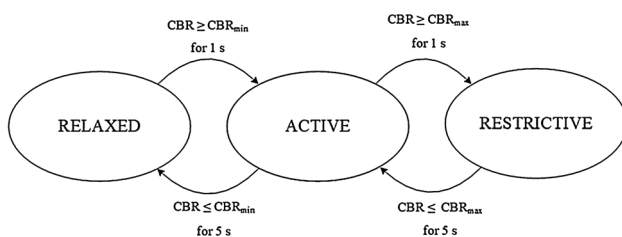


Fig. 1 The State Machine defined by ETSI for distributed congestion control

Adapting beaconing frequency based on PTE cannot always create the required awareness. There are situations where, although the PTE of vehicles is low, vehicles require high beaconing frequencies. For example, when vehicles are close to a junction even if they have low speed or are stationary [31]. Moreover, investigation in [30] revealed that considering information such as acceleration and speed instead of PTE to adapt beaconing frequency increases the performance of safety applications. In addition, the power control approach used in the algorithm results in unfairness in beacon transmission power [6].

In [18] beacon adaptation mechanism is relied on three parameters, the local density of vehicles, the CBR and the collision rate that are computed by vehicles. The local density of vehicles is predicted for short horizon of 100 ms. Then, if any of the above parameters is not in a predefined range, the beaconing adaption is triggered. If the parameter is higher than a defined threshold, first the beacon frequency is reduced until the frequency reaches a minimum level then, the transmission power is reduced. If the parameter is lower than a threshold, first the transmission power is increased to reach the highest level then the transmission frequency is increased. In this work, the beaconing requirements of safety applications has not been addressed. In addition, the mechanism creates overhead as vehicles require information on other vehicles outside their one-hop neighborhood to be able to predict the local density of vehicles for near future. Vehicles provide this information for their neighbors by including a few excess bytes of information in their beacons.

In [20] a distributed beacon congestion control (DBCC) scheme was proposed so that vehicles with more neighbors and better link quality with its neighbors will have higher beacon frequency. In DBCC, machine learning was used to predict quality of links of vehicles with their neighbors then based on the predicted quality, a parameter called link weight is calculated for every vehicle. A maximization problem of the beacon frequency adaptation under a TDMA broadcast MAC is formulated and a greedy heuristic algorithm is proposed to solve the problem. Fairness and application requirements of beaconing have not been considered in DBCC. In addition, each vehicle broadcasts the information of link weights of itself and its one-hop neighbors in its beacons.

ML-CC [19] is a centralized congestion control strategy for junction areas in which, RSUs assign the beacon transmission parameters to vehicles. These parameters are data rate, transmission power and contention window size and AIFS of MAC protocol. Using unsupervised K-mean clustering algorithm, RSU classifies the received beacon messages in four clusters. Then the transmission parameters that minimize the communication delay for the

centroid of each cluster is selected. RSU sends these parameters to the vehicles at the congested junction.

EPCR [21] is a combined power and frequency distributed congestion control algorithm. It adjusts the transmission power of beacons based on a desired target distance that beacons should reach at and adjusts beaconing frequency in order to control the channel load. To adapt transmission power each vehicle requires to estimate path loss exponent (PLE) of the wireless environment. To estimate PLE, vehicles need to know transmission power of their neighbors. Therefore, every vehicle should include its beacon transmission power in its beacon messages. The estimated PLE is used to compute the required transmission power so that the beacon messages reach to a desired distance which is set by application. For channel load control, beacon frequency is adapted by applying LIM-ERIC [3].

In [17] a Joint Adaptation of Transmission power and Bit rate (JATB) algorithm was presented. JATB presents a lookup table that vehicles can pick up the transmission power and bit rate based on the estimated number of their one-hop neighbors. The lookup table was produced by solving an optimization problem that maximizes packet success rate and minimizes end-to-end delay and busy time.

3 Non-cooperative beacon frequency and power control (BFPC) game

The non-cooperative beacon power and frequency control game is explained in this section. For easy reference, Table 1 lists the notation used in this paper.

Let $\mathcal{G} = \{\mathcal{N}, \{\mathcal{X}_i\}_{i \in \mathcal{N}}, \{\mathcal{Q}_i\}_{i \in \mathcal{N}}\}$ denote the BFPC game, where $\mathcal{N} = \{1, 2, \dots, N\}$ is the set of players (vehicles), and $\mathcal{X}_i \subset \mathbb{R}^2$ is the set of two-tuples $x_i = (p_i, r_i)$ of possible beaconing powers and frequencies for player i . \mathcal{X}_i is called the strategy set of player i , and the tuple $x_i \in \mathcal{X}_i$ is called the strategy of player i . Each player selects its strategy independently. The vector $\mathbf{x} = (x_1, x_2, \dots, x_N) \in \mathbf{X}$ shows the selected power and frequency of all the players, where $\mathbf{X} = \prod_{i=1}^N \mathcal{X}_i$. The expression \mathcal{Q}_i is the payoff function of player i and is indicated as $\mathcal{Q}_i(\mathbf{x}) = \mathcal{Q}_i(x_i, \mathbf{x}_{-i})$, where \mathbf{x}_{-i} denotes the vector consisting of the beacon powers and frequencies of all the players except the i th player.

The payoff functions $\mathcal{Q}_i(\mathbf{x})$ are defined as follows:

$$\begin{aligned} \mathcal{Q}_i(x_i, \mathbf{x}_{-i}) &= U_i(x_i) - J_i(x_i, \mathbf{x}_{-i}) \\ &= u_i \ln(r_i + 1) + w_i \ln(p_i + 1) - \frac{c_i p_i}{1 - CBR_i(\mathbf{x})} \end{aligned} \tag{2}$$

Table 1 Notations

\mathcal{N}	The set of players (vehicles)
N	The number of players
p_i	The transmission power of player i
r_i	The beacon frequency of player i
x_i	Two-tuple (p_i, r_i) , strategy of player i
\mathbf{x}	The vector of strategies of all players
\mathbf{x}_{-i}	The vector of strategies of all players except player i
\mathcal{X}_i	The strategy set of player i
\mathbf{X}	The strategy space of all players
U_i	The utility function of player i
J_i	The price function of player i
\mathcal{Q}_i	The pay-off function of player i
CBR_i	Channel busy ratio that player i experiences
m	Nakagami fading parameter
T_{frame}	Required time to transmit a beacon message
λ	Wavelength
d_{ij}	Distance between players i and j
γ	Path loss exponent
C_{Tl}	Carrier sense threshold level
c_i, u_i, w_i	Positive parameters of price, frequency and power utility

where u_i, w_i and c_i are the positive parameters of frequency utility, power utility, and price, respectively. The $CBR_i(\mathbf{x})$ is the channel load that player i experiences. Payoff functions (2) consist of a utility function $U_i(x_i) = u_i \ln(r_i + 1) + w_i \ln(p_i + 1)$ and a price function [32] $J_i(x_i, \mathbf{x}_{-i}) = c_i p_i / (1 - CBR_i(\mathbf{x}))$. By increasing beaconing frequency or power, both the utility function and the price function are increased. In high channel load, the price function would be greater which discourages the vehicles of using high beacon frequency or power, so this leads to control the channel load.

The derived $CBR_i(\mathbf{x})$ in [2] which is based on the mathematical model of channel load in [33] as follows is employed for $CBR_i(\mathbf{x})$.

$$CBR_i(\mathbf{x}) = \sum_{j=1}^N T_{frame} \times \frac{\Gamma\left(m, \frac{mC_{Tl}}{\Omega_{ij}}\right)}{\Gamma(m)} r_j = \sum_{j=1}^N h_{ij} r_j \tag{3}$$

where

$$\Omega_{ij} = \frac{p_j \lambda^2}{(4\pi)^2 d_{ij}^2} \tag{4}$$

and

$$h_{ij} = T_{frame} \times \frac{\Gamma\left(m, \frac{mC_{Tl}}{\Omega_{ij}}\right)}{\Gamma(m)} \tag{5}$$

and $\Gamma(\cdot)$ is the Gamma function, $\Gamma(\cdot, \cdot)$ is the Upper Incomplete Gamma function, C_{T_i} is the threshold power level of carrier sense, p_j is transmitter power of player j , d_{ij} is the distance between j th and i th 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 transmit a beacon message.

Eq.(3) indicates the channel load that player i experiences is a weighted sum of beaconing frequencies of all the other players $(\sum_{j=1}^N h_{ij}r_j)$. The weights (h_{ij}) are a function of beacon power of the players (p_j) and distance between players (d_{ij}) .

It is worth noting that $CBR_i(\mathbf{x})$ is independent of p_i because d_{ii} in (4) is zero. Therefore, p_i has been considered as a coefficient in the price function so that for player i , the price of using network resources increases by increasing beacon power. In addition, it is easily verified that $h_{ii} = T_{frame}$. Furthermore, the sum over all the nodes of the network in (3) does not mean that all the nodes should be in communication range of each other. For more information on the mathematical model used for $CBR_i(\mathbf{x})$ the reader is referred to [2].

3.1 Existence of Nash Equilibrium (NE)

The payoff functions (2) are twice differentiable. Thus, the game is a submodular game if (6) and (7) hold [34, 35].

$$\forall i \in \mathcal{N}, \frac{\partial^2 Q_i}{\partial r_i \partial p_i} \leq 0 \tag{6}$$

$$\forall i, j \in \mathcal{N}, i \neq j, \frac{\partial^2 Q_i}{\partial y_i \partial z_j} \leq 0 \tag{7}$$

where y and z could be r or p . For BFPC we have:

$$\frac{\partial^2 Q_i}{\partial r_i \partial p_i} = -\frac{c_i h_{ii}}{(1 - CBR_i(\mathbf{x}))^2} < 0 \tag{8}$$

$$\frac{\partial^2 Q_i}{\partial r_i \partial r_j} = -\frac{c_i p_i h_{ii} h_{ij}}{(1 - CBR_i(\mathbf{x}))^3} < 0 \tag{9}$$

$$\frac{\partial^2 Q_i}{\partial p_i \partial p_j} = -\frac{c_i \frac{\partial CBR_i(\mathbf{x})}{\partial p_j}}{(1 - CBR_i(\mathbf{x}))^2} \tag{10}$$

$$= -\frac{c_i r_j h_{ii}}{\Gamma(m)(1 - CBR_i(\mathbf{x}))^2} \times \frac{(k_{ij})^m}{p_j^{m+1}} e^{-\frac{k_{ij}}{p_j}} < 0$$

$$\frac{\partial^2 Q_i}{\partial r_i \partial p_j} = -\frac{c_i r_j p_i h_{ii}^2}{\Gamma(m)(1 - CBR_i(\mathbf{x}))^3} \times \frac{(k_{ij})^m}{p_j^{m+1}} e^{-\frac{k_{ij}}{p_j}} < 0 \tag{11}$$

$$\frac{\partial^2 Q_i}{\partial p_i \partial r_j} = -\frac{c_i h_{ij}}{(1 - CBR_i(\mathbf{x}))^2} < 0 \tag{12}$$

where

$$k_{ij} = \frac{m C_{T_i} (4\pi)^2 d_{ij}^m}{\lambda^2} \tag{13}$$

Thus, BFPC is a submodular game and the set of its equilibrium points is nonempty [34].

3.2 Uniqueness of NE

Uniqueness of equilibrium point is very important for non-cooperative games. In such games, players do not communicate their strategies with other players therefore, in case of existence of more than one equilibrium point the game might not converge to the desired point. In this section, it is proved that if the BFPC game has two equilibrium points these points should be the same.

A submodular game has a greatest and a least equilibrium point (Theorem 3.1 in [34]). Therefore, if \mathbf{x}_1 and \mathbf{x}_2 are the greatest and the least equilibrium points of BFPC, respectively, we have

$$\forall i \in \mathcal{N}, \forall p_{1i}, r_{1i} \in \mathbf{x}_1 \& p_{2i}, r_{2i} \in \mathbf{x}_2 \tag{14}$$

$$p_{1i} \geq p_{2i} \& r_{1i} \geq r_{2i}$$

at equilibrium point:

$$\frac{\partial Q_i}{\partial p_i} = \frac{w_i}{p_i + 1} - \frac{c_i}{1 - CBR_i(\mathbf{x})} = 0 \tag{15}$$

Thus,

$$p_{1i} + 1 = \frac{w_i(1 - CBR_i(\mathbf{x}_1))}{c_i} \tag{16}$$

and

$$p_{2i} + 1 = \frac{w_i(1 - CBR_i(\mathbf{x}_2))}{c_i} \tag{17}$$

As $p_{1i} \geq p_{2i}$, considering (16) and (17), we should have $CBR_i(\mathbf{x}_1) \leq CBR_i(\mathbf{x}_2)$; because CBR is an increasing function with respect to all p_i and r_i , then this is not possible unless we have

$$\forall i \in \mathcal{N}, p_{1i} = p_{2i} \& r_{1i} = r_{2i} \tag{18}$$

Therefore, the NE is unique.

3.3 Stability of NE under gradient dynamics

The unique equilibrium point of a submodular game is globally stable and gradient dynamics converge to the equilibrium point from any initial point (Theorem 2.1 in [35]). Therefore, every vehicle i requires to updates its

frequency and power as (19) shows so that reaches the equilibrium point.

$$p_i \leftarrow p_i + \frac{\partial Q_i}{\partial p_i}, r_i \leftarrow r_i + \frac{\partial Q_i}{\partial r_i} \quad (19)$$

Algorithm 1 shows the BFPC mechanism for frequency and power adaptation based on the gradient dynamics where r_{min} , r_{max} , p_{min} and p_{max} are the minimum and maximum allowed beacon frequency and power. As Algorithm 1 shows, no share of information between the vehicles is required in the Algorithm and every vehicle updates its frequency and power using local information. Therefore, it has no overhead. In contrast, in other congestion control mechanisms such as mechanisms presented in [4–6, 8, 9], some information should be communicated between vehicles so that the mechanism works. This information depend on the mechanism could be the CBR that each vehicle experience, the beacon frequency or beacon power of the vehicles or the number of vehicles each vehicle has in its neighborhood.

Table 2 Simulation parameters

Parameter	Value
Carrier frequency	5.89 GHz
Thermal noise	– 100 dBm
Carrier sense threshold	– 90 dBm
MAC protocol	IEEE 802.11p
Bit rate	6 Mbps
Beacon size	500 Bytes
Sampling time	500 ms
Propagation model	Nakagami $m = 2.0$
r_{min}, r_{max}	1, 10 Hz
p_{min}, p_{max}	1, 100 mW

Algorithm 1 Beacon power and frequency update based on the gradient dynamics

- 1: Every vehicle measures CBR
- 2: Every vehicle updates its beacon power according to:

$$p_i \leftarrow \left[p_i + \frac{w_i}{p_i + 1} - \frac{c_i}{1 - CBR_i(\mathbf{x})} \right]_{p_{min}}^{p_{max}}$$

- 3: Every vehicle updates its beacon frequency according to:

$$r_i \leftarrow \left[r_i + \frac{u_i}{r_i + 1} - \frac{c_i p_i T_{frame}}{(1 - CBR_i(\mathbf{x}))^2} \right]_{r_{min}}^{r_{max}}$$

4 Simulation results

Simulations have been conducted to validate the stability and convergence of BFPC algorithm as well as to indicate its performance in different scenarios. For simulations, OMNeT++ [36] as network simulator and SUMO [37] as mobility generator were used. Simulation parameters are as indicated in Table 2.

4.1 Scenarios with stationary vehicles

For the experiments in this section, a 1000 m track with stationary vehicles distributed homogeneously was modeled. The experiments were performed in two conditions (1) when the track has three lanes with 396 vehicles and (2) when the track has five lanes with 660 vehicles. The

vehicles update their beacon power and frequency according to the Algorithm 1. Asynchronous or synchronous beacon updates do not change the results and the algorithm converges to the same beacon power and frequency. For bit rate of 6 Mb/s and beacon size of 500 Bytes, T_{frame} in Algorithm 1 is equal to 6.6×10^{-4} . To validate the convergence of the algorithm from any initial point, the vehicles at the beginning of the simulation have random frequency and power, as Fig. 2 shows.

First we study the effect of Parameters w_i , c_i and u_i on BFPC. Figure 3 shows the results of experiments in condition 1 described above, with constant $u_i = 4$ and different w_i , c_i . Vehicles with higher power utility w_i use higher level of beacon power as this increases their pay-off function. Besides, with increasing price parameter c_i vehicles have less incentive to use channel capacity and use

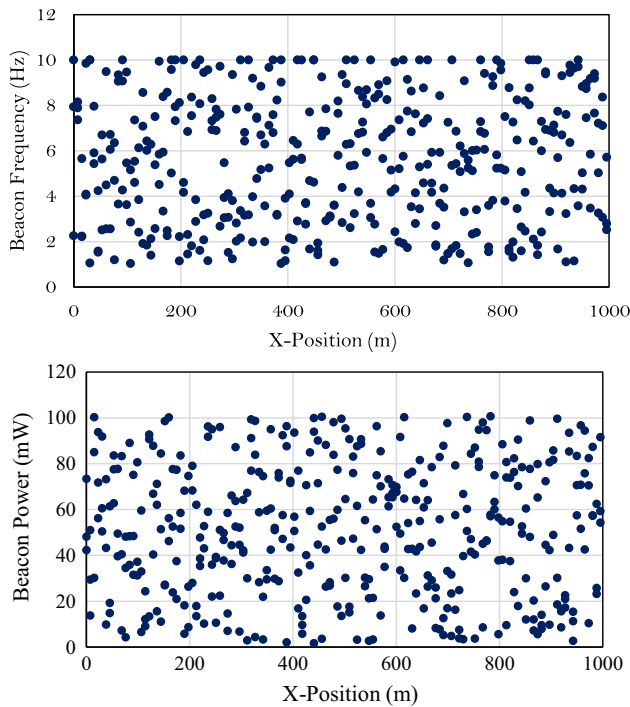


Fig. 2 Initial beacon frequency and power of the vehicles over the 1000 m track with three lanes

less power and frequency therefore, CBR is controlled in a lower level.

Figure 4 shows the effect of u_i on the outcome of BFPC. Simulations were run with parameters $w_i = 650$, $c_i = 3$, and two values for u_i , 4 and 10 in both conditions 1 and 2 described above. Greater utility parameter u_i leads to use of higher frequency by vehicles because the utility function in (2) increases.

With $u_i = 4$ and 396 vehicles (track with 3 lanes), the vehicles contribute to congestion control simply by adapting their frequencies. By increasing the number of vehicles, the vehicles reduce both their power and frequency to control the channel congestion. With $u_i = 4$, the vehicles obtain lower beacon frequency in comparison with when $u_i = 10$. In addition, it is observed that with $w_i = 650$ and $c_i = 3.0$ for a range of u_i (the results are shown only for $u_i = 4$ and $u_i = 10$), CBR is controlled in the desirable interval 0.4 to 0.8. This feature is used in the Section 4.2 to assign a higher frequency to the vehicles that need higher beaconing frequency e.g. due to higher speed or the beaconing requirement of a safety application. In all the presented configurations, good fairness in frequency and power is observed and the vehicles that are far enough from the edges of the track almost have the same beaconing frequency and power. In addition, the achieved beaconing frequency and power is stable.

Figure 4 also shows the results of experiment in condition 2 by applying JATB congestion control mechanism.

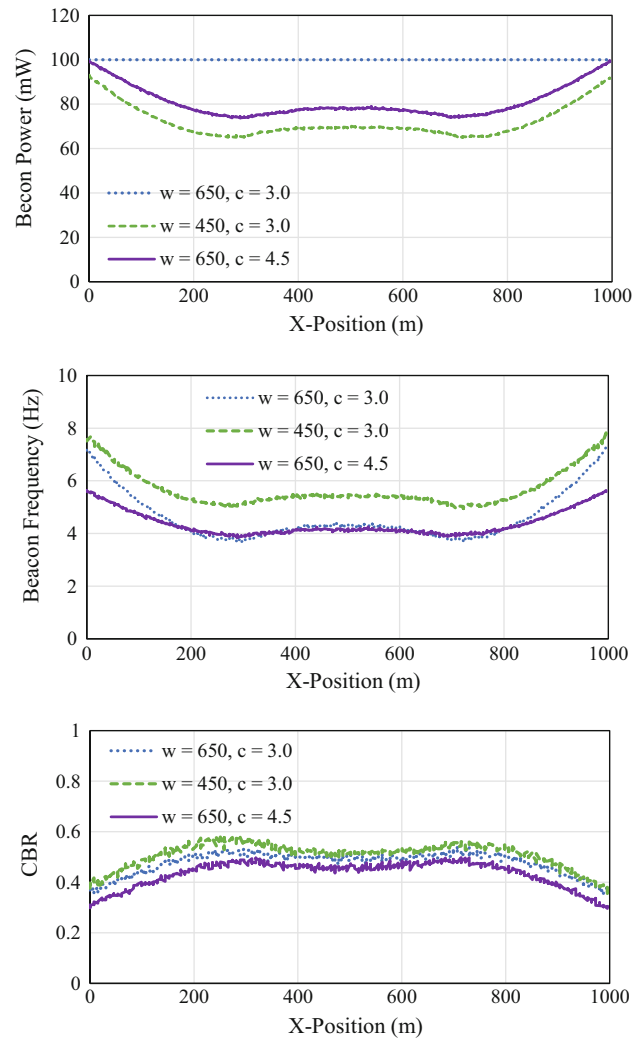


Fig. 3 Beacon power and frequency and CBR over the 1000 m track with stationary vehicles in three lanes with $u_i = 4.0$ and different w_i and c_i

JATB tunes the transmission parameters based on the number of neighboring vehicles. In this experiment, vehicles simply pick up the lowest transmission power in JATB look up table (4 mW) which results in waste of bandwidth because the CBR level is controlled around 0.2 which is far from desired level 0.65. Using very low power level although reduces the channel load, it decreases the awareness of vehicles too.

The results of simulation in condition 2 by applying ETSI DCC are presented separately in Figs. 5 and 6 to make it more visible. As already described, in ETSI DCC vehicles, based on the experienced CBR, might work in one of the states Relaxed, Active or Restrictive. The parameters that vehicles use in each state have been indicated in Table 3 and the threshold CBRs, CBR_{min} and CBR_{max} , for changing state are 0.15 and 0.4.

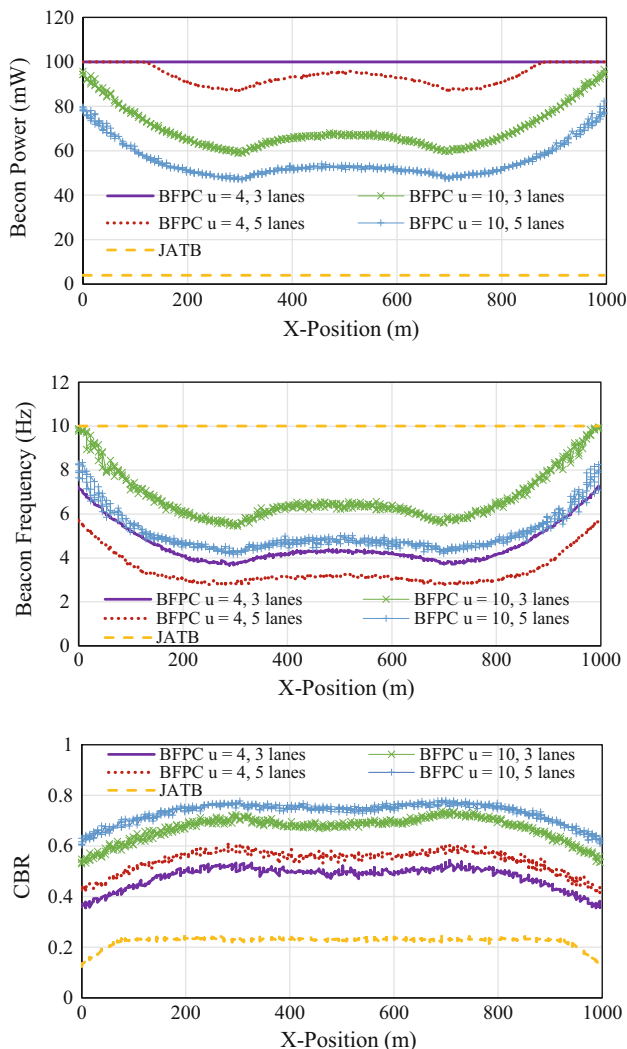


Fig. 4 Beacon power and frequency and CBR over the 1000 m track with stationary vehicles in two conditions (1) three lanes (396 vehicles) and (2) five lanes (660 vehicles), where $w_i = 650$ and $c_i = 3.0$

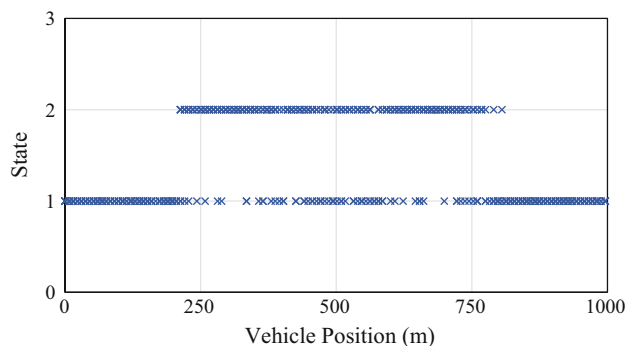


Fig. 5 The state of vehicles over a 1000 m track with five lanes when the initial state of all the vehicles is state 0

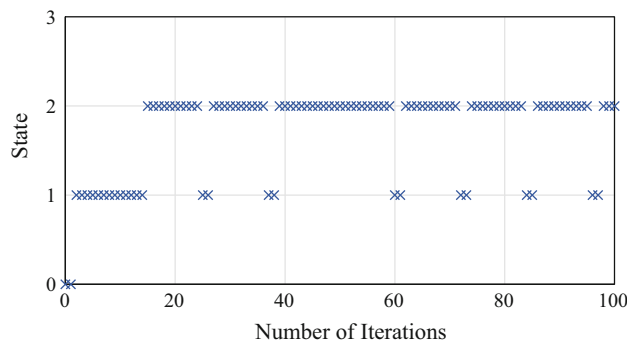


Fig. 6 Changes in the state of a vehicle at position $x = 334$ m over the track

Table 3 ETSI DCC states' parameters [12]

	Relaxed	Active	Restrictive
Beacon frequency	25 Hz	2 Hz	1 Hz
Transmit power	33 dBm	23 dBm	− 10 dBm
Bit rate	3 Mbps	6 Mbps	12 Mbps
Carrier sense threshold	− 95 dBm	− 85 dBm	− 65 dBm

Figures 5 and 6 show the results of the experiment. States 0, 1 and 2 represent Relaxed, Active and Restrictive respectively. Figure 5 shows the state of vehicles over the track. It is observed that even vehicles very close together are in different states, e.g. in the middle of the track some vehicles are in Active and some are in Restrictive state. Vehicles in state 1 use beacon frequency and power of 2 Hz and 200 mW and vehicles in state 2 use beacon frequency and power of 1 Hz and 0.1 mW. These figures reveals clearly the unfairness in channel usages in ETSI DCC. Figure 6 shows the changes in state of a vehicle at position $x = 334$ m over the track. The x-axis shows the number of iterations of the DCC mechanism. The state of the vehicle keeps on changing and it does not converge to a state which signifies the instability of ETSI DCC. As ETSI DCC fails to provide a stable beaconing we do not provide its results in the next scenarios.

4.2 Scenarios with moving vehicles

Based on the results in Sect. 4.1, the parameters $c_i = 3$, $w_i = 650$, and $u_i = [v_i]_4$ were used for the reported experiments in this section. v_i is the speed of vehicle i and the minimum value for u_i will be four. The utility $u_i = [v_i]_4$ was selected as an example to show how every vehicle can adjust its parameters individually and obtain a higher frequency based on its beaconing requirements. Vehicles can adjust their u_i based on their speed, acceleration or even position. The design of the parameters are out of the scope

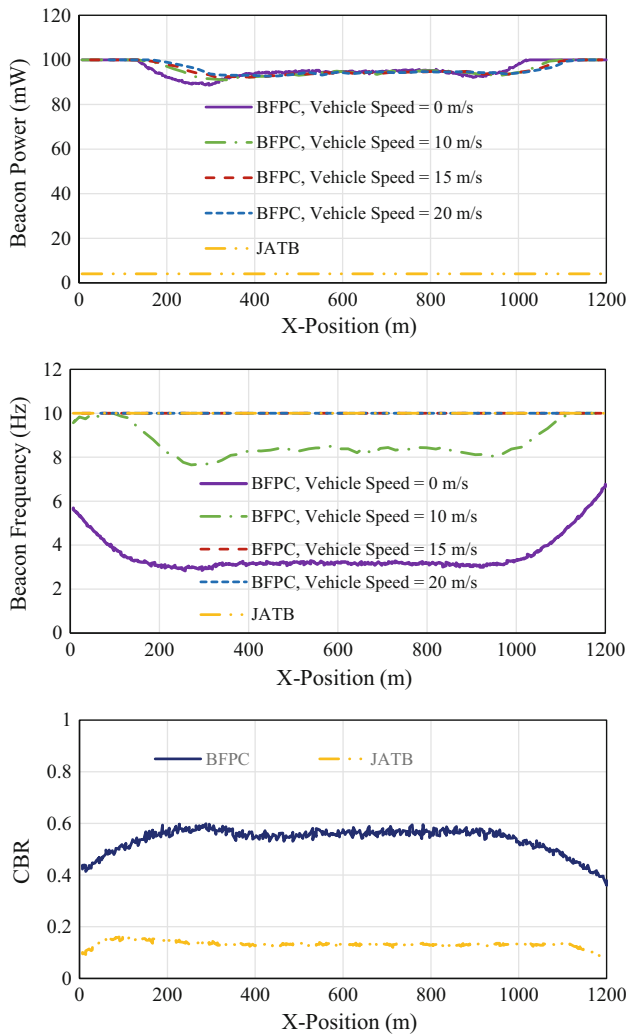


Fig. 7 Beacon power and frequency and CBR over a 1200 m track with two lanes of stationary vehicles and three lanes of moving vehicles with speeds of 10 m/s, 15 m/s and 20 m/s - $w_i = 650$, $c_i = 3.0$ and $u_i = [v_i]_4$

of this paper and our purpose is to indicate how the protocol works. With the stated configuration, all the vehicles use the same parameter w_i , therefore all of them obtain the same power. The vehicles with higher speed use greater u_i , then they obtain higher beaconing frequency. This configuration conforms to the Algorithm X with which vehicles adapt their beacon frequency based on their dynamics and adapt their power to control channel load. However, the mechanism used there to adapt beacon power results in unfair beacon power [6].

For this section, a highway scenario in which there is a traffic jam on one direction and a free flow of traffic on the other direction was simulated. The length of the track is 1200 m and has two lanes of stationary vehicles (316 stationary vehicles) and three lanes of moving vehicles with speeds of 10 m/s, 15 m/s, and 20 m/s. Figure 7 shows

beacon frequency, beacon power, and CBR for the experiment. It is observed that all the vehicles achieve the same power. The achieved beacon frequency is proportional to the parameter u_i as long as the algorithm does not restrict the beaconing frequency to the minimum or maximum frequencies (r_{min} or r_{max}). This can be explained as follows. At equilibrium point we have: $\partial Q_i / \partial p_i = 0$ and $\partial Q_i / \partial r_i = 0$ thus,

$$p_i + 1 = \frac{w_i(1 - CBR_i(\mathbf{X}))}{c_i} \tag{20}$$

and

$$r_i + 1 = \frac{u_i(1 - CBR_i(\mathbf{X}))^2}{p_i c_i T_{frame}} \tag{21}$$

As all the vehicles use the same c_i and the measured CBR for the vehicles at the same x-position on the track is equal, then according to (20) vehicles at the same x-position gain the same power. For vehicles i and j with the same measured CBR (the same x-position on the track), the following holds:

$$\frac{r_i}{r_j} \approx \frac{u_i p_j c_j}{u_j p_i c_i} \tag{22}$$

and as explained vehicles i and j gain the same beacon power therefore:

$$\frac{r_i}{r_j} \approx \frac{u_i}{u_j} = \frac{[v_i]_4}{[v_j]_4} \tag{23}$$

In other word, the fairness in beacon power and weighted fairness in beacon frequency are achieved.

The results of applying JATB is also indicated in 7. The power level is controlled in 4 mW and the CBR is around 0.1 which is far from 0.65. The other problem with JATB is that it assigns to all vehicles the same level of transmission parameters without considering their speed or other safety requirements.

Figure 7 shows that only the vehicles with speeds of 0 m/s and 10 m/s contribute to congestion control by adapting their frequencies and all the vehicles almost use the maximum power. In the next experiment, the number of stationary vehicles is increased to 946 vehicles (six lanes of stationary vehicles). Figure 8 shows the results in this case. By increasing the number of vehicles and consequently increasing the channel load, vehicles with speed of 15 m/s also contribute to congestion control by reducing their frequency. In addition, all the vehicles use lower power than the power they used in the experiment with less number of vehicles. Again, there is fairness in beacon power and weighted fairness in frequency and the CBR is controlled around 0.65.

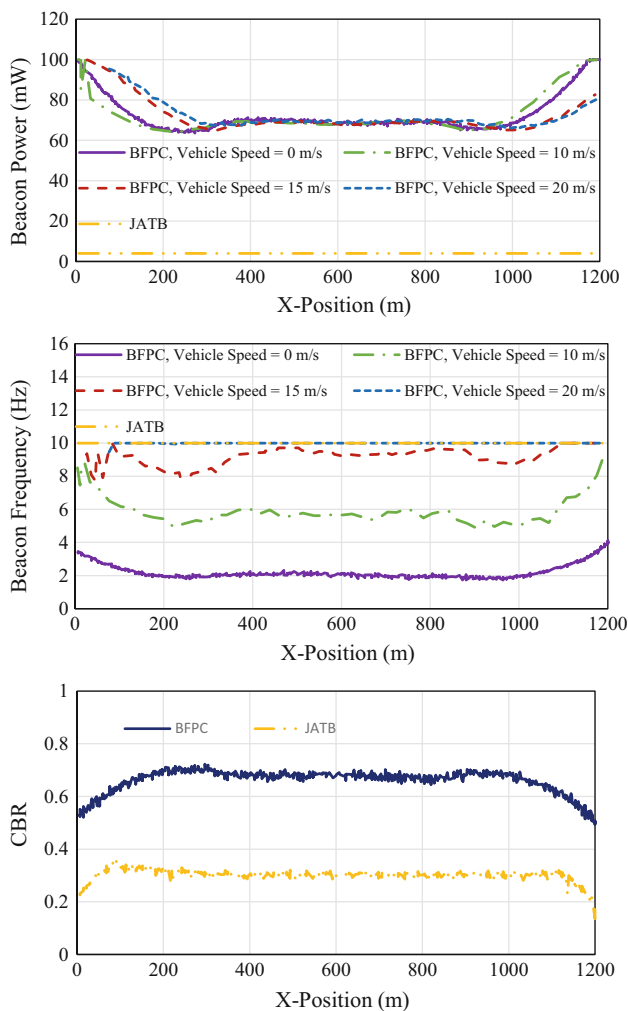


Fig. 8 Beacon power and frequency and CBR over a 1200 m track with six lanes of stationary vehicles and three lanes of moving vehicles with speeds of 10 m/s, 15 m/s and 20 m/s - $w_i = 650$, $c_i = 3.0$ and $u_i = [v_i]_4$

5 Conclusion

The problem of channel congestion due to beaconing was addressed with joint adaptation of beacon frequency and power. An approach was proposed that is based on non-cooperative game theory, in which the strategy spaces of the players are two-dimensional. The existence, uniqueness and stability of the NE was proven mathematically, and an algorithm based on the gradient dynamics for solving the game was proposed. The stability and convergence of the algorithm was validated by simulation. Simulation results indicated that the algorithm converges to the NE from any initial point. It was seen that by selecting appropriate values for the parameters of the algorithm, fairness in beacon power and weighted fairness in beacon frequency is achieved, and CBR is controlled at an appropriate level. In addition, unlike other beaconing control algorithms

fairness is obtained without control overhead. The fairness in BFPC is achieved based on the fairness of the NE. The algorithm has per-vehicle parameters. So every vehicle by adapting them can gain beaconing that can meet its safety application requirements while fairness in beaconing between vehicles with the same requirement (parameter) is maintained.

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Forough Goudarzi received the M.Sc. degree from Sharif University of Technology, Tehran, Iran and the Ph.D. degree from Brunel University London in 2017 both in Electrical and Electronic Engineering. She worked for more than 10 years in industry before her Ph.D. Currently, she is a Research Fellow in Wireless Communication at Nottingham Trent University, UK, working on EU Horizon 2020 REMOURBAN project. Her research interests include wireless networks and connected vehicles. She has voluntarily served as a reviewer in various journals and conferences.



Hamid Asgari received the Ph.D. degree in Electrical and Electronics Engineering from the University of Wales, Swansea, UK in 1997. He has been with Thales UK Research, Technology and Innovation (RTI) since 1996. He is currently Verification and Validation Technical Lead in Autonomous Systems Research Group and Network Lead in Security, Communications and Networking Research Group at RTI. Hamid is also a Visiting Professor at King's College London since February 2014. He is a highly experienced and skilled professional in leading large R&D teams, a technical expert in systems' and communication networks' evaluations and a professional in providing scientific and academic contributions. He has been leading R&D teams and participating in collaborative European Commission (EC) and Innovate UK projects since the year 2000. His expertise is in System's and Networks performance verification and validation, Advanced and Future Networking and Security concepts, Wired/Wireless Networks Architectures and Technologies, Network, Service and Quality of Service (QoS) Management. He has a proven track record of publications in the most respected scientific journals and peer reviewed conferences. Prof. Asgari is an IET Fellow and Senior member of both the IEEE and ACM.



Hamed Safa Al-Raweshidy received the B.Eng. and M.Sc. degrees from the University of Technology, Baghdad, Iraq in 1977 and 1980, respectively, the Post Graduate Diploma degree from Glasgow University, Glasgow, UK 1987, and the Ph.D. degree from Strathclyde University, Glasgow in 1991. He has worked with the Space and Astronomy Research Centre, Baghdad, Perkin Elmer, Waltham, British Telecom, Oxford University, Manchester

Metropolitan University, and Kent University, Canterbury, UK.

Currently, he is the Director of Wireless Network and Communications Centre at Brunel University, London, UK.

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