Distributed Vehicular Traffic Congestion Detection Algorithm for Urban Environments

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Abstract— **Vehicular traffic congestion is a well-known economic and social problem generating significant costs and safety challenges, and increasing pollution in the cities. Current intelligent transport systems and vehicular networking technologies rely heavily on the supporting network infrastructure which is still not widely available. This paper contributes towards the development of distributed and cooperative vehicular traffic congestion detection by proposing a new vehicle-to-vehicle (V2V) congestion detection algorithm based on the IEEE 802.11p standard. The new algorithm allows vehicles to be self-aware of the traffic in the street, performing congestion detection based on speed monitoring and cooperation with the surrounding vehicles. Cooperation is achieved using adaptive single-hop broadcasting which depends on the level of congestion. The paper presents the congestion detection algorithm and the cooperative communication in detail, and presents performance evaluation using large-scale simulation in Veins framework based on OMNeT++ simulator and SUMO vehicular mobility simulator. Results show that precise congestion detection and quantification can be achieved using a significantly decreased number of exchanged packets.**

Keywords— traffic congestion detection and management; vehicular ad hoc networks; intelligent transport systems; cooperation;data aggregation;

I. Introduction and Related Work

According to the results of the survey provided by the Centre for Economics and Business Research and traffic information company Inrix, the cost of traffic congestion for the UK economy is estimated on more than £4.3bn a year [1]. In addition to the economic costs, traffic congestion also affects the quality of life and the environment, by causing pollution which has well-known negative effects on health and climate. Traffic congestion usually occurs in the city areas, mostly in urban and highway environments and is usually formed when road capacity is smaller than traffic demand.

Alleviating traffic congestion is currently done via conventional traffic monitoring solutions based on infrastructure which provide fixed-point traffic information. These solutions include various types of infrastructure from traditional traffic lights, to smart video cameras and inductive loops. Fixed point solutions provide traffic estimates based on measurements taken at a specific location where they are placed. Because of that, such systems might not provide an accurate representation of the traffic conditions over larger road segments. Additionally they would have to be installed at every intersection in order to cover the area of the whole city. Finally, the cost of such solutions is extremely high and deploying them at every intersection is not practically feasible.

On the other hand, as an alternative to the traditional infrastructure-based traffic monitoring and management systems there are solutions based on newly developed 802.11p standard designed specifically for use in vehicular ad hoc networks (VANETs) [2]. There are two types of communications in VANETs, vehicle to vehicle (V2V) and vehicle to infrastructure (V2I). Since V2I communications also require supporting infrastructure, V2V communications is the only completely distributed way of exchanging the traffic related information.

Many different solutions for V2V communications are being developed and they are usually divided in two categories. The first one relates to safety and traffic information, such as current accidents or traffic congestions while the second assumes different ways of infotainment, such as internet access, gaming and advertisement. These applications are based on periodical exchange of messages between vehicles containing information about vehicles position, speed, and direction with other data regarding congestions, accidents, etc.

Having in mind the unique nature of vehicular ad-hoc networks in terms of node behavior and mobility, some well-known problems that exist in other types of mobile ad-hoc networks also exist in VANETs. These issues are especially common for urban environments where the number of nodes is high and sometimes over the capacity of city streets. Some of them are broadcast storm, hidden terminal problem, scalability issues, and increased contention in the wireless channel. As discussed in [3] the broadcast storm problem, is common in VANETs especially in traffic jams, and it might cause collisions which has negative effect on the operation of safety applications. Some of the suppression techniques are recommended to overcome this problem including adaptive broadcasting [3]. The hidden-terminal is also recognized as a problem in VANETs and has been addressed before as well, like in [4]. Scalability is also well-known challenge in VANETs and has been previously addressed as in [5]. It is important to underline that common fact about all these problems is they usually occur when the number of nodes who are broadcasting at the same time is high, which is a feature of VANETs in urban scenarios, especially in traffic jams.

Unlike previously mentioned problems which are well known in other types of ad-hoc networks, the traffic congestion detection and management by using VANETs has recently become the hot research topic. Focus so far has been on the highway scenarios mostly considering V2I communications, which rely on supporting infrastructure such as roadside units (RSUs).

One of the first papers dealing with distributed traffic congestion detection and management is [6], where traffic information system called SOTIS is presented. The system assumes that each vehicle monitors the local traffic situation by analyzing the received data packets with detailed information from other vehicles, while each vehicle sends information about its location, speed, direction, etc. SOTIS was evaluated by simulation only in highway scenario, and it assumed periodic broadcasting as a way of exchanging the information. Traffic View [7] is a framework for dissemination and gathering of traffic information about the vehicles on the road. It is based on dissemination of information about the average speed of vehicles on the road. Additionally each vehicle further aggregates received information and it keeps records about all the nodes rather than about certain area. Each vehicle then broadcasts the message about the vehicles it knows about. This approach was simulated only based on 802.11b standard and in highway environment. Another work related to distributed V2V traffic congestion detection and forecasting algorithm is presented in [8] where authors introduced new definition of traffic congestion. They define the road as congested only when the probability of finding it in the same state in the near future is high. The algorithm assumes that each road segment needs to be observed for a day and that vehicles send their traversal times to centralized entity. Additionally, it remains unclear what type of communication vehicles use in order to exchange messages. In [9] authors presented cooperative approach for congestion detection which is based on V2V communications and fuzzy logic. Vehicles use periodic broadcasting messages to detect the congestion together with system for classification of traffic congestion developed by Skycomp. This system defines metrics based on aerial surveys of different highways. Congestion detection algorithm has been evaluated in highway scenario. Finally, the authors in [10], developed distributed traffic management system based on V2V communications, and evaluated its effectiveness on real traffic scenario. The system is based on gossip based routing where vehicles periodically broadcast the messages containing street section delay as a measure of congestion. Upon the vehicle receives the message it will estimate the traffic condition. The authors concluded that real-time and up to date traffic information can reduce the traffic congestion in realistic scenario.

As previously mentioned, solving the traffic congestion problem by using VANETs has been one of the hot research topics recently. Most of the work so far focused on solving this problem by V2I communications and such work is not presented here. On the other hand, we found a number of papers which used V2V communications for traffic congestion detection, management and forecasting and some were presented in this chapter. Although, all of the presented solutions are based on V2V communications, they still have certain limitations. These include:

- Dependence on extra information about traffic conditions obtained either from third party companies or local authorities. These sometimes include centralized entities such as traffic centers, etc.
- Some of the solutions were designed only for the highway scenarios, while most of them were actually only evaluated in the highway scenario.
- Majority of the papers presented assume that message exchanging is based on simple periodic broadcasting without considering additional possibilities such as adaptation of the broadcast interval. This is especially important since in the congested traffic periodic broadcasting might lead to one of the previously described problems such as broadcast storm problem and network overload.

Therefore we propose the algorithm which contributes towards distributed V2V traffic congestion detection in urban environments independent of any additional information and relying on an adaptive broadcasting algorithm. This algorithm enables each vehicle to determine its traffic condition and then through cooperation share this information with other vehicles. The result of such cooperative approach is in reducing the number of broadcasting nodes while at the same time having available the information about quantification of traffic congestion.

The rest of the paper is organized as follows: In section II we present the algorithm, while we evaluate it in the section III. Finally we make conclusions and explaining our future steps in section IV.

II. Congestion Detection Algorithm With Adaptive Broadcasting

According to the WAVE standard [2] VANET applications are based on periodical broadcasting of Wave Short Messages (WSMs). In situations when the number of nodes is high, like in traffic jams, the problems like broadcast storm, hidden terminal, and limited scalability are more likely to occur. It is also inefficient that all vehicles periodically send messages about the same traffic jam, and therefore it is important to reduce the number of broadcasting vehicles. In order to achieve that we propose an adaptive broadcasting algorithm based on congestion detection mechanism, which detects and quantifies the level of congestion in vehicle's neighborhood.

Before explaining the algorithm, it needs to be pointed out that we assume that each vehicle is equipped with a GPS device in order to determine its location. Also we assume that each street section has its own identification A_{id} which is always known to each vehicle. Finally all vehicles have their own databases where they store messages received from other vehicles.

Typical view of urban traffic jam is shown in Fig.1. As already mentioned, most papers suggest vehicles are exchanging data about their current position (GPS coordinates), speed, direction, traversal time, etc. [11]. On that assumption each of them processes received data in order to find out if and where traffic congestion exists. We propose that instead of broadcasting many parameters, each node broadcasts two simple parameters:

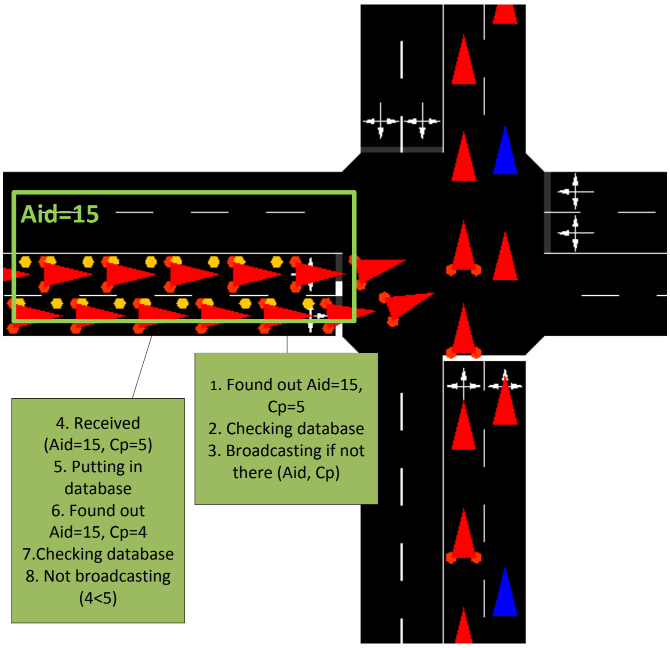

Fig. 1. Traffic jam at intersection.

- Location identification A_{id} and
- Congestion parameter C_p, which tells if the vehicle is in congestion or not.

The advantage of approach like this is that requires less processing times at receiving vehicles, because each vehicle now receives congestion information which has already been processed. This is particularly useful for delay-sensitive safety applications.

The most common definition of traffic congestion used in literature is based on traversal time and is defined in [12] as the travel time or delay in excess of that normally incurred under light or free-flow travel conditions. In this case of defining congestion each vehicle would need to have upfront information about free-flow travel times for the whole environment, for example a city. Having in mind that this is not practically feasible and that free-flow travel time is changing during the day, we think another approach should be considered, independent of external information like these.

Our algorithm consists of five procedures which are done consecutively by each vehicle independently and they are: speed monitoring, congestion detection, localization, aggregation and broadcasting, as shown in Fig. 2. The pseudo code for the algorithm is shown in Fig. 2.

A. *Speed Monitoring*

We propose that speed should be the indicator of traffic congestion and that the level of congestion, should be defined according to time intervals during each vehicle has certain speed range. If we define Vt as the threshold speed for our framework, and in the case the current speed Vc is smaller than this threshold speed, the congestion parameter will indicate the level of congestion. The moment when Vc becomes different than Vt is the starting point of congestion detection algorithm.

A) Speed Monitoring:
if $V_c \neq V_t$ go to B.

B) Congestion Detection:
if $V_c < V_t$ then
(start timer τ_c, when $\tau_c=\eta\cdot 10s \Rightarrow C_p=\eta$)
else (start timer τ_c, when $\tau_c=10s \Rightarrow C_p=0$)

C) Localization:
find A_{id} of the current location, go to D

D) Aggregation:
get $C_d(A_{id})$
if $C_p \neq 0$ then
if $C_p(A_{id}) > Cd(A_{id})$ then E, $C_d(A_{id})=C_p(A_{id})$
else skip E
else if $C_p(A_{id}) \neq C_d(A_{id})$ then E, $C_d(A_{id})=Cp(A_{id})$ then E
else skip E

E) Broadcasting:
broadcast the (C_p, A_{id})

Fig. 2. Pseudo code for the congestion detection algorithm.

B. *Congestion Detection*

The outcome of congestion detection process is the congestion parameter C_p which has certain value based on the time interval in which the current speed of the vehicle is smaller or greater than V_t. Vehicle needs to spend certain amount of time τ_p having this speed and then congestion parameter is set to certain value. There are six possible values of congestion parameters, and each is determined by the length of time which passed during that condition.

The value of C_p is determined by $C_p=\eta\cdot\pi$, where π can be 0, in case $V_c>V_t$, and 1 in case $V_c \leq V_t$. η can have one of the values $\eta=\{1, 2, 3, 4, 5\}$ depending on τ_p time interval:

$$\eta=1 \text{ } if \text{ } 10<\tau_p\leq 20,$$

$$\eta=2 \text{ } if \text{ } 20\leq \tau_p \leq 30,$$

$$\eta=3 \text{ } if \text{ } 30\leq \tau_p \leq 40,$$

$$\eta=4 \text{ } if \text{ } 40\leq \tau_p \leq 50,$$

$$\eta=5 \text{ } if \text{ } 50\leq \tau_p.$$

The C_p parameter is included in the WSM message when vehicle is broadcasting. Additionally, we refer to the congestion parameter value from the database as C_d.

C. *Localization*

As previously discussed, each street section (for example part of the street between two junctions) has unique identification parameter A_{id}. After node determines its current state, whether there is congestion or not, it does the localization process. This process retrieves the identification of the node's current location and sets A_{id} parameter to this value, and it is included in the WSM message together with the C_p parameter. It is also used to store data received from other vehicles into database.

D. *Aggregation*

Aggregation process is done after congestion detection and its outcome decides if the node will broadcast the message or not. This procedure is responsible for adaptation of broadcast interval according to information that vehicle obtained itself and information it received from other vehicles.

The decision on whether it should broadcast the message or not, vehicle derives from comparison of C_p and C_d parameters for the same area A_{id}. In case $V_c < V_t$ vehicle will broadcast only if $C_p > C_d$. This means that vehicle will broadcast the information only in case it detected higher level of congestion than other vehicles for the same area. This is due to the nature of traffic congestions, which cannot change its state in relatively short period of time [8]. In case $V_c > V_t$ message will be broadcasted only if $C_p \neq C_d$.

E. Broadcasting

Finally, after all previous procedures are finished successfully vehicle might broadcast the message containing C_p and A_{id} parameters. This way all nodes who receive this message will know about traffic situation in A_{id} area. By following previously described steps vehicles will cooperate and only some of them will choose to broadcast instead of all broadcasting periodically.

III. Simulation Setup and Evaluation Results

In order to evaluate the congestion detection mechanism and its impact on vehicular communication we developed simulation environment based on Veins simulation framework [12]. This framework is based on OMNeT++[13] network simulator bi-directionally coupled with SUMO traffic simulator [14]. Both simulators are well-known and have been used for simulations by many authors, while Veins is capable of simulating full 802.11p standard, which is the main reason for choosing it.

A. Simulation Setup

Evaluation of our algorithm is based on two simulations which are bi-directionally coupled: the network simulation and the road traffic simulation , responsible for vehicle's mobility. Since we are interested in managing traffic congestion in urban environments, we modelled Manhattan-like city section in dimensions of 1km x 1km in the SUMO traffic simulator. There are five horizontal streets and five vertical, with junctions at every 250 meters. Each street has two lanes in each direction, and at junctions vehicles are allowed to turn right or left, or to continue moving straight. There are 200 vehicles in the simulation, grouped in 5 traffic flows, each taking different route in total distance of 2000m. We made these routes to intersect at some point in order to simulate high number of vehicles, which is larger than capacity of street sections. This would result in traffic congestion, which we want to detect by our algorithm. Finally, the maximum speed of the vehicles was set to 50km/h. On the other hand, communication between the vehicles is simulated in OMNeT++ by using Veins framework which simulates 802.11p standard and is responsible for coupling with traffic simulation in SUMO.

We implemented our algorithm as application layer module in Veins and we compared it to the broadcasting application layer with fixed broadcast interval. Since most of the VANETs applications will be based on exchanging both beacons and data packets, both of applications we simulated are based on sending beacons and data as well. Beacon interval B_i=*15s* is same for both simulations, while they have different data intervals. First we simulated our proposed algorithm, which we refer to as *Protocol A* and its data interval D_i will be adaptive and depend on level of congestion in the street section. Second simulation we refer to as *Protocol B* and has fixed data interval D_i=*10s*. During this simulation we recorded and evaluated the following parameters:

- Congestion parameter and vehicle's speed,
- Total time average of number of received data packets,
- Average number of sent packets,
- Average number of times when node went in back-off,
- Average total busy time of the node and
- Average data broadcast rate.

B. Results

In order to evaluate congestion detection mechanism we recorded how congestion parameter of each vehicle changes in time, together with its speed. The maximum speed of each vehicle is set at 50km/h (11.11m/s), but the actual speed depends on traffic conditions. Therefore we recorded speed of vehicles to determine if the vehicle really is in the congestion. Additionally, we chose one of the vehicles that was in congestion and plotted its speed and congestion parameter C_p on the same graph, as seen in Fig. *3*. Simulation showed that our congestion detection mechanism precisely quantifies the level of congestion of each vehicle, and as soon as speed becomes lower than threshold our algorithm starts calculating the congestion level. Once the congestion level reaches the maximum value C_p=*5*, it will stay that way until vehicle's speed becomes greater than speed threshold V_t.

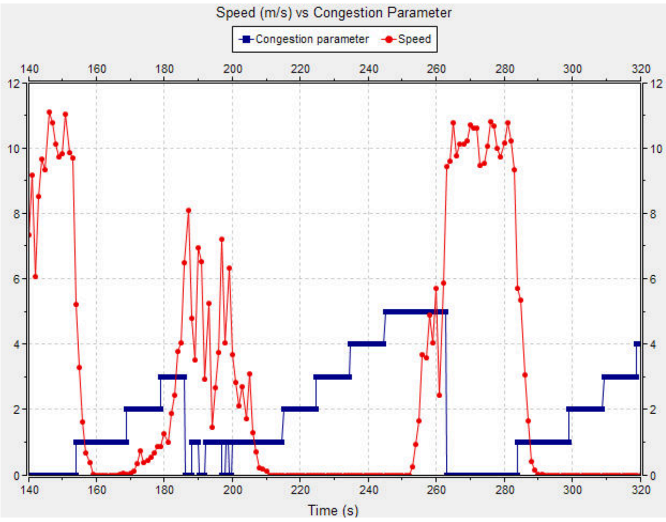

Fig. 3. Congestion parameter of a vehicle against its speed.

Now that we know that our algorithm enables each vehicle to know the congestion level of its current location, we also wanted to prove that vehicle knows correct information about neighbouring areas as well. In order to prove this first we chose one of the areas A_{id} and recorded C_p values for the same area in two vehicles. One of the vehicles visits this area while the other is not going through this area at all, but receives information about it from other vehicles. These C_p values for both vehicles are shown in Fig.4 which shows that they are overlapping most of the time meaning that vehicle which does not go through certain area has correct information about the congestion level there.

After the examination of congestion detection mechanism, we tested its impact on the communication parameters and the network as well. In order to see how congestion detection mechanism impacts the adaptation of data broadcasting interval we recorded several parameters during simulation, including time average of received data packets, number of times each node went into back-off mechanism, total time while node was busy, and we calculated data interval as well. Fig.5. shows time average of received data packets per vehicle plotted against time, showing that adaptation of data broadcast interval according to our algorithm results in reducing the number of received packets compared to conventional broadcasting.

Table.1 shows the overview of parameters at the end of both simulations including previously mentioned parameters. According to these results we can say that our algorithm contributed towards reducing the number of both sent and received data packets, which resulted in less overall contention for the medium which means that there will be less collisions.

Finally, in order to understand how our algorithm impacts the broadcasting interval we calculated average broadcast rate by dividing average number of sent packets per node with average time that each node spent in the simulation. Results show that our algorithm will significantly reduce broadcasting interval of each node.

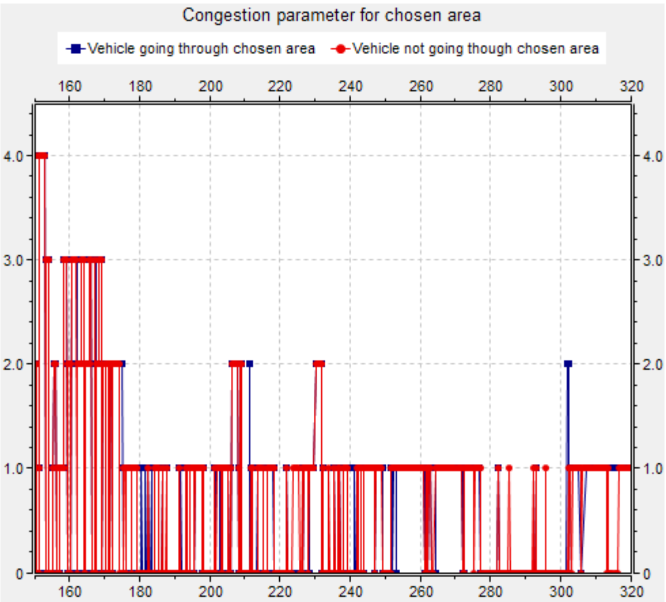

Fig. 4. Comparison of congestion parameters for the same area of vehicles moving on different routes.

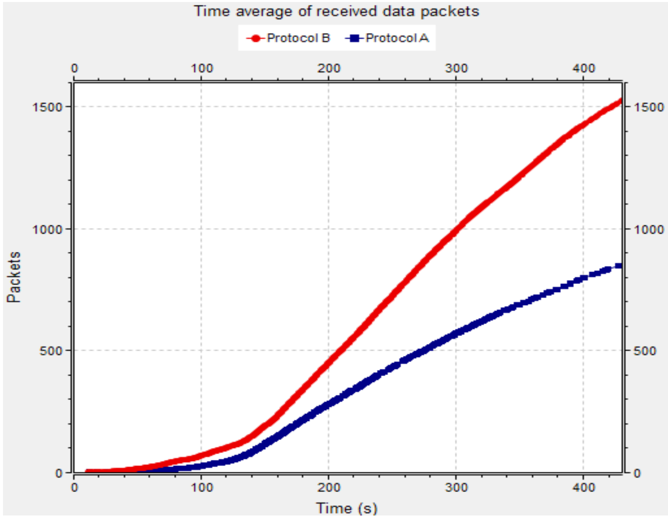

Fig. 5. Time average of received data packets in Protocol A and Protocol B.

TABLE I. OVERVIEW OF SIMULATION RESULTS

Parameter	Protocol A	Protocol B
Average number of sent packets	19	29
Average number of received data packets	1424	2666
Average number of times when node went into back-off	61	80
Average total busy time (s)	0.4	0.55
Average data broadcast rate (packets/s)	0.065	0.096

IV. CONCLUSION

In this paper we presented an algorithm designed to detect and quantify the level of traffic congestion which is based on V2V communication and 802.11p standard. The main contribution of the proposed algorithm is it detects and quantifies the level of traffic congestion in completely distributed way, independent of any supporting infrastructure and additional information such as traffic data from local authorities. It relies solely on observation of traffic conditions by each vehicle and information obtained from other vehicles. Communication is based on adaptive broadcasting. Results show that congestion detection performed by each vehicle corresponds to actual vehicle's speed, and that congestion quantification is correct. Finally, the algorithm ensures that less amount of data is sent which contributes towards reducing the network load, especially important for VANETs since there will be many different applications running on limited number of channels.

Our future work will include development of more advanced cooperative solutions for distributed congestion detection and management.

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