

Joining Forces for VANETs: A Combined Transmit Power and Rate Control Algorithm

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Abstract—In this paper, we tackle the problem of network congestion in IEEE 802.11p-based vehicular networks and propose a novel mechanism for the combination of power and message interval control in a single algorithm loop, which outperforms separate power and interval control algorithms. The solution addresses the need for controlling the load generated by periodic messages and is the result of extensive comparative simulations aimed at identifying the most effective combination strategy. A reference system in-line with the ongoing European standardization activities is adopted.

I. INTRODUCTION

Vehicular networks based on short-range communication technologies have been studied by several projects and industry consortia as a means to increase road safety and traffic efficiency. Cooperative systems, a particular form of vehicular networks where vehicles and the infrastructure exchange information in a cooperative fashion, are now being assessed in large field trials [?], while dedicated standardization activities [?], industry consortia [?] and governmental support [?] are expected to finally boost their deployment.

The communication technology selected for these systems [?] [?] is a variation on the widespread CSMA-based IEEE 802.11 [?] standard family. Due to its versatility and enormous popularity, this technology offers the best trade-off between cost and performance in terms of communication range and medium access control. However, being this technology not originally meant for such a high number of highly mobile stations in direct communication range, mechanisms for the prevention of network congestion need to be employed. Further, traditional end-to-end congestion control mechanisms at the transport layer are not suitable for Vehicular Ad-hoc Networks (VANETs), where most data traffic is broadcasted and the dynamics of the network topology make end-to-end congestion estimations impractical.

Due to the above reasoning, research on VANETs has been focusing on transmit power control and packet size/interval control as means to prevent network congestion. The goal of these schemes is to limit the load generated by *heartbeats*, periodic messages used in VANETs, in order to reserve resources for urgent, event-driven messages. When adopted individually, these approaches exhibit good potentials but they are affected by an intrinsic limitation, i.e., the mutual assumption on a constant packet data rate and transmit power. Moreover, theoretic performance of transmit power control schemes is not expected to be achieved due to the high complexity and

physical limitations of 802.11 radio front-ends with respect to output power dynamic range and accuracy.

In this paper we propose a novel approach for the control of network congestion caused by periodic data traffic. The proposed scheme combines in one single algorithm loop the control of transmit power and packet rate (interval). By taking into account the mutual effect of power and packet rate, this combination results in measurably better performance as compared to separate algorithms and reduces the power control requirements on front-ends by leveraging on packet rate control. An extensive comparison of combined strategies based on simulation results represents another important contribution of this paper to the existing literature.

This paper is organized as follows: Section II provides an analysis of the relevant existing works. Section III overviews the ultimate goals of this work as well as the methodology and the combined strategies adopted and compared in this paper. Section ?? provides a detailed description of the algorithms that implement the identified combined strategies, whereas Section ?? introduces the simulation environment and presents the comparative simulation results and Section ?? concludes the paper.

II. RELATED WORK

As thoroughly described in [?], due to the highly dynamic network topology and the broadcast nature of messages, the traditional end-to-end approach to congestion control is not suitable for VANETs, which require algorithms be distributed and not based on end-to-end metrics. In the followings, we summarize selected mechanisms for the individual and parallel execution of control of power and packet generation rate for VANETs and explain why these approaches yield sub-optimal performance. Further, schemes for the combination of power and physical data rate control for standard WLANs are also mentioned as examples of integrated approaches, though inapplicable to VANETs.

Transmit Power Control. In [?], the transmit power is chosen exclusively based on the number of nodes, i.e., it is increased if the number of neighbors is below a low-threshold and decreased if the number of neighbors is above an high-threshold. The authors show that the algorithm achieves high scalability over wide range of user densities and speeds but do not assess the approach against fairness. With this scheme, the load reduction caused by some nodes decreasing their power

is enough to allow the other nodes to maintain a higher power, which represents an unfair allocation of resources among vehicles. In [?], each node, based on the positions of vehicles within its carrier-sense (CS) range, computes the maximum power level such that, if all nodes within the CS range use this level, the aggregated load will not exceed the threshold. Then, each node sets its power as the minimum between the computed power and the corresponding levels collected from other nodes. This approach guarantees fair allocation and control of resources but it requires multi-hop information propagation in order to obtain more complete knowledge of the surrounding. In addition, it assumes that the transmit power can be set with very fine granularity.

Packet Generation Rate Control. In [?], the packet generation rate is changed according to the vehicle's speed, i.e., the rate increases as the vehicle's speed increases. In addition to that, as soon as a deceleration is detected, the host vehicle maintains the packet rate set before the deceleration for an interval which is set according to the deceleration. Although speed and density are often correlated, there are situations where both density and speed are considerably high (highways intersections, urban fast ways), in which this approach would not succeed in controlling the network load. Therefore the packet generation policy needs to be complemented by a network-based load generation control. In [?], every node monitors and estimates the channel load by using the number of neighbors. The packet rate is controlled in a distributed way in order to keep the channel load under a threshold, while fairness is obtained by distributedly assigning fractions of resources to each node. The present work builds on the experience gained in [?] and overcomes its limitations related to the inaccurate channel load estimation. The scheme proposed in [?], in fact, does not take into account nodes located outside the communication range but inside the CS range.

Power and Data Rate Control for Standard WLANs. In [?], the proposed scheme makes use of a combination of transmit power and data rate in order to eliminate collisions from hidden terminals and enhance the spatial reuse by reducing the effect of exposed terminals. Authors of [?] and [?] present two joint adaptation data rate and power mechanisms that aim at simultaneously improving the energy efficiency and throughput performance. These approaches make use of direct channel estimation based on acknowledgments and are therefore not suitable for VANETs broadcasted periodic messages.

Independent Power and Packet Rate Control for VANETs. The authors of [?] present two congestion control mechanisms based on power and packet rate adaptation. They calculate the channel busyness ratio as the time where the MAC-layer is indicated as busy, divided by the time consumed for observation. Power and packet rate are increased/decreased if the channel busyness ratio is below/above a fixed threshold. Fairness is addressed by means of explicit signaling. In this approach, rate and power control algorithms are separated and do not mutually influence each other, leading to the wrong mutual assumptions mentioned above.

III. DESIGN GOALS AND STRATEGIES

In this section, we first recall the problem statement and describe the goals of this work. Then, we overview the various strategies undertaken in the algorithm design process and compared in this paper. The followed approach consists of improving the building blocks (the individual power and interval control mechanisms) first, and abstracting various combination schemes in a second step.

A. Goals

Due to the random nature of the 802.11 Medium Access Control, without an admission control mechanism self-implemented by each station the communication medium can easily get overloaded and even saturated. Further, even when the channel utilization is below the saturation level, the reliability of the packet delivery and the channel access time considerably degrade as the load increases. Another problem related to the 802.11 MAC protocol is the potential unfairness due to the lack of distributed resources allocation functions.

In light of the above problem statement, the goal of this work is to design a totally distributed, low-complexity algorithm for network congestion control in VANETs that:

- Combines both power and packet rate control overcoming the limitations of power-only and rate-only approaches
- Keeps the load generated by periodic messages under a pre-defined threshold
- Provides fair allocation of resources among vehicles, presuming that each of the vehicles is transmitting potentially critical information for road safety purposes
- Reserves free resources for the distribution of event-driven messages, which are assumed to be intrinsically more urgent than *heartbeats*.

B. Strategies

Individual power-only and rate-only control. These algorithms are the building blocks of the combined strategies and were individually improved. Concerning the power-only control, the goal was to reduce the complexity and overhead, as well as to adopt realistic output power granularity and dynamic range. Regarding the rate-only control, we focused on achieving better load estimation and resources utilization than in [?]. We simply named the two resulting algorithms Improved Power Control (IPC) and Improved Rate Control (IRC), both detailed in Section ??.

Parallel Execution. Following this approach, IPC and IRC are executed simultaneously and independently. This strategy extends the work carried out in [?], where the two individual control algorithms are compared but not jointly executed.

Sequential Conditional Execution. According to this approach, the two individual algorithms are executed sequentially, where the usage of the second one is subject to a specific condition. In other words, this strategy consists of having a primary algorithm run continuously and a secondary one intervene when necessary. Figure ??(a) illustrates SPRC, where power control is executed assuming a common packet rate R and rate control is enabled only if the transmit power

reaches its minimum level. Symmetrically, in the approach shown in Figure ??(b) (SRPC), the rate control is always active and the power control intervenes when the rate should be decreased further than a pre-defined minimum threshold.

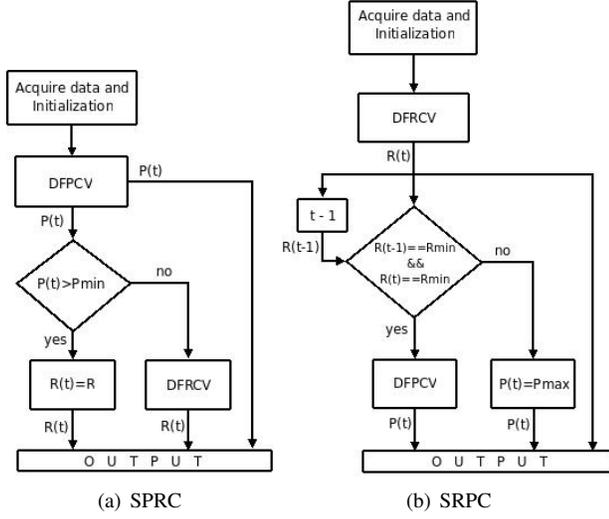


Fig. 1. Sequential Conditional Execution.

Combined Execution. This approach combines in one single algorithm both transmit power control and packet rate control (CPRC), providing stations with a certain degree of flexibility, which for example allow them to increase their packet rate while decreasing the transmit power (an important feature for time-critical safety applications which are sensitive to the message issuing frequency). The transmit power is adjusted based on a relation rate-power similar to the one depicted in Figure ??, which is based on the vehicular density.

IV. ALGORITHMS DESCRIPTION

The proposed algorithms are based on the framework introduced in [?], which consists of three phases: channel monitoring, load change estimation and action. During the first phase a node observes the traffic condition of the channel during a predefined interval T , named monitoring interval. At the end of each monitoring interval the algorithm computes the metrics required to estimate the channel condition (load change estimation) and provides the new transmission power and/or maximum data packet rate to be used during next interval (action).

The following algorithms adopt the Channel Busy Time $CBT_i(t)$ as metrics, which is defined as the fraction of time in which the signal strength received by the node i is above the clear channel assessment threshold (CCA). A typical threshold value used in the literature which provides a sufficiently reliable channel is $CBT_{Th} = 0.2$.

A. Improved Rate Control (IRC)

In order to achieve fairness in the resource utilization, we allocate an equal amount of resources to each node by means of direct partitioning. Therefore the packet rate for a generic node i is computed by:

Fig. 2. Rate-power relation of the Combined Execution

$$R_i(t) = \frac{CBT_{Th}}{N_i(t) + 1} \cdot \frac{C}{P_{SIZE}} \quad (1)$$

where $N_i(t)$ is the number of nodes that have the node i in their CS range, C is the capacity of the channel and P_{SIZE} is the packet size (500 B). Unlike [?], we infer $N_i(t)$ from $CBT_{PER,i}(t)$, which is the fraction of $CBT_i(t)$ due to the heartbeats only:

$$N_i(t) = \frac{CBT_{PER,i}(t)}{R_{AVG}} \cdot \frac{C}{P_{SIZE}} - 1 \quad (2)$$

where R_{AVG} is the average outgoing data packet rate, computed among node i 's neighbors.¹ The IRC algorithm is obtained from the two equations above as follows:

$$R_i(t) = \frac{CBT_{Th}}{CBT_{PER,i}(t-1)} \cdot R_{AVG}(t-1) \quad (3)$$

In addition, a first order low-pass filter is used in IRC to reduce the instantaneous fluctuations of $R_i(t)$.

B. Improved Power Control (IPC)

In IPC, a node i estimates the vehicular density in its surroundings d_i and adjusts its transmission power $P_i(t)$ in order to affect a number of nodes smaller than a pre-defined threshold N_{MAX} , where the pre-defined threshold is derived from CBT_{Th} . In order to achieve higher fairness, each node by means of an additional 8-bit protocol header field² densities d_j computed by its neighbors, and estimates the vehicular density D_i as the average between d_j and its local density d_i . N_{MAX} is obtained from (??):

$$N_{MAX} = \frac{CBT_{Th}}{R} \cdot \frac{C}{P_{SIZE}} - 1 \quad (4)$$

where R is a statically set packet generation rate. By using the vehicular density, every node can estimate the range which includes N_{MAX} nodes:

$$CS_{MAX,i} \simeq \frac{N_{MAX} + 1}{2 \cdot D_i} \quad (5)$$

An empirically set factor Δ is used to derive the communication range from the carrier-sense range:

$$CR_{MAX,i} \simeq \frac{CS_{MAX,i}}{\Delta} \simeq \frac{CBT_{Th}}{2 \cdot D_i \cdot \Delta \cdot R} \cdot \frac{C}{P_{SIZE}} \quad (6)$$

Finally, the node i chooses the output power as the maximum level such that the corresponding CR is lower than $CR_{MAX,i}$:

$$p_i(t) = \max_p [CR[p] < CR_{MAX,i}] , p \in \{P_{MIN}, \dots, P_{MAX}\} \quad (7)$$

¹We assume that R_{AVG} is locally uniform, i.e., it does not spatially vary between the communication range and the carrier sense range.

²The protocol overhead is deemed acceptable, since it pays off in terms of fairness. However, the average density computation is an optimization that can also be removed if the overhead is considered critical.

Fig. 3. Second step of the Combined Execution

C. Combined Power and Rate Control (CPRC)

The algorithm consists of two steps. In the **first step**, each node estimates the node density D in the surrounding and, based on that, for each available level of transmit power p determines the maximum transmission rate $R_{MAX}[p]$ that can be adopted such that, assuming that every node in the resulting communication range $CR[p]$ uses that rate, the aggregated load due to periodic data traffic is below the pre-defined threshold. The relation power-rate can be obtained by inverting (??):

$$R_{MAX}[p] = \frac{CBT_{Th}}{2 \cdot CR[p] \cdot D \cdot \Delta} \cdot \frac{C}{P_{SIZE}} \quad (8)$$

Figure ?? shows the maximum values of rate (stars) computed for each possible level of transmit power using (??) with $p \in \{P[1], \dots, P[5]\}$. The stars determine a curve which identifies a relation rate-power (continuous curve). Since the points are computed taking into account the density D , the curve moves according to the nodes density (dashed curves): if the density increases, the rate-power relation becomes more restrictive, i.e. the same transmission rate corresponds to a lower transmit power. If the density decreases, nodes can send with full power even for higher values of rate.

In the **second step** illustrated in Figure ??, by means of inter-message arrival time measurements, each node collects information regarding the transmission rate used by its neighbors r_i . Then, each node computes the maximum r_{MAX} among r_i , including its own packet generation rate. r_{MAX} identifies the darker area below the power-rate curve in Figure ?? which represents the entire set of power and rate values than a node can choose from such that the aggregated traffic load does not exceed the pre-defined threshold.

The policy illustrated in Figure ?? introduces a cooperative behavior, where, for example, nodes that are not directly involved in a potentially dangerous situation (e.g. turning right at an intersection) decrease their power to allow nodes affected by the dangerous situation (e.g. turning left at the intersection) to increase their sending rate. It should be noted that this approach does not introduce unfair conditions for accessing the channel. In fact, those nodes which decrease their transmit power as a consequence of a rate increase operated by one or more of their neighbors, can increase their sending rate as well and occupy the same amount of resources.

V. EVALUATION

A. Simulations Environment

The proposed algorithms were evaluated by means of the network simulator ns-2.31 with the IEEE 802.11 MAC and PHY extensions Mac80211Ext and WirelessPhyExt described in [?] and the highway traces described in [?]. The simulated scenario consists of 512 nodes in a 15 km highway, three lanes per direction with an average speed of 120 km/h and an average vehicular density of 36 vehicles/km. We use the same scenario as in [?] and [?] to allow for direct performance comparison.

The adopted physical data rate for our simulations is 6 Mbps, corresponding to QPSK modulation with 1/2 coding rate with a 10 MHz channel, which is also suggested in [?] and adopted as default modulation scheme in [?]. The values of sensitivity and CCA threshold used in the simulations are -87 dBm and -90 dBm, respectively, which are values in between the standard requirements [?] and the performance of a quality receiver. A detailed list of the tab:parameters is given in Table ??.

TABLE I
SIMULATIONS PARAMETERS

Code location in NS-2	Parameter name	Value
Mac/802.11Ext	aCWmin	15
Mac/802.11Ext	aCWmax	1023
Mac/802.11Ext	SlotTime	13 μ s
Mac/802.11Ext	SIFS	32 μ s
Mac/802.11Ext	PreambleLength	32 μ s
Mac/802.11Ext	PLCPHeaderLength	8 μ s
Phy/WirelessPhyExt	freq	5.9 GHz
Phy/WirelessPhyExt	noise_floor	-99 dBm
Phy/WirelessPhyExt	CSThresh	-90 dBm
Phy/WirelessPhyExt	BasicModulationScheme	1 (QPSK)
Phy/WirelessPhyExt	bandwidth	6 Mbps
Antenna/OmniAntenna	X	0
Antenna/OmniAntenna	Y	0
Antenna/OmniAntenna	Z	1.5 m
Antenna/OmniAntenna	G_t, G_r	4 dB

B. Power Values

We assumed that the transmitter is capable of sending at 5 different levels of output power, which are expected to be derived in a calibration phase from as many communication ranges (100, 200, 300, 400 and 500 m). The five levels are obtained by inverting the free-space law and adopting the tab:parameters specified in Table ?. An additional value of 4 dB is added in order to account for the attenuation of cables and connectors.

C. Metrics

The adopted metrics for the algorithms evaluation are presented in the followings. The 3D-CBT shown in Figure ?? is a 3-dimensional graphical representation of the CBT with the nodes' position on the highway on the X-axis, the time on the Y-axis, and the CBT on the Z-axis. This chart reveals both spatial and temporal behaviors of the algorithms, allowing for example to visually estimate time stability and uniformity under variable density. Another adopted metrics is the probability of message reception within a given distance from the reference node, which is computed as the fraction of the total number of message arrivals correctly received. Finally, the transmission rate and power as functions of the position on the highway are also considered in order to evaluate the capability of the proposed algorithms to provide fair resources allocation.

D. Comparative Results

Power vs Rate Control. The individual algorithms are evaluated in the presence of event-driven messages generated with a frequency of 10 Hz in the interval 5 to 15 seconds after the simulation start. Event-driven messages are disseminated by means of a simple contention-based forwarding (CBF) scheme.³ Event-driven messages are not subject to power nor rate control. On the contrary, periodic messages use either IRC with a fixed power level $P_{MAX} = P[5]$ or IPR with a fixed packet rate $R = 10Hz$, which is a frequency that fulfills the requirements of most applications according to [?].

Figure ??(a)-(b) reveals that, although both algorithms effectively limit the periodic traffic, rate control can maintain the CBT closer to the target level, due to the coarser granularity of power control. Both algorithms provide fair allocation of resources, which is shown by the spatial local uniformity of power (IPC) and rate (IRC) in Figure ??(a). The usage of lower transmit power for periodic messages and the lower CBT achieved with IPC result respectively in a lower probability of periodic message reception and a slightly higher probability of event-driven message reception than IRC (Figure ??).

Parallel vs Sequential Execution. In the evaluation of both parallel (PPRC) and sequential (SPRC) combinations, event-driven messages are generated as described above. In order to perform a meaningful comparison it was necessary to increment the rate R used by PPRC in (??) and by SPRC in Figure ??(a) to 20 Hz. In fact, due to the low density of the reference simulation scenario, with a generation rate of 10 Hz, as shown in Figure ??(a)-(b), the reduction of one among power and rate is enough to reduce the load.

Both combined strategies achieve the goal of maintaining the load around the target value (see Figure ??). On the one hand both algorithms set similar level of power, as they both include IPC (see Figure ??), but on the other hand the condition in SPRC decreases the role and the benefit of rate control. In fact, in PPRC the rate control acts like a fine tuner of the load generated by a node, bringing the CBT closer to the target. In SPRC, rate control only intervenes sporadically and the coarse granularity of power control prevails.

Another interesting result is that the sequential execution of rate control and power control as depicted in Figure ??(b) proved impractical, due to mutual compensation effects.⁴ We conclude that in a sequential combination of rate and power control schemes, the primary algorithm must be density-based and the secondary one must be CBT-based.

Power-only vs Combined Power and Rate Control. In the combined algorithm, the selection of the transmit power is rate-aware. This means that the algorithm should be able to cope with nodes that increase their outgoing packet rate. In order to assess this, we modified the scenario by introducing nodes locate in 3 parts of the highway (4,000 to 5,000 m, 8,400

to 8,600 m and 12,000 to 12,200 m) which use respectively 15, 20 and 15 Hz, whereas elsewhere the outgoing packet rate is 10 Hz. Figure ?? shows a snapshot at 10 s of the CBT obtained with IPC and CPRC and Figure ??(d) the corresponding levels of rate and power for CPRC. Since IPC adjusts the power assuming a common packet rate of 10 Hz, it cannot control the load in the critical sections of the highway, whereas CPRC results in a more adaptive control of the congestion level.

(a)(b)
IPPRCC

Fig. 4. Channel Busy Time over Time and Position

(a)(b)
IPPRCC
and
IRC

Fig. 5. Instantaneous Levels of Power and Rate

(a)(b)
IPPRCC
vss
IPPRCC

Fig. 6. Probability of Correct Message Reception

Fig. 7. Channel Busy Time of IPC vs CPRC

VI. CONCLUSIONS

In this paper we compared several strategies for the combination of rate and power control in VANETs and suggested an integrated algorithm (CPRC) that selects the transmit power being aware of the outgoing rate. CPRC allows applications to issue periodic messages at higher rates when required by contextual factors like speed and higher probability of collision, without having the network load exceed the pre-defined reliability-based threshold.

³Many CBF schemes have been proposed [?] [?]. We adopt a basic geo-unaware CBF with the sole aim of reducing the number of unnecessary retransmissions. The same CBF scheme is used in every simulation, in order to isolate effects due to the dissemination strategy from those due to the power and rate control mechanism.

⁴Being the rate control based on the measured CBT, a reduction of power causes the CBT to decrease and the rate to increase.