da Costa *et al. Journal of Internet Services and Applications* (2019) 10:15
https://doi.org/10.1186/s13174-019-0114-y

Journal of Internet Services
and Applications

RESEARCH Open Access

Efficient data dissemination protocol based on complex networks' metrics for urban vehicular networks

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Abstract

Services that aim to make the current transportation system more secure, sustainable, and efficient constitute the Traffic Management Systems (TMS). Vehicular Ad hoc Networks (VANETs) exert a strong influence for TMS applications, due to TMS services require data, communication, and processing for operation. Besides, VANET allows direct communication between vehicles, and data are exchanged and processed between them. Several TMS services require disseminated information among decision-making vehicles. However, such dissemination is a challenging task, due to the specific characteristics of VANETs, such as short-range communication and high node mobility, resulting in several variations in their topology. In this article, we introduce an extensive analysis of our proposed data dissemination protocol based on complex networks' metrics for urban VANET scenarios, called DDRX. Each vehicle must build a subgraph to identify the relay node to continue the dissemination process. Based on the local graph, it is possible to select the relay nodes based on complex networks' metrics. Simulation results show that DDRX offers high efficiency in terms of coverage, number of transmitted packets, delay, and packet collisions compared to well-known data dissemination protocols. Also, DDRX provides significant improvements to a TMS that needs efficient data dissemination.

Keywords: Data dissemination, Centrality metrics, Vehicular ad hoc networks

1 Introduction

Vehicular Ad hoc Networks (VANETs) promise a broad scope of services ranging from safety, route recommendation, driver assistance to entertainment [1]. In this context, the Traffic Management System (TMS) is one of the emerging application for VANET, since it aims to minimize the congestion and all related damages caused by traffic jam [2]. In summary, TMS requires data describing traffic patterns, such as density, speed, travel time, and geographic location of vehicles [3]. In this way, the TMS carries out the administration of the traffic flow of vehicles, freeway-traffic-flow management, individualized vehicle path planning, vehicle localization, and other services [4, 5].

VANETs play an essential role in TMS applications since the collected information could be disseminated by the VANET to be delivered to TMS via communication between vehicles (V2V) and between vehicles and any other device (V2X) [6]. However, TMSs have strict requirements regarding low latency communications and real-time responsiveness to perform such tasks. In this context, an efficient data dissemination protocol is mandatory for TMS operations to make the best decisions about congestion detection and vehicle re-routing. However, disseminate data with low overhead and delay, as well as high coverage is not a trivial task, due to VANETs have a dynamic density caused by failures in V2V communication, high mobility and short communication range [7].

The data dissemination through network flooding is the naive approach to disseminating data from a source to all vehicles located within an Area of Interest (AoI). In this approach, the source vehicle transmits the message to all vehicles within its transmission range, and each vehicle achieved also repeats this process. Retransmissions occur successively until the network is flooded with the message.

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Flooding performs well in low density, but it overloads the networking in dense scenarios, creating the broadcast storm problem [8]. Broadcast storm problem is common in dense scenarios, due to the transmissions of redundant messages or multiple transmissions in a short period [9]. Existing data dissemination protocols consider different metrics for relay node selection, reducing the number of transmissions and also maintaining a high coverage [10]. Therefore, data dissemination protocols for VANETs must deal with the broadcast storm problem, high delays, low coverage, and packet collisions [11].

Disseminating data based on contextual knowledge beyond the 1-hop neighbors can further enhance the selection of relay nodes, due to it enables to identify a common point of communication from a topological analysis, e.g., a node that has a higher number of neighbors [10]. In this context, the network can be represented by a dynamic graph, where the vehicles are considered as vertices and the communication links between them as edges. However, a graph with global knowledge increases the overhead and inaccuracy, due to the topology changes caused by moving vehicles. Therefore, vehicles must have topology knowledge of a set of nearby vehicles, e.g., 1 and 2-hops neighbors, to improve the performance for data dissemination [12].

Based on this graph, it is possible to analyze the network behavior based on complex networks' metrics [13]. Complex networks enable the representation of relations between elements of a given network by graphs, helping to indicate the impact that these relationships bring to the network [14]. For instance, cut vertex represents the importance of a given vertex as a function of some graph invariants. Hence, data dissemination protocols can be enhanced with complex networks' metrics.

In this article, we introduce an extensive analysis of our proposed **D**ata **D**issemination p**R**otocol based on comple**X** networks metrics for urban vehicular networks, called **DDRX**, to diagnose the impact of the data dissemination in urban VANET scenario with different vehicle density in two use cases. We also introduce detailed information about the operation of DDRX protocol. Specifically, each vehicle must have contextual knowledge of 2-hops neighbors to build a subgraph, which in this case is the number of hops, to identify the best vehicle to continue the dissemination process. Afterward, DDRX considers complex networks metrics for the decision-making, i.e., betweenness centrality, and degree centrality. In this way, DDRX provides data dissemination with low overhead and delay, maximizing coverage, and minimizing the number of packet collisions.

We performed simulation in two use cases: *i*) disseminating data message within an AoI compared to existing data dissemination protocols; *ii*) DDRX for disseminating data in a well-known TMS application. In the first use case, simulation results showed that DDRX is able to reduce the overhead, collisions and delay in 80.28%, 88.23%, and 33.33%, respectively, compared to existing data dissemination protocols in the literature, keeping the coverage above 95.17%. In the second use case, we concluded that the efficient data dissemination provided by DDRX enhance TMS efficiency by improving traffic conditions, and also network utilization. In particular, the DDRX applied to TMS reduce the congestion time, total travel time, number of pollutant emissions, and fuel consumption.

This article extends our previous work [12, 15, 16] by introducing a detailed description about the operation of DDRX protocol, including algorithm, a description of the complex networks' metrics, and an evaluation about the impact of the number of possible relay nodes (i.e., vCutting) on the number of selected relays. We also introduced an extended evaluation in a more challenging and realistic urban VANET scenario (i.e., downtown of São Paulo city). Therefore, the contributions of this work can be summarized as follows:

i) a distributed approach to identify a set of relay nodes for data dissemination based on complex networks' metrics;
ii) detailed information on the operation of the DDRX protocol, including the two algorithms for the operation of DDRX protocol;
iii) description and mathematical formalism about the considered of the complex networks' metrics by DDRX;
iv) extended evaluation in a more realistic scenario for both data dissemination and traffic management, including new scenario, metrics, and evaluated protocols.

The remainder of this article is organized as follows. Section 2 discusses the relevant related works in this area. Section 3 introduces the system model used in this article, DDRX protocol, and its operation. Section 4 shows the evaluations by simulation of the DDRX performance. Finally, Section 5 presents the conclusions.

2 Related work

This section introduces a state-of-the-art on protocols to provide data dissemination over urban VANET scenarios, and also identifies gaps in the literature, leading investigations to design a data dissemination protocol based on complex network metrics for urban VANET scenarios.

Viriyasitavat et al. [17] proposed the Urban Vehicular broadCAST (UV-CAST) protocol, which focuses on data dissemination for both dense and sparse VANET scenarios. In UV-CAST, each vehicle can operate in one of two states: broadcast suppression or store-carry-forward

(SCF). When a vehicle receives a message for the first time, it checks whether it is an edge vehicle or not, i.e., those that are at the border of a connected component. UV-CAST assumes that these vehicles are more likely to meet new neighbors, and thus, they store the message and carry it until they find a new neighbor. Conversely, if the vehicle is not a border vehicle, it performs a broadcast suppression algorithm to forward the message. However, UV-CAST introduces a high overhead, since each vehicle has to broadcast the packet at each contact with neighbor vehicles that do not received this packet yet.

Ros et al. [18] proposed an Acknowledged Broadcast from Static to highly Mobile (ABSM) protocol. In its operation, it disseminates data messages based on the Connected Dominating Set (CDS), i.e., a set of optimal vehicles to forwarding the message. If a vehicle is not on the CDS, then it is directly connected to some vehicle that is on the CDS. Therefore, if all vehicles on the CDS retransmit the message, then all vehicles on the network will be covered. However, calculating the CDS is a $\mathcal{NP}$-hard problem, since it employed a heuristic that uses information from neighbors to determine if a vehicle belongs to the CDS or not. Vehicles belonging to CDS receive higher priority for message relaying. Besides, ABSM considers periodic beacon message exchange in order to recognize the receipt of messages to ensure data delivery to networks with intermittent connectivity. When a vehicle receives a message, it waits for the recognition of its neighbors and then compute the delay to forward the message. With this, the latency depends on how often beacons are exchanged.

Meneguette et al. [19] introduced the Autonomous Algorithm for Dissemination of Information in Vehicular Networks (ALADDIN). It considers forwarding zones to mitigate the broadcast storm problem, which is an area where the vehicles inside are considered more suitable for disseminating the message, as well as to reach more neighbors. ALADDIN also takes into account the concept of autonomic computing to decide when to relay a data message, which is computed based on a propagation efficiency based on number of messages transmitted and number of beacons received in each vehicle. In this sense, each vehicle knows when to relay or maintain the message. ALADDIN includes unwanted overhead for storing multiple messages when a vehicle identifies a partition on the network (SCF) and finds another vehicle capable of continuing the dissemination process.

Cunha et al. [10] introduced the Clustering Coefficient and node DEGREE protocol (CC-DEGREE), which identifies the best relay nodes based on two metrics: *i*) the clustering coefficient, i.e., the number of connections between a neighboring vehicle divided by total number of connections possible between the neighbor vehicles; *ii*) the node's degree, i.e., number of direct neighbors (1-hop) that this node possesses. From these two metrics, an awaiting timer is assigned for vehicles to continue the forwarding process. However, the CC-DEGREE computes clustering coefficient based only on position of each vehicle, resulting in a low variability for dense scenarios and impacting the relay nodes selection. This leads to the allocation of waiting times similar to several vehicles, increasing the collision probability.

Akabane et al. [9] developed the Context-Aware Routing pROtocol (CARRO), which explores the geographic context knowledge for data dissemination in VANETs. CARRO protocol selects vehicles located in high-priority geographic sectors in its communication radius to continue the dissemination process, that is, in forwarding zones. It also considers the SCF mechanism when the number of vehicles in the same area is not satisfactory to continue the dissemination process. Each vehicle transmits beacons periodically to obtain context information about the neighboring vehicles at 1-hop. However, CARRO considers the SCF to mitigate the network partition problem, which increases the delay. Each vehicle also has to transmit packets in each contact with neighboring vehicles that have not yet received this packet, increasing the overhead.

Bakhouya et al. [20] proposed an adaptive and decentralized approach (AID) for disseminating information in VANETs. The vehicle decides whether or not to forward the message depending on the number of times it receives the same data message at a given time interval. In a dense network scenario, several vehicles may decide to drop the message, since this message has been forwarded by several other vehicles, reducing the broadcast storm problem. However, the AID does not have good results in a sparse and dense network scenario, showing that its strategy of selecting the relay vehicles is not efficient.

Kim et al. [21] proposed a simple and efficient strategy for data dissemination in VANETs, called of Distance Based Relay Selection (DBRS). Upon receiving a data message, the vehicle selected to forward the message is the one that is furthest in the communication radius of the sending vehicle. In this way, it keeps the message for a time interval inversely proportional to the distance to the destination vehicle. If a vehicle scheduled to forward a message overhears the retransmission of that same message from another vehicle, it cancels its retransmission to avoid the broadcast storm problem.

Table 1 summarizes the analyzed data dissemination protocols for the VANET scenarios. We classify these protocols based on two sets of criteria: forwarding strategy and assumptions required for protocol operation. Based on the analysis of data dissemination protocols, we conclude that it is essential to have high coverage for data dissemination in a given AoI, but with low overhead in

Table 1 Summary of data dissemination protocols

Routing protocol	Forwarding strategy used						Assumptions required		
	Position	Statistical	Heuristic	SCF	Distance	Local topology	Beaconing	GPS	Neighbors position
AID [20]		✓							
ABSM [18]			✓			✓	✓	✓	✓
UV-CAST [17]				✓	✓			✓	
ALLADIN [19]	✓			✓	✓		✓	✓	
CARRO [9]	✓			✓	✓		✓	✓	
DBRS [21]	✓				✓			✓	
CC-DEGREE [10]	✓			✓	✓	✓	✓	✓	✓
DDRX	✓				✓	✓	✓	✓	✓

the relay decision process. This involves being aware of the contextual knowledge beyond the 1-hop neighbors without increasing overhead to enhance the relay selection decision, allowing to obtain a high coverage with low overhead and delay.

3 The DDRX protocol

In this section, we introduce DDRX protocol overview and operation. It selects the best relay nodes in a sender-based way to disseminate data over urban VANET scenarios. DDRX reduces the overhead and delays while keeping high coverage by selecting relay nodes based on complex networks' metrics. In this way, each vehicle must maintain the local knowledge of it is in 1 and 2-hops neighbors, which will be used to establish a subgraph, enabling to analyze this subgraph based on complex networks' metrics.

3.1 Overview

Figure 1 shows a data dissemination scenario, where there are a set of vehicles inside an AoI (i.e., red dotted ellipse). The AoI is created from a given event, which has its dimensions defined based on the category of this event [22, 23]. Source vehicle (i.e., the red vehicle in the Figure) has a message to disseminate within the AoI, but it has only 3 neighbors within its radio range. In this sense, the message must be transmitted via relay nodes to reach other vehicles inside the AoI. Hence, the source vehicle has to choose relay nodes to perform the data dissemination with high coverage, as well as low overhead and delay.

In such a scenario, it is required to analyze the iterations between the network nodes to select the best vehicles to retransmit the data message. In this way, we consider using the concept of Complex Networks to analyze the interactions between vehicle pairs. Conceptually, Complex Networks are understood as an abstraction that allows analyzing the relations between pairs of objects in the form of graphs and, also, the impact that such relations bring to this analyzed graph. This graph is called the network. In this context, centrality metrics are essential to quantify the importance of a given node for the network, which is based on certain specific characteristics in the interaction between the nodes and topological structure [24].

Definition I: We consider an urban VANET scenario composed of v vehicles (nodes), and each vehicle has an

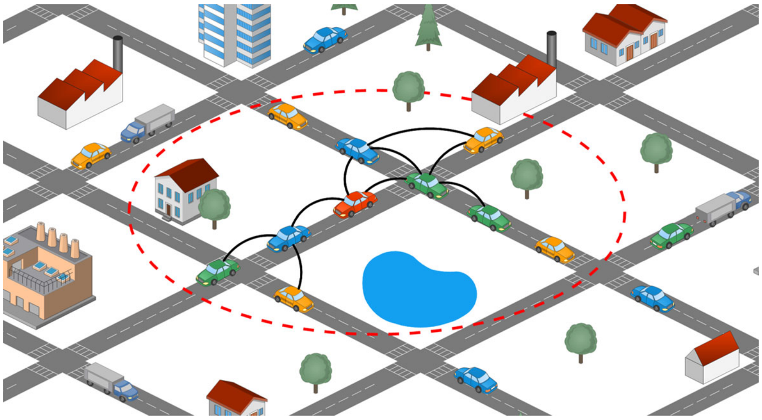

Fig. 1 Data dissemination in a urban VANET scenario

individual identity ($i \in [1, n]$). These vehicles are represented in a dynamic graph $G = (V, E)$, where the vertices $V = \{v_1, \cdots, v_n\}$ represent a finite set of vehicles, and edges $E = \{e_1, \cdots, e_m\}$ build a finite set of asymmetric wireless links between neighbour vehicles. Each vehicle $v_i \in V$ is aware of its own location $L_i(x, y)$ by means of positioning system, such as GPS. We denote $N(v_i) \subseteq V$ as a subset of all 1-hop neighbours within the radio range *radius* of a given vehicle v_i. Further, each vehicle v_i is equipped with an IEEE 802.11p-compliant radio transceiver, through which it can communicate with $N(v_i)$. Each vehicle v_i maintains information of its neighbours, e.g., location, direction, and the neighbourhood of its neighbours. Finally, let $E'_v \subseteq E$ be the set of communication links between v_i and its neighbors $N(v_i)$. Table 2 summarizes the main symbols used in this article.

Each vehicle must maintain local knowledge by creating a subgraph $G[E'_u]$ with all 2-hop neighbors, which is used to select the relay node based on complex networks' metrics. DDRX aims to identify the relay node closer to the communication edge with a higher number of neighbors. It is essential to mention that DDRX does not introduce any additional message overhead to build the subgraph $G[E'_u]$ since it adds some specific fields in the beacon message that are already transmitted by vehicles.

3.2 Neighborhood knowledge discovery

DDRX takes advantage of beacons that are already exchanged by vehicles to obtain the contextual knowledge of its neighbors, avoiding extra overhead. Specifically, each vehicle v_i transmits periodic beacons by default containing its id *id* and other information, where DDRX includes the information about its current position $L_i(x, y)$, and its 1-hop neighbors $N(v_i)$. Upon receiving such beacon, vehicle saves/updates such information on its list of neighbors $listN(v_i)$, constructing an edge-induced subgraph $G\left[E'_u\right]$ with contextual knowledge about 2-hop neighbors for each nearby vehicles $u \in listN(v_i)$. This represents the connection links between the vehicle v_i with its 1-hop and 2-hop neighbors since building a subgraph with a global knowledge increases the overhead and inaccuracy, due to the topology changes caused by moving vehicles.

Table 2 Summary of symbols

Symbol	Description
G	Graph with all the vehicles in the scenario
$V(G)$	G's set of vertices. G
$E(G)$	G's set of edges. G
v	A vehicle $\in V(G)$
$L_i(x, y)$	Current position with of x and y coordinates
id	Unique identification of the vehicle.
$N(v_i)$	Neighbors list at 1-hop of v
$listN(v_i)$	Neighbors list at 2-hop of v
$G[E'_u]$	Subgraph containing the neighbors at 1 and 2-hops
$\phi(v)$	Function for identification of the cut vertex.
$vCutting$	Set of identified Cut Vertices
v_s	Sender vehicle
v_c	Candidate vehicle for data retransmission
R_{max}	Communication radius
T	Time window for updating

Contextual information becomes outdated in a short period due to vehicle mobility. Given this, it is required a mechanism for updating information about nearby vehicles $listN(v_i)$. Existing implementations in the literature consider fully updating the list of neighbors at the end of a time window T or updating the list of neighbors based on the non-receiving of beacons [10, 25]. We consider the first update approach with $T = 4$ seconds, which proved to exhibit promising results, as shown in Section 4. It is also similar to those adopted in other relevant research [26, 27].

3.3 Relay selection

In the relay node selection step, DDRX considers two complex networks' metrics: *i*) degree centrality, and *ii*) betweenness centrality. The degree centrality reflects the popularity of a given vertex in the graph in terms of the number of neighbors [28] computed based on Eq. 1.

$$G(i) = \sum_{j=1}^{n} a_{ij} \tag{1}$$

Where, i means the vehicle that wants to find its degree centrality, j represents all other vehicles, n is the total number of vehicles, and a denotes the adjacency matrix, in which the cell a_{ij} is set to 1 if there is connection to the node j and 0 otherwise.

The betweenness centrality metric indicates the importance of a given vertex for the subgraph $G[E'_u]$ according to the number of minimum paths that travels through such vertex, which is computed based on Eq. 2. In summary, the betweenness is directly related to the vertex whose removal disconnects the network, also called as cut vertex[1] [29, 30].

$$B(i) = \sum_{s \neq t \neq i \in V} \frac{\sigma_{st}(i)}{\sigma_{st}} \tag{2}$$

Where, s, t and i are nodes belonging to the set of nodes V, σ_{st} is the number of minimum paths of node s for node t, and $\sigma_{st}(i)$ is the number of minimum paths from s to t that pass through the node i. However, calculating the betweenness centrality indices for each $v \in G$ becomes

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[1] Also known as Articulation Point.

costly computationally, with complexity $\mathcal{O}(|V||E|)$ using the Brandes' algorithm in unweighted graphs [31].

DDRX applies the Tarjan's Algorithm [32] to find the cut vertices in the subgraph $G[E'_u]$. The key idea of Tarjan's algorithm is to decompose the subgraph $G[E'_u]$ into a Depth-First Search (DFS) tree to find the cut vertices, which represents the most central node. DFS has the complexity of $\mathcal{O}(|V+E|)$, i.e., linear, since it visits every node in $G[E'_u]$ exactly once, declining to revisit any node that has already been visited. In this way, each vehicle finds a set of cut vertices *vCutting* by decomposing its $G[E'_u]$ into a DFS and applying function $\phi(v)$ for each $v \in V(G[E'_u])$ based on Eq. 3. This function returns 1 for each cut vertex.

$$\phi(v) = \begin{cases} 1 & \text{if } v \text{ is root and } N(v_i) > 1, \\ 1 & \text{if } v \text{ is not root with a neighbor } u \\ & \quad \text{such that } N(v_i)\backslash\{u\} \cap N(u_i)\backslash\{v\} = \emptyset \\ 0 & \textit{otherwise} \end{cases} \tag{3}$$

Figure 2 introduces an example of the subgraph $G[E'_u]$ for a given vertex v from the scenario of Fig. 1. In this example, the vertex v has to select a set of relay nodes to perform the data dissemination within the AoI, and thus the vertex v computes the cut vertex based on Eq. 3 from its subgraph $G[E'_u]$. In this way, the vertex v selects the vertices u and x as relay nodes, since they satisfy the conditions imposed in the Tarjan's algorithm. This is because the removal of u and x causes the direct disconnection of s, t and w with the remainder of the subgraph, respectively.

It is important to disseminate the message in all directions in order to increase the protocol coverage. In this way, DDRX identifies in which forwarding zone each cut vertex belongs based on its position. Figure 3 depicts the forwarding zone for the vertex v also for the scenario showed in Fig. 1. DDRX considers 4 zones, namely: *firstZone* = $[0, 90]°$(e.g., vertex y in Fig. 3), *secondZone* = $[91, 180]°$(e.g., vertex u in Fig. 3), *thirdZone* = $[181, 270]°$(without vertex in Fig. 3) or *fourthZone* = $[271, 359]°$(e.g., vertex x in Fig. 3).

Depending on the network density, there might have more than one cut vertex in a given forwarding zone. In this way, DDRX computes a re-transmission gain for each relay node based on Eq. 4. The gain takes into account two factors: *i)* relative distance between the vehicle v and its neighbor u; and *ii)* neighborhood coefficient, which indicates the number of neighbors $|N(v_i)|$, i.e., degree centrality, of a given vehicle v divided by the highest neighborhood degree $maxN(v_i)$ in $G[E'_u]$. All these parameters are multiplied by a value w to maintain the result in the interval $[0, 1]$, as denoted in Eq. 4. DDRX aims to select the relay node that is a cut vertex in each forwarding zone with higher degree centrality and closer to the communication radius.

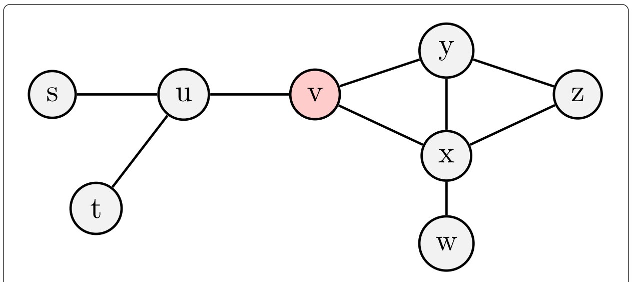

Fig. 2 Subgraph $G[E'_u]$ example considered by DDRX

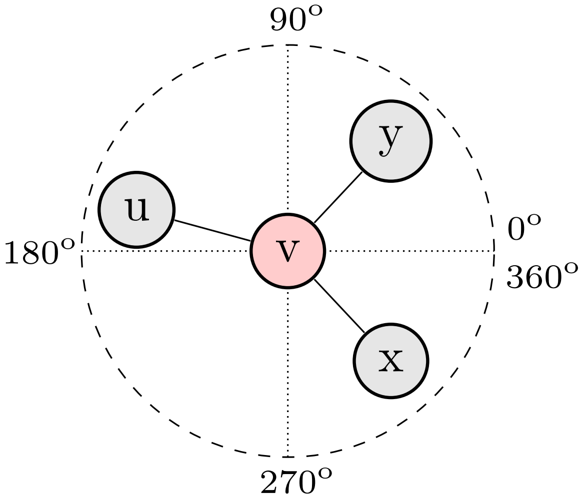

Fig. 3 Forwarding zones

$$\underset{v \in V(G[E'_u]) \mid \phi(v)=1}{\arg\max} \; w\left(\frac{distance(u,v)}{R_{max}} + \frac{|N(v_i)|}{maxN(v_i)}\right) \tag{4}$$

On the other hand, DDRX selects vehicles with the highest number of neighbors, i.e., high degree centrality, as a relay node, as soon as a given forwarding zone has not any cut vertex in the subgraph $G[E'_u]$. This increases the dissemination probability since a relay node with more neighbors might deliver the message to more 1-hop vehicles [10].

After selecting the relay nodes, DDRX adds its respective *ids* in the message and broadcast it. Upon receiving the message, each receiver checks if it has already transmitted such message previously to avoid redundant retransmission. A given vehicle must drop the message, as soon as it has already received. Otherwise, the information about the selected relays contained in the message is checked. As soon as the vehicle has the same *id* as indicated in the message, it starts a new selection process as described above. The algorithm continues until the packet deadline expires or the maximum number of vehicles within the AoI receive such message.

3.4 DDRX's operation

Algorithm 1 introduces the processing of a data message required for DDRX operation, where DDRX selects only the vehicles that are inside the AoI to relay the message *MSG* (line 2). Besides, a vehicle only performs the retransmission as soon as it is the first time it is receiving *MSG* and has been indicated as a relay node in the field *relays* contained in *MSG* (lines 3 and 4), which decreases the number of redundant messages and packet collisions considerably. Hence, the list of neighbors is used to create the subgraph $G\left[E'_u\right]$ to select the best neighbors used to continue the retransmission process (line 4 and 5). The selected relay node identifiers *ids* are included in the field *MSG.relays*, and then a relay scheduling time *st* that follows a uniform distribution ($st \in [0.0, 0.05]$) is established (line 6 to 9). The scheduling time *st* decreases the probability of packet collisions. On the other hand, the algorithm drops the *MSG* as soon as it is not the first time the vehicle receives the message *MSG* (line 10 to 15).

Algorithm 1: onData(MSG)

```
   Input: MSG // Message received
   Output: // Retransmission or not of MSG
1  begin
2      if v is inside in AoI then
3          if new message then
4              if $v \in$ MSG.relays then
5                  list($Nv_i$); // Neighbors list
6                  idRelays ← processGraph(list($Nv_i$)); // Algorithm 2
7                  add idRelays in MSG.relays;
8                  st ← simTime() + uniform(0.0, 0.05);
9                  scheduleAt(st, sendMessage(MSG));
10         else
11             if MSG.isScheduled() then
12                 cancelEvent(sendMessage(MSG));
13                 discard MSG;
14             else
15                 discard MSG;
```

The Algorithm 2 introduces the creation of the subgraph $G[E'_u]$ and the analysis the network behavior based on complex networks' metrics. The algorithm must receive the neighborhood list $list(Nv_i)$ of the vehicle that has the data message to create the subgraph $G[E'_u]$ (line 2). Afterward, it applies the Tarjan's algorithm in the subgraph $G[E'_u]$ to identify the cut vertices *vCutting* (line 3). The algorithm identifies in which forwarding zone each cut vertex belongs by computing the angle between the cut vertex and the vehicle with data message based on location information (line 6).

The algorithm creates a relay list with the best vehicle to relay the data message in each zone (lines 7–22). In this sense, the algorithm selects the relay node in each forwarding zone with the higher re-transmission gain computed based on Eq. 4, and thus it selects the relay node that is a cut vertex in each forwarding zone with higher degree centrality and closer to the communication range.

The same procedures used previously are also valid as soon as the subgraph $G\left[E'_u\right]$ does not have cut vertex (line 24). However, a vehicle with the highest index of degree centrality and closest to the radius of communication is used. The subgraph $G\left[E'_u\right]$ is destroyed to release computational resources from the vehicle since it is no longer valid (lines 23 and 25). Finally, the algorithm returns the relay list with the best vehicle to relay the data message in each zone (line 26).

4 Evaluation setup

In this Section, we introduce the evaluation of DDRX protocol for disseminating data in urban VANET scenario. We present the evaluation methodology and parameter. Afterward, we evaluate the efficiency DDRX in two use cases: *i*) disseminating data message within an AoI; *ii*) DDRX for disseminating data for TMS application. We evaluate the impact of different vehicle densities on the coverage, number of transmitted packets, delay, number of packet collisions, travel time, congestion time, average vehicle speed, travel distance, fuel consumption, and CO2 emission.

4.1 Use case i: data dissemination

We consider a single data message to be disseminated on an AoI to evaluate the DDRX operating alone in VANET without any other application requiring data dissemination. We considered an urban scenario of 1 km^2 from the downtown of São Paulo city[2], Brazil. In such a scenario, we analyzed the performance of DDRX compared to Flooding, AID, DBRS, UV-CAST, CARRO, and CC-DEGREE data dissemination protocols. In the following, we introduce the simulation methodology, evaluation metrics, and results.

4.1.1 Methodology

Simulation experiments have been performed by using the framework Veins 4.3 of the OMNeT++ 4.6 [33]. Veins provide the protocol stack of the IEEE 802.11p standard for V2V communication and an obstacle model for signal attenuation. For the simulation of vehicle traffic and mobility, we considered SUMO (Simulation of Urban

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[2] Available at http://openstreetmap.org/export#map=15/-23.5727/-46.6802

Algorithm 2: processGraph($list(Nv_i)$)

```
    Input: $list(Nv_i)$
    Output: $relayList$ // Nodes selected to
        retransmit message
1   begin
2       $G[E'_u] \leftarrow buildSubgraph(list(Nv_i))$;
3       $vCutting \leftarrow tarjanAlgorithm(G[E'_u])$;
4       if $vCutting.size > 0$ then
5           foreach $i \in vCutting$ do
6               $angle \leftarrow atan2(y_s - y_c, x_s - x_c) \cdot \frac{180}{\pi}$;
                // $x_c$ and $y_c$ are the
                    coordinates of element $i$
                    of the $vCutting$
                // $x_s$ and $y_s$ are the
                    coordinates of the
                    vehicle with the message
7               if $angle \geq 0.0$ & $angle \leq 90.0$ then
8                   $i \leftarrow$ Calculation of Equation 4
9                   if $i \leftarrow max(firstZone)$ then
10                      relayList.set(0,i);
11              else if $angle > 90.0$ & $angle \leq 180.0$ then
12                  $i \leftarrow$ Calculation of Equation 4
13                  if $i \leftarrow max(secondZone)$ then
14                      relayList.set(1,i);
15              else if $angle > 180.0$ & $angle \leq 270.0$
                then
16                  $i \leftarrow$ Calculation of Equation 4
17                  if $i \leftarrow max(thirdZone)$ then
18                      relayList.set(2,i);
19              else
20                  $i \leftarrow$ Calculation of Equation 4
21                  if $i \leftarrow max(fourthZone)$ then
22                      relayList.set(3,i);
23          destroyGraph($G[E'_u]$);
24      else
            // Same steps from lines 6 to
               22.
25          destroyGraph($G[E'_u]$);
26      return relayList;
```

MObility) [34], which is an open source traffic simulator to model and to manipulate objects in the road scenario. This allows us to reproduce the desired vehicle movements with random cruise speed and V2V interactions according to empirical data. We considered an area of 1 km^2 from the downtown of São Paulo city, Brazil, which was obtained through the OpenStreetMap and imported by SUMO to generate the move records of vehicles.

We considered the effects of signal attenuation caused by buildings, where we assume that each block has an 80m x 80m obstacle, which represents high-rise buildings. The vehicles density ranged from 200, 400, 600, 800, and 1000 vehicles/km^2, with an AoI of 1 km^2 to evaluate the impact of vehicle density on the performance of data dissemination protocols. The vehicles speed respects the limits imposed by the scenario, i.e., a maximum of 50 km/h in each of the roads. We set the bit rate on the MAC layer as 18 Mbit/s and the transmit power as 2.2 mW. These parameters, together with the *Two-Ray ground* propagation model results in s communication range of 300 m. We consider 1 Hz as the beacon frequency to be disseminated, and each simulation lasts for 200 s, which is considered as sufficient to evaluate data dissemination algorithms [19].

Once the simulation remains stable, i.e., most of the vehicles were in the scenario, we select a vehicle closest to the center of the scenario to start the dissemination process by transmitting a single data message with a size of 2048 bytes. We performed each simulation scenario 33 times with different randomly generated seeds, and the results present the values with a confidence interval of 95%. Table 3 summarizes the main simulation parameters considered in this use case.

We consider the following metrics to evaluate the performance of data dissemination protocols: *i) Coverage*: percentage of vehicles within the AoI that actually receives data packets; *ii) Number of Transmitted Packets*: total number of data message transmitted by all vehicles during the dissemination process; *iii) Delay*: the average time taken to disseminate a data message from the source to all vehicles within the AoI; and *iv) Collisions*: total number of packet collisions on the MAC layer.

4.1.2 Results

Figure 4 shows the number of possible relay nodes (i.e., *vCutting*), and the number of selected Relays to demonstrate the efficiency in the relay selection performed by DDRX. By analyzing the results, we can conclude that the number of cut vertices grows as vehicle density increases,

Table 3 Simulation parameters for the use case I

Parameter	Value
Transmission power	2.2 mW
Transmission range	300 m
Bit rate	18 Mbit/s
Area of interest	1 km^2
Beacons frequency	1 Hz
Data message size	2048 bytes
Simulation time	200 s

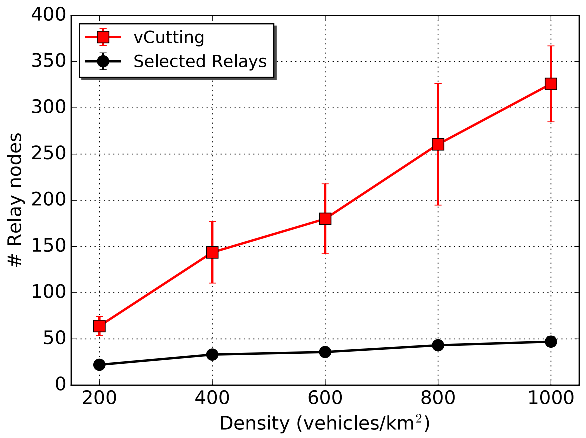
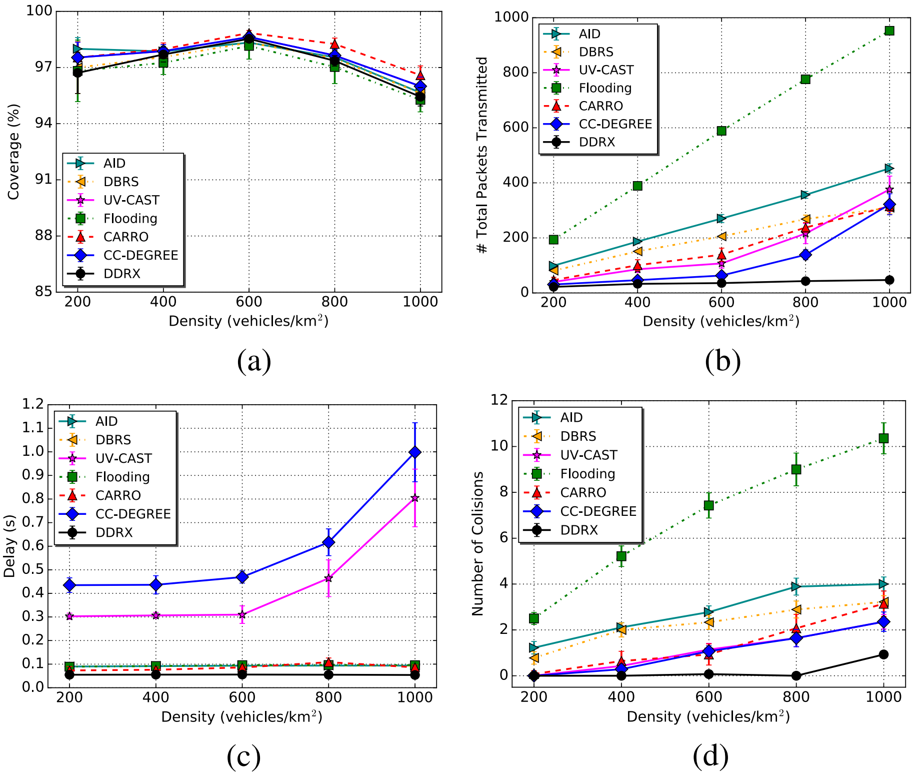


Fig. 4 The number of candidates identified and candidates selected as the relay nodes

since the number of vehicles belonging to the subgraph also increases. More cut vertices provide more possibilities for relay node selection. It is essential to highlight that DDRX efficiently selected almost the same number of relay nodes at all densities, without compromising acceptable levels of coverage. The trade-off between coverage and retransmission will be discussed later.

Figure 5a presents the coverage reached by data dissemination protocols evaluated. By analyzing the results, we can observe that all protocols reach at least 96% coverage in lower density and above 95% in higher density. The AID protocol even in the smallest density, reaches 98.2% of coverage, but as the density increases its coverage decays compared to the CARRO protocol. The CC-DEGREE has 97.8% coverage in the smallest density and exceeds the other protocols in the highest density, with 96.9% coverage. This behavior also occurs with other protocols. The DDRX protocol stands out for increasing its coverage according to increased density, that is, increases from 96.9% to 98.9% up to 600 vehicles, but has decay in coverage as the other protocols. DDRX has a lower coverage compared to other protocols at lower densities since the CC-DEGREE and CARRO protocols consider the SCF mechanism to guarantee delivery of messages while Flooding it sends the data indiscriminately, the AID protocol selects the relays statistically, and the DBRS protocol considers only distance for the relay selection. The coverage rates achieved by the Flooding are reflected from the lack of selection of relay nodes, impacting on the increase in the number of transmissions, as shown in Fig. 5b.

Figure 5b depicts the number of transmissions that each protocol needs to disseminate data on the network.



(a) (b)

(c) (d)

Fig. 5 Evaluation of the DDRX data dissemination protocol. **a** Coverage. **b** Transmitted messages. **c** Delay. **d** Collisions

DDRX decreases the number of transmissions at 93.76%, 86.74%, 82.17%, 78.40%, 78.05%, and 69.87% compared to Flooding, AID, DBRS, CARRO, UV-CAST, and CC-DEGREE protocols, respectively. This is because DDRX selects relay nodes in each forwarding zone. Especially, CC-DEGREE protocol considers the transmission of the packet in each contact with a neighboring vehicle that has not yet received this package, increasing the number of transmissions and delays as shown in Fig. 5c. As expected, Flooding has a high number of transmissions, due to all vehicles receiving the data message perform the transmission process again. Both CC-degree and DDRX use centrality metrics to select relay nodes. However, the CC-DEGREE increases the number of transmissions by not combine metrics of centrality to refine the choice of the relays further. It is important to emphasize that it is essentially data dissemination with a low number of transmissions do not affect the performance of other applications that share the wireless channel.

Figure 5c shows the delay for data delivery. DDRX protocol disseminates the message with 89.84%, 86.37%, 33.34%, 33.34%, 33.34%, and 25.01% lower delay than the CC-DEGREE, UV-CAST, AID, AID, DBRS, Flooding, and CARRO protocols, respectively. The CC-DEGREE and UV-CAST deliver the message with more delay compared to the other protocols in both sparse and dense scenarios, since CC-DEGREE and UV-CAST consider the SCF mechanism. The CARRO protocol delivers the message with lower delay, even considering the SCF since it does not exclusively consider the SCF for message delivery verification. As can be seen, the selection of relays in the AID and DBRS protocols do not employ considerable delay in the retransmission of the data message. Finally, DDRX protocol delivered the data with a delay of 0.05 s, since the scheduling time obeys the range [0.0, 0.05] as shown in Algorithm 1. A low delay is important to some applications, such as the dissemination of warning messages or congestion detection.

Figure 5d shows the average number of packets collisions on the MAC layer. This enables us to observe how the protocols deal with the aspect of the distributed operation. As expected, Flooding has the highest number of collisions, being the result of non-coordination in the process of packet retransmission, since many vehicles access the channel at the same time. DDRX protocol has 97.11%, 92.86%, 91.08%, 85.40%, 81.98% and 81.30% a lower number of collisions than Flooding, AID, DBRS, CARRO, UV-CAST, and CC-DEGREE, respectively. This is due to the efficient relays selection performed by DDRX, where the number of candidates is reduced from the identification of the cut vertices in each forwarding zone, and also by assigning a uniform distribution at the time the selected vehicles schedule their transmissions.

4.2 Use case iI: traffic management system

We analyze the relevance of an efficient data dissemination protocol for a TMS service to make the best decisions about congestion detection and vehicle re-routing. We considered an urban scenario of 2.5 km^2 from the downtown of São Paulo city[3], Brazil. In such a scenario, we analyzed the performance o DDRX in terms of travel time, congestion time, average vehicle speed, travel distance, fuel consumption, and CO2 emission. In the following, we introduce the simulation methodology, evaluation metrics, and results.

4.2.1 Methodology

We considered a region of 2.5 km^2 of the downtown of São Paulo city, Brazil, extracted from the tool OpenStreetMaps and implemented on Veins OMNeT++ framework. We considered a vehicle density of 1500 vehicles/km^2 to guarantee the occurrence of congestion. The vehicles speed respects the limits imposed by the scenario, i.e., a maximum of 50 km/h in each of the roads. We set the bit rate on the MAC layer as 18 Mbit/s and the transmit power as 2.2 mW. These parameters, together with the Two-Ray ground propagation model, results in a communication range of 300m. We consider 1 Hz as the beacon frequency, and each simulation lasts for 7500 s. We consider 100 s for the rerouting range [35, 36]. We performed each simulation scenario 33 times with different randomly generated seeds, and the results present the values with a confidence interval of 95%.

We implemented DDRX in a TMS called FASTER [37], where it segments the scenario in different districts (i.e., sub-regions) to aggregate the traffic information of the roads. Each vehicle collects and transmits data of average speed and identification of the pathways in its radio range through beacons. FASTER is divided into two phases, the first aggregates the traffic information in one same district, and the second sends information to other districts. This reduces the overhead in the network for the construction of global traffic knowledge. We considered DDRX to eliminate the first data dissemination, i.e., the creation of knowledge in each district, causing the dissemination of traffic knowledge in the whole scenario.

We conducted simulations with three sets up Original Vehicular Mobility Trace (OVMT), FASTER [37], and DDRX. The OVMT means a baseline scenario without any TMS mechanism. On the other hand, FASTER divides the data dissemination into two steps, i.e., intra- and inter-districts, such as explained in Section 2. Finally, DDRX is used to create traffic knowledge in single dissemination for the whole scenario, such as described above. Vehicles considering a TMS could be rerouted in order to minimize the congestion and all related damages caused by traffic

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[3] Available at http://openstreetmap.org/export#map=15/-23.5727/-46.6802

jam, which impacts the performance of a TMS in terms of travel time, congestion time, average speed, total distance, CO2 emission, and fuel consumption. We consider the following metrics to evaluate the protocols based on TMS point of view: *i) Travel Time:* quantifies the total time for vehicles to complete their travels on the scenario; *ii) Congestion time:* average time of vehicles stopped in traffic jams; *iii) Average speed:* average speed reached by vehicles from the beginning to the end of their travels; *iv) total distance:* average distance traveled by all vehicles; *v) fuel consumption:* average fuel consumption of all vehicles; and *vi) CO2 emission:* average CO2 emission of all vehicles. We considered EMIT model to compute CO2 emission and fuel consumption. EMIT is a simple statistical model to compute instant CO2 emissions and fuel consumption based on vehicles acceleration and speed, which is derived from the HBEFA (Handbook Emission Factors for Road Transport), which implemented in framework Veins [38].

4.2.2 Results

Figure 6a shows the travel time for OVMT, FASTER, and DDRX. As expected, the OVMT has the longest travel time, since it has no mechanism to control the congestion that occurred. As a consequence, the vehicles have an average congestion time of 41.16 min, i.e.. approximately 94.51% of all travel time (see Fig. 6b). In contrast, both DDRX and FASTER detected congestion based on traffic information dissemination phases, and thus they manage to reduce travel time by 49.62% and 37.24% respectively. Regarding congestion time, DDRX and FASTER reduce by 76.11% and 62.24% compared to OVMT. The DDRX provides better results than OVMT and FASTER since it provides efficient data dissemination to build global traffic knowledge faster, which directly impacts the improvement of road traffic.

TMS must compute new routes with lower traffic congestion, and thus it is crucial to analyze the average speed reached by the vehicles, indicating that the vehicles were not routed to roads with a high rate of congestion (see Fig. 6c). As the OVMT keeps the vehicles stationary in traffic jams, the average speed reached is around 7.38 km/h. On the other hand, DDRX and FASTER reached an average speed of 15.47 and 14.31 km/h, respectively, but they increased the traveled distance at 142.56% for

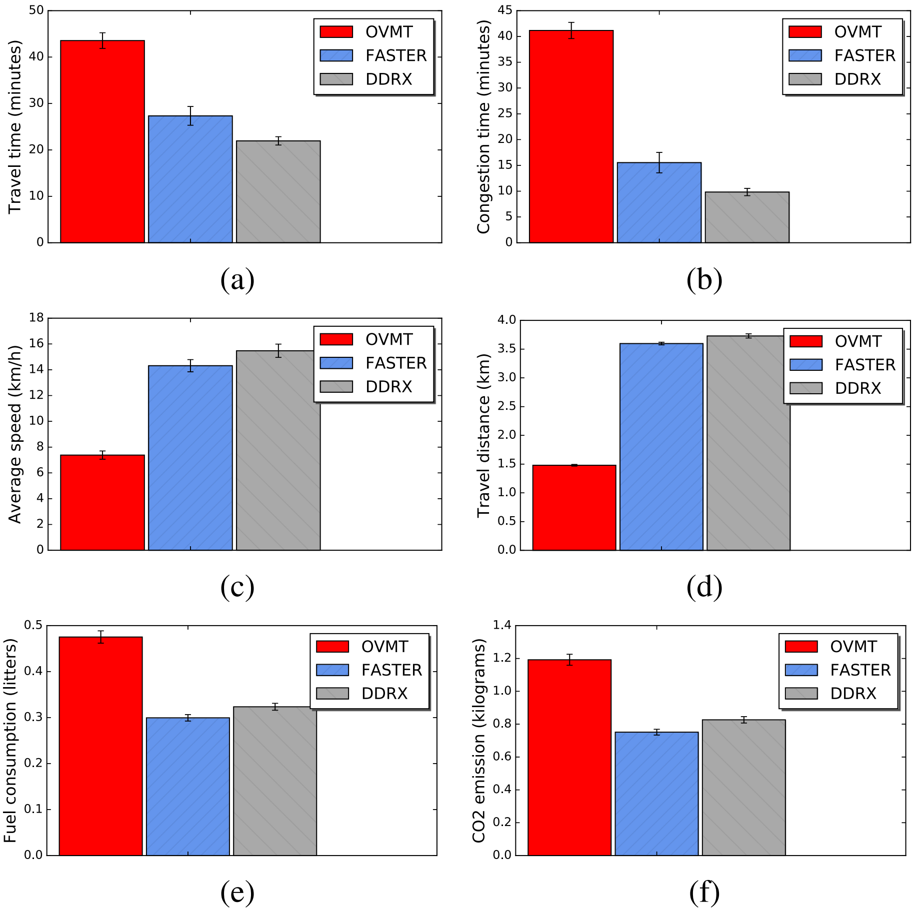

Fig. 6 Evaluation of the DDRX for traffic management. **a** Travel time. **b** Congestion time. **c** Average speed. **d** Total distance. **e** Fuel consumption. **f** CO2 emission

FASTER and 151.35% for DDRX (see Fig. 6d). The longest distance traveled by DDRX is due to the selection of new routes, where many vehicles can select longer routes to avoid congestion.

Figure 6e and f show the fuel consumption and CO2 emissions by OVMT, FASTER, and DDRX to evaluate the impact of vehicle rerouting, which is directly related to travel time, congestion time, and distance traveled. OVMT has an average fuel consumption of 0.47 l, while FASTER and DDRX reduces fuel consumption by 38.29% and 31.91%. This is due to the shorter time the vehicles were trapped in the traffic jam. Also, FASTER and DDRX decrease CO2 emissions by 36.97% and 31.09% compared to the OVMT, respectively, for the same reasons of fuel consumption.

5 Conclusion

Data dissemination over VANET is a challenging task due to the specific characteristics of VANETs, such as highly dynamic mobility, short time of contact between vehicles, and short-range communication. In this way, this article showed the efficiency of the DDRX for data dissemination with low overhead, collisions, and delay, while keeping high coverage. In DDRX, each vehicle must maintain local knowledge of its 1 and 2-hops neighbors, which will be used to construct a subgraph. Based on such subgraph, DDRX selects the best vehicles to retransmit the message based on network complex metrics, i.e., betweenness centrality, and degree centrality.

Simulation results showed that DDRX reduces delay, overhead and collisions, maintaining good coverage compared to AID, DBRS, UV-CAST, CC-DEGREE, CARRO, and Flooding protocols. Additionally, DDRX was evaluated by operating in conjunction with a TMS, called FASTER, which requires efficient data dissemination to make decisions about traffic management for congestion control. Results showed that DDRX enhanced FASTER performance in the process of vehicle rerouting. Thus, it is demonstrated that the efficient dissemination of data is fundamental for the proper functioning of TMS services. As future works, we intend to apply other centrality metrics in the algorithm and utilize the DDRX concepts for creating a TMS that is based entirely on complex network metrics.

Abbreviations

ABSM: Acknowledged broadcast from static to highly mobile; AID: Adaptive approach for information dissemination; ALLADIN: Autonomous algorithm for dissemination of information in vehicular networks; AoI: Area of interest; CARRO: Context-aware routing pROtocol; CC-DEGREE: Clustering coefficient and node DEGREE; CDS: Connected dominating set; DBRS: Distance based relay selection; DDRX: Data dissemination pRotocol based on compleX networks metrics; DFS: Depth-first search; DSP: Dynamic shortest path; EBkSP: Entropy balanced k shortest paths; EcoTrec: Eco-friendly routing algorithm for vehicular traffic; FASTER: Fully-distributed VANET-based TMS to improve vehicle traffic efficiency; FOX: Fast offset XPath; GPS: Global positioning system; OVMT: Original vehicular mobility trace; RkSP: Random k shortest paths; RSU: Road side units; SCF: Store-carry-forward; SUMO: Simulation of urban mObility; TMS: Traffic management systems; UV-CAST: Urban vehicular broadCAST; VANET: Vehicular ad hoc networks; V2V: Vehicle-to-vehicle; V2X: Vehicle-to-everything

Acknowledgements

This work was partially supported by the grant 2018/16703-4 of the Sao Paulo Research Foundation (FAPESP). The authors would like to thank the grants 304673/2016-1, 308003/2015-2, 401802/2016-7, and 431474/2016-8, Brazilian Research Council (CNPq) for financial support.

Authors' contributions

All authors contributed equally. All authors read and approved the final manuscript.

Funding

Not applicable.

Availability of data and materials

Please contact the author for data requests.

Competing interests

The authors declare that they have no competing interests.

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Received: 12 December 2018 Accepted: 16 July 2019

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