Clustering and 5G-enabled Smart Cities: A Survey of Clustering Schemes in VANETs

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ABSTRACT

This chapter highlights the importance of Vehicular Ad-hoc Networks (VANETs) in the context of the 5G-enabled smarter cities and roads, a topic that attracts significant interest. In order for VANETs and its associated applications to become a reality, a very promising avenue is to bring together multiple wireless technologies in the architectural design. 5G is envisioned to have a heterogeneous network architecture. Clustering is employed in designing optimal VANET architectures that successfully use different technologies, therefore clustering has the potential to play an important role in the 5G-VANET enabled solutions. This chapter presents a survey of clustering approaches in the VANET research area. The survey provides a general classification of the clustering algorithms, presents some of the most advanced and latest algorithms in VANETs, and it is among the fewest works in the literature that reviews the performance assessment of clustering algorithms.

INTRODUCTION

Nowadays, smart cities represent a very important research direction for academia, industry and governments that are eager to embrace various technologies, which will make cities "smarter". The main purpose of smart cities is to improve all the facilities provided in a city (e.g. buildings, infrastructure, transportation, energy distribution, etc.) in order to improve the citizens' quality of life, while creating a sustainable environment. Related to the transport, the declared aim of smart cities is to promote sustainable forms of transportation, to build intelligent public transportation systems based on real-time information, traffic management systems for congestion avoidance, safety applications (e.g. collision avoidance) and green applications (e.g. intelligent routing aiming to reduce fuel consumption, gas emissions or energy consumption). Moreover, self-driving cars play an important role in the context of smart cities, due to their potential of improving citizen's life by improving their comfortability. Various statistics demonstrate that people are spending a lot of their time in the vehicles, in traffic[1]. Self-driving cars would allow people to spend this time in a useful or relaxing manner (e.g. working, reading or simply sleeping).

In this context, Vehicular Ad-hoc Networks (VANETs) or simply vehicular networks represent a hot research topic both for academia and industry due to their high potential to create not only smarter cities, but also smarter roads. This potential relies in the *on the wheels connectivity* provided by VANETs that can also meet the *always connected* need of drivers and passengers as they are spending much of their daily time in their vehicles. Moreover, VANET has a crucial role in the context of self-driving vehicles (Ydenberg, Heir & Gill, 2018). VANETs are based on "smart" vehicles that are able to communicate to each other and to the infrastructure via vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I)

[1] http://inrix.com/scorecard/

communications, known under the generic term of V2X communications, but also via other wireless communications technologies (e.g. cellular, WLAN).
V2X communications are considered the dedicated enabling technology of VANETs. They have exclusively dedicated spectrum that is of high importance particularly for safety applications. As this technology has a low penetration rate and also some limitations (i.e. short-lived and intermittent connectivity), in some architectures, other access technologies are employed as well, in order to support the diversity of VANET applications (i.e. safety, traffic management and infotainment applications). Due to the importance of VANET, cellular technologies that have a high market penetration have considered to accommodate this type of communications starting from 4G. More improvements and developments are planned in 5G. LTE for instance was mainly considered for the communication between vehicle and infrastructure because according to the studies performed, it seemed to be unable to support the huge amount of messages exchanged by vehicles during rush hours. The general consensus is that VANETs and their diversity of applications cannot rely on a single type of access technologies. Thus there is a need of bringing together multiple technologies, V2X communications, cellular technologies and WLAN, in order to enable support for a wide range of VANET applications.
In this context, clustering can play a very important role in the design of VANET architectures: on one hand clustering addresses some of the V2X communications limitations such as sparse deployment of the infrastructure, and intermittent connections and on the other hand it optimizes the communication via cellular access technology. In addition, clustering algorithms in VANET address some of the main VANET challenges: scalability and stability, and have been integrated in a various range of applications. This chapter presents a thorough survey of clustering algorithms in VANETs.
There are some reviews in the literature dedicated to clustering in VANET (Vodopivec, Bester & Kos, 2012; Cooper, Franklin, Ros, Safaei & Abolhasan, 2017), but these do not provide any classification of the performance assessment of these algorithms. This review is an extension of the one presented in (Tal&Muntean, 2014) and similar to this is trying to address a gap that there is in the literature, namely the lack of a well-structured analysis of the performance assessment of clustering algorithms in VANET, while considering new and significant stages in this research field.
The structure of the chapter is as follows. In the first sections, an overview of vehicular networks, their enabling technologies, applications and challenges is presented. The following sections are dedicated to clustering: general concepts of clustering, survey of clustering in VANETs – application, classification, performance assessment and representative algorithms. The chapter ends with future directions and conclusions.

BACKGROUND

Introduction to VANETs

Vehicular Ad-hoc Networks (VANETs) or simply vehicular networks are a specific class of mobile ad-hoc networks (MANETs), where the mobile nodes are represented by vehicles. Although they are a class of MANETs, they have specific characteristics that differentiate them, characteristics which will be discussed in a dedicated section. VANETs are mostly based on the communication between vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) or infrastructure-to-vehicle (I2V), generally referred to as V2X communications. This type of communications is mainly supported by a specific type of wireless access called Wireless Access for Vehicular Environment (WAVE). WAVE contains the standards dedicated to vehicular environment (Uzcategui & Acosta-Marum, 2009): IEEE 802.11p and IEEE P1609.x standards. IEEE 802.11p, developed to provide wireless access in vehicles, is a new amendment of IEEE 802.11 standard body (IEEE 802.11p, 2010). This is a justified decision in the context of the wide adoption and subsequently the low cost of IEEE 802.11 technologies. Both, IEEE 802.11p and IEEE 1609.x standards, are based upon the allocation of Dedicated Short Range Communications (DSRC) spectrum band. This initiative, started in USA in 1999, allocated dedicated spectrum of frequency to be used exclusively by V2X communications. In Europe, spectrum allocation was harder to achieve, as each country has different regulations, but agreement was eventually made on a spectrum similar to the USA. Seven channels of

10MHz in the 5.9GHz range are allocated for use in DSRC/IEEE 802.11p standard. Out of the 7 channels, 6 are service channels (SCH), while the one left is the control channel (CCH). CCH is reserved for system control and safety messages, an SCH channel is dedicated to safety messages as well, whereas the rest of SCHs are mainly used to exchange non-safety and larger data.

While IEEE 802.11p covers the Physical and MAC layers, IEEE P1609.x covers the entire VANET scope of services from application down to the MAC layer.

- IEEE P1609.1 (IEEE P1609.1, 2006) is the WAVE Resource Manager standard, defining the interfaces and services of WAVE applications and the format of data messages.
- IEEE P1609.2 (IEEE P1609.2, 2006) is the WAVE Security Services for Applications and Management Messages standard that defines the WAVE security: anonymity, authenticity and confidentiality and also the exchange of messages.
- IEEE P1609.3 (IEEE P1609.3, 2007) is the WAVE Networking Services that defines routing and transport services. It provides description and management to the protocol stack, network configuration management and also provides the transmission and reception of WAVE short messages.
- IEEE P1609.4 (IEEE P1609.4, 2006) is the WAVE Multi-channel Operations that provides the DSRC frequency band coordination and management.

In addition to V2X communications, other types of technologies are also used in supporting vehicular applications. Depending on how these VANET enabling technologies are employed in the vehicular applications, three types of VANET architectures are defined: pure ad-hoc, pure WLAN/cellular and hybrid (K.C. Lee, U. Lee & Gerla, 2010).

In the ad-hoc architecture, there is V2V communication only, without any infrastructure support. This scenario is feasible since the infrastructure and wireless access points are not everywhere and their deployment is limited by the cost or geography. Information exchanged between vehicles can be of extreme value, especially in difficult conditions or special circumstances (e.g. an icy road section previously detected by another car or an accident blocking the road).

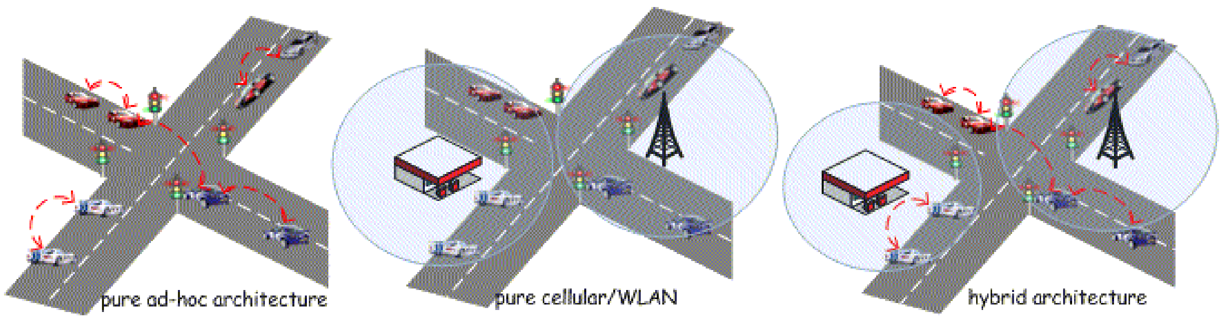

Figure 1. VANET Architectures

In WLAN/cellular architecture, cellular base stations and WLAN access points facilitate vehicles' connection to the Internet and provide support for vehicular communications-based applications. Initially, in this type of architecture, the vehicles did not have support for directly communication with each other in a distributed manner with few exceptions. In this context, clustering can be successfully employed to limit for instance the cellular network communications. However, starting with 4G important steps have been made towards direct communication between vehicles. From Release 12 (Rel.12) a new feature known as Proximity Services was specified within 3GPP[2]. Proximity Services Direct Discovery and Proximity Services Direct Communication enable Device-to-Device (D2D) communications (Lin, Andrews, Ghosh & Ratasuk, 2014). However, this release of the Proximity Services specification has not considered the requirements of V2X communications as it provides low mobility support. Therefore, D2D

[2] 3GPP TS 23.303. (July 2015). Proximity-based services (ProSe); Stage 2.V12.5.0 (Rel-12).

communications specified in Rel.12 is not really suitable for V2V communications, especially not in highway scenarios characterized by high speeds. Cellular V2X communications, also called C-V2X was standardized in 3GPP based on LTE Release 14[3], but this supports basic safety scenarios only. Improvements of these specifications aiming to support the diversity of VANET applications are planned in 5G[4].

In the hybrid architecture all types of communications are present. Vehicles can talk to each other and exchange information (V2V communications), but also can communicate with fixed infrastructure that is deployed alongside the road also referred to as *road side unit* (RSU) (V2I) or with access points, or wireless towers (WLAN, cellular). This is the most complex architecture and provides support for more complex applications. Especially infotainment applications which require richer content are based on this type of architecture, but also complex traffic management systems. Similar to the previous architecture, clustering can be a viable solution for an optimal communication between vehicle to infrastructure, if this is done via cellular technologies. In the case of V2I communications, clustering can be the response to limited range of communications, sparse deployment of RSUs and intermittent communication.

In VANET architectures the communication capabilities of a vehicle are provided by an in-vehicle component referred to as the *on-board unit* (OBU) that can have multiple network interfaces (V2X, UMTS, LTE, etc.). Note that this component was envisioned to be integrated in the cars by the car manufactures, but in the latter VANET solutions OBU can stand for different devices with wireless capabilities such as the driver's smartphone. OBU also supports intra-vehicle communication needed to collect the data from the vehicle's sensors and devices, data that is then used in the applications enabled by VANET. Most VANET applications assume that the position of the vehicle is known, so a GPS or other positioning system is considered to be integrated in OBU (or co-exist with OBU).

VANET Applications

A large plethora of applications have been envisioned and proposed for VANETs. These can be categorized in three big classes (Karagiannis et al., 2011): active road safety applications, traffic efficiency and management applications and infotainment applications. Moreover, VANET is considered one of the main enabling technology of self-driving cars (Ydenberg, Heir & Gill, 2018).

Active road safety applications aim to provide a safer driving environment by reducing the probability of accidents and preventing the loss of lives. Such applications are traffic signal violation warning, emergency electronic brake light, pre-crash sensing, lane change warning, cooperative forward collision warning, etc. These are mainly pro-active approaches that are trying to avoid accidents. Reactive safety approach based on VANETs can be developed in the context of emergency systems. "Green" routes for emergency vehicles can lead to saving many human lives. In their survey, Martinez, Toh, Cano, Calafate, & Manzoni (2010) emphasized on both the great potential of V2I/V2V communications in enhancing the emergency services and the need of designing systems based on this type of communications that ensure efficient emergency service delivery. The architecture and principles of a complete solution, a VANETs-based traffic management system ensuring "green" routes for emergency vehicles has been proposed in (Djahel, Salehie, Tal, & Jamshidi, 2013).

Traffic efficiency and management applications' goal is to improve the overall efficiency of transportation by managing the navigation of the vehicles via cooperative co-ordination (e.g. cooperative adaptive cruise control (Chang, Tsai & Liang, 2017)). Also, they aim to improve not only the overall efficiency, but the efficiency per vehicle via speed management applications (e.g. avoiding stopping to the

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[3] 3GPP Release 14, http://www.3gpp.org/release-14

[4] 5G Americas whitepaper, Cellular V2X Communications Towards 5G, http://www.5gamericas.org/files/9615/2096/4441/2018_5G_Americas_White_Paper_Cellular_V2X_Communications_Towards_5G__Final_for_Distribution.pdf

intersections (Rakha & Kamalanathsharma, 2011)). This type of applications is situated somewhere at the border between safety and infotainment applications.
Infotainment applications are applications that are not directly related to traffic safety or efficiency, but they are designed for the needs and comfort of the users. These applications can be split into two big classes: entertainment applications and driver assistance applications.
Entertainment applications include solutions for different service delivery such as for instance live video streaming or multimedia delivery over VANETs (Lobato, Rosario, Gerla & Villas, 2017).
Driver assistance applications comprise countless VANETs-based solutions. This type of applications provide driver with useful information in driving process, but not only (e.g. applications that provide valuable information for driver, such as price of fuel or closest charging station, etc. are also included). Example of such applications are routing applications (Doolan & Muntean, 2017), free parking discovery applications (Lu, Lin, Zhu & Shen, 2009), applications that give driving/riding advices based on certain criteria: e.g. how to drive/ride in certain conditions in order to reduce gas emissions, fuel (Rakha el al., 2011) or energy consumption in the case of electric cars (Tielert, Rieger, Hartenstein, Luz & Hausberger, 2012) or electric bicycles (Tal, Zhu & Muntean, 2013; Tal, Ciubotaru & Muntean, 2016), etc.

VANET Characteristics and Challenges

VANETs have specific characteristics that differentiate them from any other type of ad-hoc networks. Some of these characteristics are very attractive for the researchers, while the others are creating new technical challenges that need to be addressed. The following features are among the attractive ones:
Theoretical unlimited power is considered due to the fact that any vehicle-node is capable of generating power while moving. In the case of classic MANET mobile nodes, power is a very serious issue. However, this VANET characteristic is not applicable to the case of electric vehicles (EVs), where energy preservation is vital for increasing the travel range.
High computational and storage capabilities; unlike the handheld devices in classic MANETs, vehicles can afford significant computational, storage and communication capabilities. This capability is partially made possible by the previously mentioned characteristic.
Predictable mobility is possible in VANETs due to the fact that vehicle movement is constrained by the roads, traffic regulations and driver behavior. So, given parameters such as the current position, current speed, route, average speed and/or learning about driver behavior, it is possible to predict the next position of the vehicle. On the contrary, the node mobility in classic MANETs is very hard to predict.
The challenging set of VANET features includes:
High mobility; vehicle-nodes have very high speed compared to the nodes from MANETs. In highway scenarios speeds of up to 300km/h may occur, while in city scenarios speeds of up to 70km/h.
Rapidly changing topology; the aforementioned high node mobility in VANETs leads to a frequent link disconnection between the vehicle-nodes and consequently to a rapidly changing network topology.
Diversity of conditions; mainly refers to the diversity of the network density that can be very sparse or on the contrary, very dense. In a city scenario, especially during rush hours, the network is extremely dense, while in a highway scenario the network can be very sparse.
Frequent disconnections in the network; mainly caused by the two previously mentioned characteristics. Road dead-ends is another factor that can produce frequent disconnections in VANETs.
Potentially large scale VANETs are networks with a potential high number of nodes. There is no limitation in terms of number of nodes, as it is in the case of other networks, so vehicle-nodes can potentially expand over the entire road network.
Diversity of applications; as presented in the previous section, a large plethora of applications have been envisioned for VANETs in the areas of traffic safety, traffic management and efficiency, and infotainment ranging from multimedia applications to driver assistance services. The requirements of these applications are as diverse as their range is. Consequently, much VANET- dedicated technology needs to be designed so these networks can cope with all this diversity of applications.

CLUSTERING AND VANETS

Introduction to Clustering

Clustering is a division technique that creates groups of similar objects (Wanner, 2009) mainly with the purpose of dealing with scalability. The similarity between objects is built upon one or more clustering metrics that are extremely varied and highly dependent on the context clustering is applied in. Clustering is widely used in data analysis, data mining, statistics, text mining, information retrieval, etc. Clustering has been widely adopted in MANETs, as it provides support for good system performance, good management and stability of the networks in the presence of mobility and large number of terminals (Yu & Chong, 2005). Thus, clustering helps solve some of the main issues in MANETs: scalability and stability (Wanner, 2009).

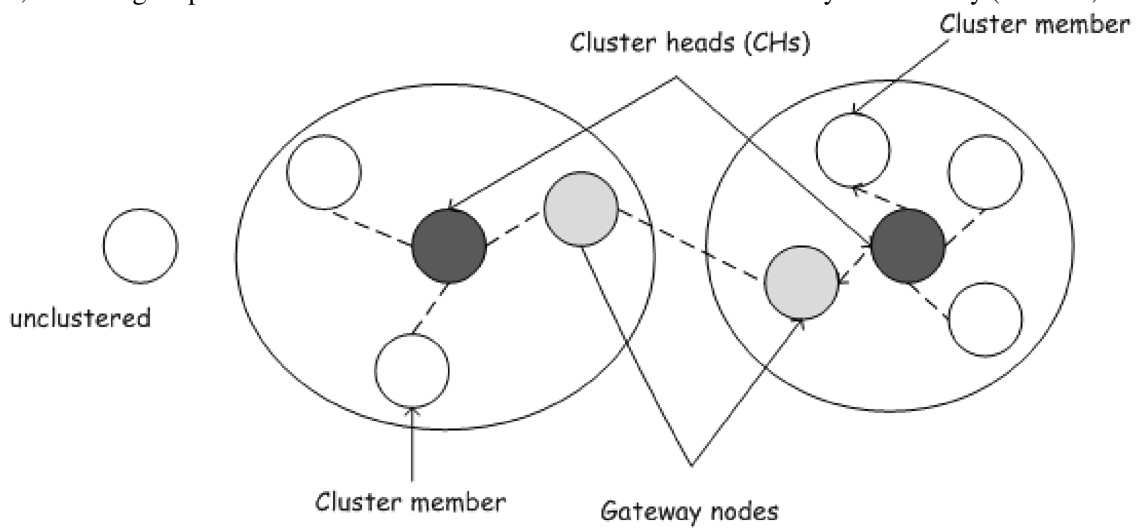

Figure 2. Illustration of node states in MANET clustering

In MANETs, clustering involves dividing the nodes into virtual groups based on some rules that establish if a node is suitable to be within a cluster or not. These rules are defined based on clustering metrics that in MANETs can be node type, battery energy level, mobility pattern, etc.

In general, a clustering scheme considers that a node can be in one the following situations (Yu & Chong, 2005), based on the node membership and task associated to the node. If node situations are associated with states, one could consider the following as possible node states:

- *unclustered*, also known as non-clustered or independent, when it does not pertain to any cluster
- *cluster member* or clustered when the node is within a cluster
- *cluster head* (CH) when the node has extra-responsibilities in a cluster. Usually, CH is the main controller of the cluster, the main coordinator of the communication within the cluster (i.e. intra-cluster communication) and has a main role in the functionality that is supposed to be provided by the cluster.
- *gateway node* is the node that ensures the communication between the clusters, also called inter-cluster communications.

A general classification of MANET clustering schemes is based upon the following criterion: *CH-based clustering*, if there is a CH in the clusters created or *non-CH-based clustering*, if there is no CH in the cluster created. Note that in CH-based clustering, the performance of clustering is highly dependent on CH election as this node has the main responsibilities in its cluster. Therefore in this type of clustering algorithms the focus is mainly on CH selection algorithms. Another general classification of clustering is based upon the number of hops between node pairs in the cluster: *1-hop clustering* or *multi-hop clustering*.

Successfully applied in MANETs to address stability and scalability, clustering was adopted in VANETs, where these issues are even more augmented. At the beginning, MANET clustering algorithms were adopted and directly applied to VANETs without any modifications, but as this research direction evolved, new clustering algorithms dedicated to VANETs were designed to address their specific characteristics.

Clustering in VANETs

The clustering concepts presented in the context of MANETs are valid in VANETs context as well, especially given the fact that clustering in VANETs has evolved from MANETs. There are only some additional aspects that need to be mentioned and that derive from the adaptation of clustering to VANET-specific conditions.

Clustering metrics were adapted not only to address VANET challenges imposed by their specific characteristics such as high mobility, rapidly changing topology and diversity of conditions, but also to take advantage of some of these characteristics, such as predictability of their movement. Therefore, clustering in VANETs is based upon more metrics than in MANETs that need to describe the complexity of VANET environment. Among the most common metrics in VANET clustering are direction, vehicle's relative speed in comparison to other neighbouring vehicles, vehicle's relative position, but also traffic flow, the lane in urban scenarios (e.g. right lane, left lane, and ahead lane), predicted future speed and position, density of vehicles (sparse or dense), etc.

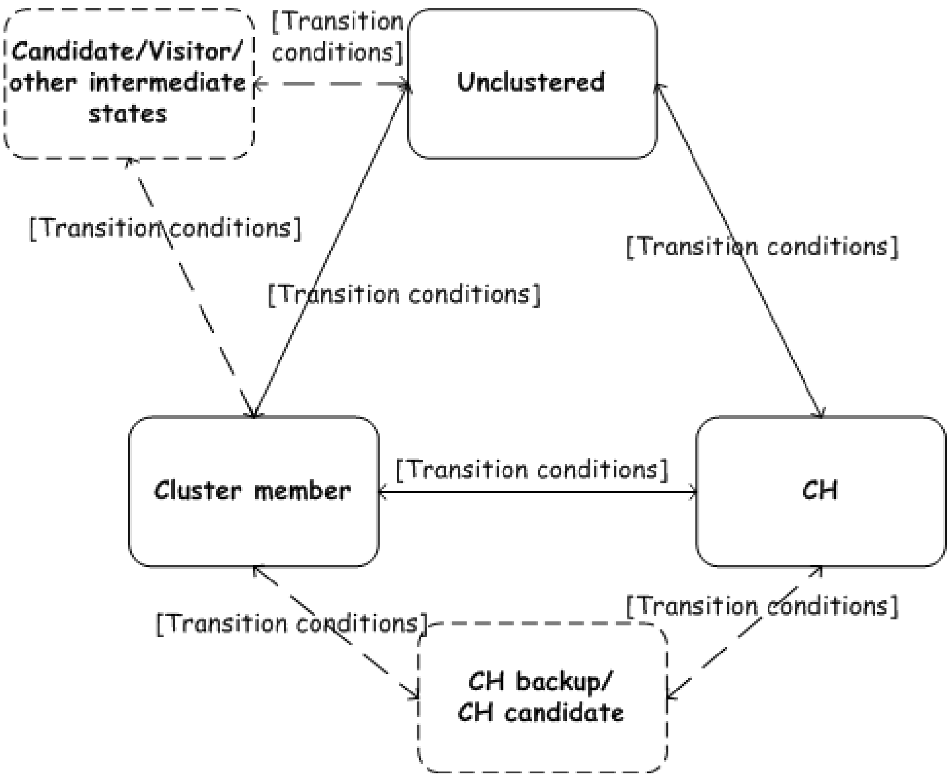

Figure 3. State machine representing CH-based clustering in VANETs

In the context of node states, as already described, additional node states have to be added in VANETs in order to address its more dynamic environment. These intermediate states include the *candidate node* and *CH backup* or *CH candidate states*. The candidate state was introduced by some approaches in order to obtain a better stability of the cluster. A node is not immediately given the cluster member state; it goes into the candidate state until it proves that it has certain stability in the cluster. The CH backup/CH candidate (quasi-CH in other approaches) state was introduced to make faster and smoother the process of changing the CH. Clustering in VANETs can be represented as a state machine, where the machine is the vehicle-node that can be in one of the following states: *unclustered*, *cluster member*, *CH* (in the case of CH-based clustering) and, optionally, in an intermediate state *candidate* and *CH backup/candidate* as previously defined (Figure 3).

Table 1. Clustering Algorithms Classification – Application Criterion

Class	**References**
Generic Clustering Algorithms	Fan et al., 2005 Cherif et al., 2009 Kuklinski &Wolny, 2009 Rawashdesh &Mahmed, 2009 Shea et al., 2009 Almalag & Weigle, 2010 Dror et al., 2011 Maslekar et al., 2011 Dror et al, 2013 Harikrishnan & He, 2013 Tal & Muntean, 2013a Ucar et al, 2013 Khan, Abolhasan & Ni, 2018
Cluster-based routing algorithms	Goonewardene et al. , 2009 Teshima et al., 2011 Wahab et al., 2013
Cluster-based data aggregation	Shoaib et al. , 2012
Cluster-based MAC algorithms	Su & Zhang, 2007 Hafeez et al., 2011
Cluster-based architectures	Sivaraj et al., 2011; Taleb & Benslimane, 2010; Benslimane et al., 2011, Tung et al., 2013 El Mouna, Tabbane, Labiod & Tabbane, 2015 Arkian, Atani, Diyanat & Pourkhalili, 2015 Duan, Liu & Wang, 2017 Amad et al., 2018
Cluster-based data & infotainment dissemination	Huang et al., 2011 Tal & Muntean, 2012
Cluster-based security solutions	Gazdar et al., 2010 Gazdar et al., 2011 Sharma & Kaul, 2018

Once adopted in VANETs, clustering gained popularity mostly due to its efficiency in addressing network stability issues. Clustering algorithms were implemented in the design of a large variety of VANET solutions: MAC protocols, routing protocols, data aggregation, security solutions, inter-vehicle communication, and data and infotainment dissemination solutions and various architectures such as cluster-based heterogeneous networks architectures or vehicular cloud-based architectures. In addition, various generic clustering algorithms were defined for VANETs. A classification of the clustering algorithms based on the application criterion can be seen in Table 1.

Independent of the type of VANET solution the clustering algorithm is designed for, one of the main purpose of clustering is to achieve network stability. Therefore, the clustering metrics are focusing mainly on this aspect and they relate to VANET's dynamic environment. Thus independently of the context in which clustering is applied (i.e. MAC protocols, routing protocols, etc), clustering metrics focus on the same issues and they are similar to each other. They are only dependent on the ingeniously modeling of the VANET environment and they are different from solution to solution as researchers are experimenting in trying to find the best clustering metrics to express the dynamicity of the VANETs. Similarly, in clustering performance assessment, usually first the network stability achieved is measured and then, the overall assessment of the clustering solution is performed (the overall solution where clustering is integrated; e.g. MAC protocol, data aggregation, etc). All these considerations allows for a uniform analysis of clustering algorithms in VANETs, independent of the type of solution/application in which they are integrated.

Although there is a considerable number of clustering solutions in VANETs, this research direction is still not mature. A closer analysis of the existent solutions in the literature reveals some major issues that relate to the performance assessment of clustering solutions in VANETs. So far, no analysis on this topic was provided in the literature and this is reflected by the fact that the existing clustering solutions use intuitively-defined performance assessment metrics or re-defined metrics similar with already existing ones mostly because researchers were not aware that such metrics have already been proposed in the literature. This resulted in metrics having various name versions. In particular, this is the case for the metrics used to measure the stability of the clusters, which contributes to network stability. These metrics are a direct measure of the performance of clustering algorithms in the context of VANETs, where the performance of clustering algorithms is reflected in how well clustering algorithms perform in achieving good network stability. It can be therefore concluded that the aforementioned major issues directly relate to the metrics used to evaluate the performance of clustering algorithms in VANETs.

In the absence of a study on performance assessment metrics of VANETs clustering solutions and in the absence of the standardized metrics, we performed a survey of the performance evaluation of clustering solutions in VANETs and of clustering algorithms designed for these solutions. This survey resulted in the identification and comprehensive definition, including in mathematical terms, of generic metrics that can be used in the evaluation of clustering algorithms in VANETs. Next sections describe in details the results of the study that can be considered an invaluable guide for the performance assessment of VANETs cluster-based solutions in general and VANETs clustering algorithms in particular and could support the standardization effort of these general metrics. This standardization is highly needed in order to avoid metrics being "re-invented" or intuitive assessment of the clustering solutions in VANETs to be performed. Moreover, evaluating the performance of clustering algorithms via these general metrics can greatly facilitate the comparison between clustering algorithms, independent from their type (i.e. generic algorithms or solution-specific).

Performance Assessment of Clustering in VANETs

The study conducted aimed to exhaustively analyze clustering solutions in VANETs. First, the focus was on the performance assessment of clustering solutions in general. Then the focus was moved on the evaluation of clustering algorithms designed for these solutions. As a result of the analysis performed, three major classes of performance assessment metrics for clustering solutions were identified and they are illustrated in Figure 5: network-specific metrics, application-specific metrics and topology-based metrics.

Network-specific metrics are well-known metrics applied in network communications, evaluating the performance of the clustered network mainly in terms of data transfer: throughput, loss, delay, data delivery ratio, overhead, etc.

Application-specific metrics depend on the type of the cluster-based solution employed. As emphasized above, clustering algorithms were implemented in the design of a large variety of VANET solutions: data aggregation solutions, MAC and routing protocols, security, etc. Therefore, this class includes a large variety of metrics as well. For instance, a data aggregation cluster-based solution is evaluated by measuring the size of data that needs to be disseminated, as the goal of a data aggregation scheme is to reduce the size of the data that needs to be disseminated. Note that these metrics and network-specific metrics are evaluating the performance of the overall solution based on clustering.

Topology-based metrics (hashed in Figure 5) evaluate the stability and robustness of the resulted clusters. Cluster stability translates into network stability, thus topology-based metrics are measuring the network stability. Network stability is emphasized as an important issue in VANETs due to their rapidly changing topology. Therefore, topology-related metrics are of great importance, fact acknowledged by researchers: the majority of proposed clustering solutions are using topology-based metrics in the performance assessment.

Independent of the type of VANET solution the clustering algorithm is designed for, the general aim of a clustering algorithm is to achieve network stability. In this context, the performance of clustering algorithms is not seen from a computational point of view (e.g. complexity of the algorithms). The focus is on how well clustering algorithms perform in achieving good network stability. Based on these considerations it can be said that in the context of VANETs, topology-based metrics are a measure of clustering algorithms performance.

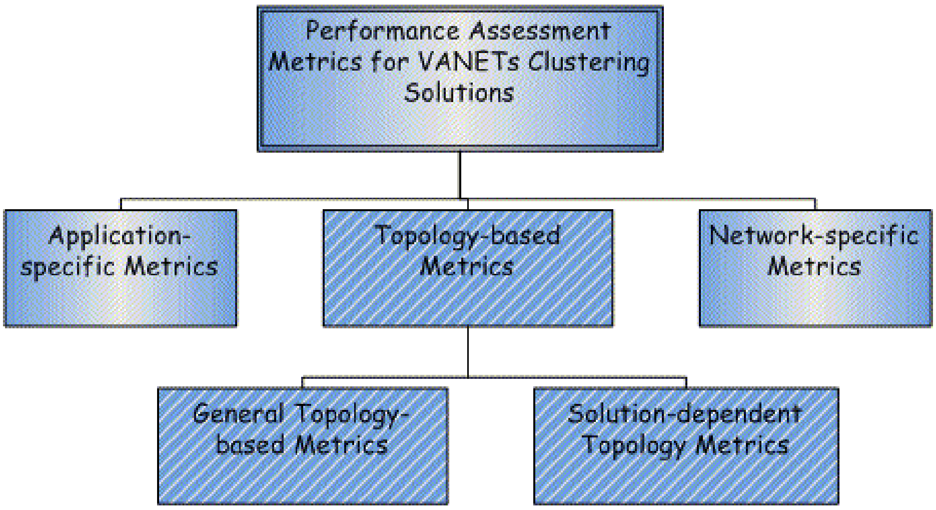

Figure 5. Classification of the performance assessment metrics used in VANETs clustering solutions

TOPOLOGY-BASED METRICS FOR CLUSTERING ALGORITHMS ASSESSMENT IN VANETS

In the previous section, topology-based metrics were identified as the metrics suitable for the evaluation of clustering algorithms in VANETs. Therefore, this section contains an in-depth analysis of the topology-based metrics. The comprehensive definition of the performance metrics subscribing to the general topology-based class from the solution-dependent topology-based class is one of the purposes of this work. The first class contains the metrics we called as being general metrics for the evaluation of clustering algorithms in VANETs.

Next the topology-based metrics identified during the analysis of VANET clustering algorithms are presented. Several aspects regarding the form of presentation need to be mentioned before getting to the presentation of the topology-based metrics. These aspects relate to several issues revealed during the study performed on the clustering solutions in VANETs.

An important issue is the inconsistency in naming the metrics. As already mentioned some of the metrics have been re-defined and consequently bare different names. In some cases of re-defining, general metrics are constrained by particular conditions/characteristics of the algorithm they are used to assess: general

metrics are defined either using particular conditions/assumptions of the algorithm or using particular parameters of the current algorithm. This is not necessary wrong as it is perfectly applicable for that particular algorithm, but can lead to misconceptions and misusing in case of other clustering algorithms. In addition, there are a considerable number of metrics that are not provided with a mathematical definition at all, being described in words only. So far, a single work in the literature (Su & Zhang, 2007) has provided mathematical definitions for some general metrics used in the evaluation of clustering.
Due to the aforementioned aspects, when presenting the metrics in the next sections, all naming versions are provided. The most representative name was chosen based on either the popularity or the degree of match with the metric description. In addition, general mathematical definitions for each of the general metrics were provided. The mathematical formulas were proposed based on the textual definitions of the metrics and the in-depth analysis of the results. The general mathematical definitions provided to some of the general metrics in by Su & Zhang (2007) were taken in the same form as presented in their work. Together with these metrics were taken the notations used in their definitions (i.e. first 6 notations from Table 2).

Table 2. Notations used in topology-based metrics definition

Notation	Explanation
$\|V(t)\|$	Total number of vehicles at time *t*
$\|C(t)\|$	Numbers of clusters at time *t*
$\|CH_i(t)\|$	Number of cluster members in cluster *i* at time *t*
$\overrightarrow{SP_i}(t)$	Velocity vector of vehicle *i* at time *t*
$\|\overrightarrow{SP_i}(t)\|$	Speed of vehicle *i* at time *t*
S	Simulation time
$CHL_i(t)$	Time period between time *t*, when vehicle *i* becomes a CH, and the moment of time vehicle *i* changes to another state.
$CL_i(t)$	Time period between time *t*, when cluster *i* is formed and the moment of time cluster *i* is dismissed.
$CMT_j^i(t)$	Time period between time *t*, when vehicle *j* becomes a cluster-member of cluster *i*, and the moment of time vehicle *j* leaves cluster *i*.

General Topology-based Metrics or General Metrics for the Evaluation of Clustering Algorithms in VANETs

Average CH lifetime ($\overline{CHL}$) (average CH duration, CH time) is one of the most popular topology-based metrics. It is applicable to the CH-based clustering algorithms only. It was used for the evaluation of VANET clustering algorithms in a considerable number of works (see Table 3). The popularity of this metric is explainable: the importance of CHs lifetime is crucial as, usually, the CH is the main controller and content forwarder in the CH-based clustered networks. Smaller CH lifetime affects the overall performance of the clustering algorithm. Higher CH lifetime implies more stable cluster topologies are found, leading to a decrease in number of re-clusterings, and consequently avoiding the waste of system resources and excessive use of computation time.
The mathematical definition of ($\overline{CHL}$), as given by Su & Zhang (2007), is shown in equation (1).

$$\overline{CHL} = \sum_{t=0}^{S} \frac{\sum_{i=1}^{|V(t)|} CHL_i(t)}{\sum_{i=1}^{|V(t)|} BC_i(t)} \qquad (1)$$

In equation (1), $BC_i(t)$ represents a function that defines the transition of a node (vehicle i) to the CH state as described by equation (2).

$$BC_i(t) = \begin{cases} 1, & \text{if vehicle } i \text{ changes to cluster head at time } t \\ 0, & \text{otherwise} \end{cases} \qquad (2)$$

$\overline{\text{CHL}}$ is one of the metrics that were re-defined in the literature. In the work proposed by Rawashdesh & Mahmud (2009), this metric is given a mathematical definition dependent on the particularity of the clustering algorithm (equation (3)).

$$\overline{\text{CHL}} = \frac{1}{L} \sum_{i=1}^{L} C_i^{\text{life}} \qquad (3),$$

where L is the number of clusters created throughout the session and C_i^{life} has the same meaning as $CHL_i(t)$. This is not a general definition, as the clusters are dismissed when the CH is changed. There are clustering algorithms (Hafeez et al., 2011) where clusters have back-up CHs. Often, when the vehicle CH changes its state, its role is taken by its back-up and the cluster is not dismissed. In this situation, equation (3) cannot be used in all CH-based clustering algorithms evaluation.

Average number of clusters ($\overline{NoC}$) is a very popular metric used to assess the performance of a large number of clustering algorithms (see Table 3). $\overline{NoC}$ is a general metric that can be applied to assess the performance of all the categories of clustering algorithms. $\overline{NoC}$ is a measure of network stability. When there are fewer clusters, better network stability is obtained. Equation (4) is proposed as a general mathematical definition of $\overline{NoC}$.

$$\overline{NoC} = \frac{1}{S} \sum_{t=0}^{S} |C(t)| \qquad (4)$$

It can be stated that the same metric is used by Maslekar et al. (2011), although instead of number of clusters, the number of CHs is measured. This is due to the fact that in this particular solution, a cluster is dismissed when its CH is dismissed. In consequence, the number of CHs is equal to the number of clusters created.

Average cluster size ($\overline{CS}$) metric (average number of cluster members) measures the average size of the clusters throughout the session. This size of a cluster is considered to be determined by the number of vehicles in the cluster. $\overline{CS}$ is a metric applicable to all clustering algorithms and was highly used in the literature (see Table 3). Its general definition, as given by Su & Zhang (2007), is shown in equation (5).

$$\overline{CS} = \frac{1}{S} \sum_{t=0}^{S} \sum_{i \epsilon C(t)} |CH_i(t)| \qquad (5)$$

Average CH change rate *($\overline{CHCR}$)* is another popular metric (see Table 3) and it is seen as a measure of cluster stability. In more stable clusters, nodes in general and CHs in particular change their cluster membership or their state less often. It is a metric that can be used for the performance assessment of CH-based algorithms. Equation (6) is proposed as the general mathematical definition of $\overline{CHCR}$.

$$\overline{CHCR} = \frac{1}{S} \sum_{t=0}^{S} \sum_{i=1}^{|v(t)|} CHD_i(t) \qquad (6),$$

where *$CHD_i(t)$* is the CH dismissed function of vehicle *i*, that was defined in equation (7) to express the transitions from CH to another type of node.

$$CHD_i(t) = \begin{cases} 1, & \text{if vehicle } i \text{ changes from cluster head to another type of node at time } t \\ 0, & \text{otherwise} \end{cases} \qquad (7)$$

Average cluster member lifetime ($\overline{CML}$) (*average cluster member duration, cluster residence time*) was used as a performance metric by Goonewardene et al. (2009); Shea et al. (2009) and Huang et al. (2011). It is a general topology-based metric measuring the overall stability of clustering. $\overline{CML}$ is a similar metric to the average CH lifetime just that the lifetime is computed for all the nodes in the cluster members not only for the CH. Same as for $\overline{CHL}$, longer average cluster member lifetime indicates a more stable clustering topology. A general mathematical definition of $\overline{CML}$ is provided in equation (8).

$$\overline{CML} = \frac{1}{|C(t)|}\sum_{t=0}^{S}\sum_{i\in C(t)}\frac{\sum_{j\in CH_i(t)} CMT_j^i(t)CMD_j^i(t)}{\sum_{k=0}^{S}\sum_{j\in CH_i(t)} CMD_j^i(k)} \quad (8),$$

where CMD_j^i(t) is the cluster member dismissed function of vehicle *j* from cluster *i* being defined in equation (9).

$$CMD_j^i(\mathrm{t}) = \begin{cases} 1, & if\ vehicle\ j\ , cluster\ member\ of \\ & cluster\ i\ is\ dissmissed \\ & from\ the\ cluster\ i\ at\ time\ t \\ 0, & otherwise \end{cases} \quad (9)$$

Cluster changes per node ($\overline{CC}$) *(average number of cluster switches per node)* measures the number of transitions of a vehicle between clusters and is used in order to measure cluster stability. The less number of transitions indicates better cluster stability. In the work proposed by Dror et al. (2011), the metric is called improperly cluster stability and was measured through average number of cluster switches per node. Based on the descriptions provided by Shea et al. (2009) and Wolny (2008) and on the evaluation of the results, equation (10) is proposed as the general mathematical formula for $\overline{CC}$, applicable to all clustering algorithms.

$$\overline{CC} = \frac{1}{S}\sum_{t=0}^{S}\sum_{i\epsilon C(t), j\in CH_i(t)} CMD_j^i(t) \quad (10)$$

where CMD_j^i(t) was defined in equation (9).

Cluster stability is stated as a metric by Wolny (2008), Dror et al. (2011) and Wahab et al. (2013). In the latter work, it is described and measured in terms of the average number of cluster switches per node during the simulation. As stated before, this metric is actually $\overline{CC}$. Wolny (2008) states that the cluster stability metric depends on the change rate of the cluster and provide a formula that is not generic, but solution-dependent and uses some undefined terms. A solution-dependent description is provided by Wahab et al. (2013) for what they call network stability metric. However, we argue that no metric can be called *cluster stability* until it is not able to comprise all the metrics that were defined so far for its measurement. In addition, cluster stability is a property of the VANETs which is assessed by most of the topology-related metrics defined and not only a metric. In consequence, cluster stability is not proposed and considered as a general metric in this work.

Average cluster lifetime ($\overline{CL}$) (Rawashdesh & Mahmud, 2009) *(average cluster lifecycle (Cherif et al. 2009))* is another general metric that can be used for assessing the performance of any type of VANETs clustering algorithm. It is a measure of cluster stability: larger average cluster lifetime translates into more stable clusters, thus a more stable network. Rawashdesh & Mahmud (2009) consider the average cluster lifetime equal to the average CH lifetime, as the clusters are dismissed whenever their CH changes. The authors define $\overline{CL}$ through equation (2) which was considered not to be an appropriate general formula for CH lifetime. It is obvious that equation (2) cannot be also considered a general formula for the $\overline{CL}$ as the cluster duration is not always dependent on the CH lifetime. This is valid in non-CH schemes and even in CH-based schemes. Equation (11) is proposed as a general mathematical definition for $\overline{CL}$.

$$\overline{CL} = \frac{\sum_{t=0}^{S}\sum_{i\epsilon C(t)} CL_i(t)}{\sum_{t=0}^{S}|C(t)|} \quad (11)$$

Cluster reconfiguration rate ($\overline{CRR}$) (Wang et al. 2008) *(number of re-clusterings (Huang et al., 2011))* is a metric defined to measure cluster stability based on the fact that a good clustering algorithm should be stable and it should not change the cluster configuration too drastically when few nodes are moving and the topology changes rapidly. This metric does not have a mathematical definition in none of the solutions that use it. Moreover, these solutions are both CH-based algorithms and they state that the re-clustering/reconfiguration happens when CH changes. Described like this, the metric becomes identical to$\overline{CHCR}$. However, equation (12) proposed a general mathematical description for the $\overline{CRR}$ applicable to all clustering algorithms.

$$\overline{CRR} = \frac{1}{S}\sum_{t=0}^{S}\sum_{i=1}^{|C(t)|} CD_i(t) \qquad (12),$$

where $CD_i(t)$ is the cluster dismissed (CD) function for cluster i as defined in equation (13).

$$CD_i(t) = \begin{cases} 1, if\ cluster\ i\ was\ dissmissed \\ \qquad at\ moment\ t \\ 0, \qquad otherwise \end{cases} \qquad (13)$$

Average relative speed compared to the CH within a cluster ($\overline{RSWC}$) (Su & Zhang, 2007) *(average cluster stability factor (Hafeez et al., 2011))* measures the topology stability of clusters. It is a general topology-based metric for all the CH-based algorithms. In all CH-based algorithms, a smaller average speed of the cluster member compared to that of the CH is translated into an increased stability of the cluster. However, $\overline{RSWC}$ is not a very common metric. It was defined and used as in equation (14) by Su & Zhang (2007). Hafeez et al. (2011) re-defined this metric as the *average cluster stability factor* and it is described depending on some particular parameters of the solution. However, a deeper analysis reveals that average cluster stability factor is identical to $\overline{RSWC}$.

$$\overline{RSWC} = \frac{1}{|C(t)|S}\sum_{t=0}^{S}\sum_{i\epsilon C(t)}\frac{\sum_{j\epsilon CH_i(t)}|\overrightarrow{SP_i}(t) - \overrightarrow{SP_j}(t)|}{|CH_i(t)|} \qquad (14)$$

Average relative speed among CHs ($\overline{RSCH}$) (Su & Zhang, 2007) is a general topology-based metric for CH-based algorithms. It measures the global topology of the network. Equation (15) represents the general mathematical definition of this metric as given by Su & Zhang (2007).

$$\overline{RSCH} = \frac{1}{S}\sum_{t=0}^{S}\frac{\sum_{i,j\epsilon C(t)\wedge i\neq j}|\overrightarrow{SP_i}(t) - \overrightarrow{SP_j}(t)|}{|C(t)|^2} \qquad (15)$$

$\overline{RSWC}$ and $\overline{RSCH}$ are more complex metrics for CH-based algorithms that are indicators of both CH and network stability, as this type of metrics are measuring better the cluster stability in general. This statement also sustained by Fan et al. (2005), that fist assessed the clustering algorithms defined using $\overline{CS}$ and $\overline{CHCR}$ and then using relative measure ($\overline{CS}/\overline{CHCR}$) arguing that this is a better measurement of cluster stability.

All the general metrics presented and defined (except the cluster stability which is not considered a metric) are summarized in Table 3. This section and the table-based summary provided represent an invaluable guide for the performance assessment of VANETs clustering algorithms in particular and of VANETs cluster-based solutions in general. Evaluating the performance of clustering algorithms via these general metrics can greatly facilitate the comparison between the clustering algorithms, independent from their type: generic algorithms or integrated in a specific solution (e.g. clustering algorithm implemented in a MAC protocol).

Solution-dependent Topology-based Metrics

Node re-clustering time (Goonewardene et al., 2009)/ **Re-affiliation frequency** (Blum, 2003) are metrics very differently named, but both described as being the time between cluster associations for a given node. Solutions using this metric consider that this is a measure of the stability of a cluster membership and shorter node re-clustering time/re-affiliation frequency means an increased stability of a cluster membership. However, we consider that average cluster membership lifetime and average CH lifetime (in case of CH-based algorithms) are a better indicator of the stability of cluster membership and we base this statement on the following considerations. Particularly in VANET clustering, as emphasized before, the nodes can be in intermediate states. They have different states like candidate, visitor and they are not clustered until they demonstrate their future stability in the cluster, meaning a long lifetime as a cluster member. This translates into longer period of re-clustering/re-affiliation frequency, but this does not mean that the topology is less stable. These considerations represent also the motivation of including this metric in the class of solution-dependent topology-based clustering metrics. In this class, we also include the **average percentage of clustered nodes** metric (Kuklinski & Wolny, 2009). A bigger average percentage of clustered nodes it is usually translated into a better stability of the network topology. However, in the aforementioned particular clustering algorithms, this metric is not applicable because at some moments of time there can be a considerable number of nodes not-clustered (candidates or visitors).

Table 3. General Metrics for the Evaluation of Clustering Algorithms in VANETs – Summary

Metric	Mathematical Definition	Popularity	Restriction
Average CH Lifetime($\overline{CHL}$)	$\overline{CHL} = \sum_{t=0}^{S} \frac{\sum_{i=1}^{\|V(t)\|} CHL_i(t)}{\sum_{i=1}^{\|V(t)\|} BC_i(t)}$, where $BC_i(t) = \begin{cases} 1, & \text{if vehicle } i \text{ changes to cluster head at time } t \\ 0, & \text{otherwise} \end{cases}$	Blum et al., 2003 Gunteret al., 2007 Su & Zhang, 2007 Rawashdesh & Mahmed, 2009 Shea et al., 2009 Huang et al., 2011 Lai et al., 2011 Tal & Muntean, 2012 Harikrishnan & He, 2013 Tal & Muntean, 2013a Ucar et al., 2013 Arkian, Atani, Diyanat & Pourkhalili, 2015	CH-based algorithms only
Average number of clusters ($\overline{NoC}$)	$\overline{NoC} = \frac{1}{S} \sum_{t=0}^{S} \|C(t)\|$	Wolny, 2008 Rawashdesh &Mahmed, 2009 Shea et al., 2009 Gazdar et al., 2010 Dror et al., 2011 Maslekar et al., 2011 Shoaib et al. , 2012 Dror et. al, 2013 Tal & Muntean, 2013a Harikrishnan & He, 2013	-
Average cluster size ($\overline{CS}$)	$\overline{CS} = \frac{1}{S} \sum_{t=0}^{S} \sum_{i \epsilon C(t)} \|CH_i(t)\|$	Fan et al., 2005 Su & Zhang, 2007 Kuklinski &Wolny, 2009 Hafeez et al., 2011 Teshima et al., 2011 Harikrishnan & He, 2013	-
Average CH change rate ($\overline{CHCR}$)	$\overline{CHCR} = \frac{1}{S} \sum_{t=0}^{S} \sum_{i=1}^{\|v(t)\|} CHD_i(t)$, where $CHD_i(t) = \begin{cases} 1, & \text{if vehicle } i \text{ changes from cluster head to another type of node at moment } t \\ 0, & \text{otherwise} \end{cases}$	Fan et al., 2005 Kuklinski &Wolny, 2009 Shea et al., 2009 Almalag & Weigle, 2010 Ucar et al., 2013 Khan, Abolhasan & Ni, 2018	CH-based algorithms only

Average cluster member lifetime ($\overline{CML}$)	$\overline{CML} = \frac{1}{\lvert C(t)\rvert}\sum_{t=0}^{S}\sum_{i\in C(t)}\frac{\sum_{j\in CH_i(t)} CMT_j^i(t) CMD_j^i(t)}{\sum_{k=0}^{S}\sum_{j\in CH_i(t)} CMD_j^i(k)}$, where $CMD_i^j(t) = \begin{cases} 1, & \text{if vehicle } j \text{, cluster member of cluster } i \text{ is dissmissed from the cluster } i \text{ at moment } t \\ 0, & \text{otherwise} \end{cases}$	Goonewardene et al., 2009 Shea et al., 2009 Huang et al., 2011 Ucar et al., 2013	-
Cluster changes per node ($\overline{CC}$)	$\overline{CC} = \frac{1}{S}\sum_{t=0}^{S}\sum_{i\in C(t), j\in CH_i(t)} CMD_j^i(t)$, where *CMD* is defined as above	Wolny, 2008 Dror et al., 2011 Dror et al, 2013	-
Average cluster lifetime ($\overline{CL}$)	$\overline{CL} = \frac{\sum_{t=0}^{S}\sum_{i\in C(t)} CL_i(t)}{\sum_{t=0}^{S}\lvert C(t)\rvert}$	Cherif et al., 2009 Rawashdesh &Mahmed, 2009	-
Cluster reconfiguration rate ($\overline{CRR}$)	$\overline{CRR} = \frac{1}{S}\sum_{t=0}^{S}\sum_{i=1}^{\lvert C(t)\rvert} CD_i(t)$, where $CD_i(t) = \begin{cases} 1, & \text{if cluster } i \text{ was dissmissed at moment } t \\ 0, & \text{otherwise} \end{cases}$	Wang et al., 2008 Huang et al., 2011	-
Average relative speed compared to the CH within a cluster ($\overline{RSWC}$)	$\overline{RSWC} = \frac{1}{\lvert C(t)\rvert S}\sum_{t=0}^{S}\sum_{i\in C(t)}\frac{\sum_{j\in CH_i(t)}\lvert\overrightarrow{SP_i}(t) - \overrightarrow{SP_j}(t)\rvert}{\lvert CH_i(t)\rvert}$	Su & Zhang, 2007 Hafeez et al., 2011	CH-based algorithms only
Average relative speed among CHs ($\overline{RSCH}$)	$\overline{RSCH} = \frac{1}{S}\sum_{t=0}^{S}\frac{\sum_{i,j\in C(t) \wedge i\neq j}\lvert\overrightarrow{SP_i}(t) - \overrightarrow{SP_j}(t)\rvert}{\lvert C(t)\rvert^2}$	Su & Zhang, 2007	CH-based algorithms only

CLUSTERING ALGORITHMS IN VANETS

Initial approaches of clustering in VANETs used clustering algorithms designed for MANETs. Lowest Id (Yu & Chong, 2005) is a state-of-the-art clustering algorithm in ad-hoc networks and was borrowed in VANETs from MANETs. Its principle is very simple. The nodes have assigned a unique fixed id which is broadcasted periodically in the network. The clusters are formed around the node with the lowest id among them, which is chosen as CH. Although its principle is very simple, it is a very efficient algorithm, more efficient than other clustering schemes, such as Highest-Degree (Yu & Chong, 2005), that take into consideration more factors (Fan et al., 2005). Highest-Degree is another state-of-the-art clustering algorithm in the area of ad-hoc networks. Its principle is similar to the Lowest Id algorithm, but the clusters are formed around the node with the highest number of neighbors. These two algorithms, as state-of-the-art algorithms in the area of ad-hoc networks, are very often used in the comparison-based assessment of the VANETs clustering algorithms and served as source of inspiration for many VANETs clustering approaches.

As emphasized before, although VANETs represent an instantiation of MANETs, they have unique features that need to be considered in order to design appropriate clustering algorithms for vehicular networks. On one hand some of the VANET's characteristics need to be overcome by the clustering schemes, such as their rapidly changing topology, high mobility and scalability, while on the other hand clustering schemes can make use of other characteristics such as predictable mobility due to the road topology, traffic regulations and driver's behavior. Researchers acknowledged these facts and VANET-dedicated clustering solutions have been proposed. After an overview of VANET clustering solutions in the literature, a very broad classification is provided here and several approaches are presented for each class for exemplification. The classification is made based on the cluster formation criterion: is the cluster formation dependent on some fixed structures such as road segments, grids, etc, or is it independent on any kind of structure and it is just following the traffic flow, vehicle's movement? In the first case, vehicles from the same structure (road segment, grid, etc) are grouped into a cluster. Thus static clusters are created bounded by this structure. Therefore, we called this type of VANET clustering algorithm under the generic name of **static clustering algorithms**. In the second case, cluster formation does not depend on any type of structures. Clusters are created by following the movement of the vehicles: vehicles with similar mobility patterns such as neighboring vehicles are grouped into clusters through exchange of clustering messages. In this type of approaches there is usually a beaconing message (a periodically broadcasted message in the network) sent either by the unclustered vehicle, either by a CH or a node with extra-responsibilities in the cluster. In the absence of predefined structures, this is necessary in order to announce the availability of joining the cluster or the availability of a cluster in zone so that a vehicle can join a cluster. The clusters created following this approach are mobile clusters, following the mobility of the vehicles and therefore we name this class of VANET clustering algorithms, **mobile clustering algorithms**.

Static Clustering Algorithms

Cherif *et al.* (2009) propose a CH-based clustering algorithm where the cluster formation is depended on fixed road segments. The communication area where vehicles can be reached by RSU via multi-hop communication is called extended communication area. This area is split into fixed length segments, vehicles located into the same segment forming a cluster. Beside CH and simple cluster member, nodes can have another status inside a cluster, called super-member. This is a node that has been a CH and is yielding the job to another node. Inside the cluster, a main area of interest is conceptually partitioned in the centre of the segment. This area is called central zone and has the radius equal to the transmission range. Central zone has an important role in the distributed election of the CH. Initially, each member in the cluster estimates the time period it is going to spend in the central zone. The main principle behind CH election algorithm is to choose as CH the vehicle with the highest probability to spend the longest duration in the central zone. The speed and the position of the vehicle are also taken into consideration. All these parameters are used in the computation of each vehicle's electing factor, based on which the CH is selected. After that, each vehicle periodically examines its status and, by using the laws of uniform motion from Physics ($distance = speed\ x\ time$) predicts its future position in the immediate next moment of time. If a CH determines that it will be leaving the central zone in this moment of time, it will resign as CH, and a new CH is elected following the same procedure.

The proposed algorithm takes into consideration the high mobility of VANET nodes and movement predictability. Algorithm's assessment is performed both via general topology-based metrics –$\overline{CL}$– and network metrics – overhead, end to end delay and delivery ratio. These are evaluated in relation to network density, but it is to be mentioned as a limitation the fact that the solution is not compared against any other clustering scheme.

Luo *et al.* (2010) propose a CH-based clustering algorithm where the cluster's formation is based on square grids. The geographical area is divided into a subset of square grids. All the vehicles pertaining to a grid form a cluster. The vehicle having the closest position to the centre of the grid is elected as CH. This clustering scheme is implemented in a cluster and position-based routing protocol dedicated to VANETs and claims to reduce the overhead and packet delivery delay. CHs are the main data forwarders, a packet is sent from CH to CH until it gets to the CH that governs in the cluster where the destination node is positioned. The performance assessment is not very thoroughly, the authors presenting just a small analysis where they make some observation about their algorithm in comparison with state-of-the-art routing algorithms. Moreover, the clustering scheme neither tries to address any of VANETs challenging characteristics nor does it take advantage of any of VANETs characteristics. Thus, the clustering scheme, only by itself is not VANETs dedicated, but the routing protocol is taking advantage of the vehicle's knowledge about their own positioning via the GPS integrated in their OBU.

Ramakrishnan *et al.* (2011) adopt a similar approach in their proposed CH-based clustering algorithm to the one previously discussed: cluster formation is based on road segments called clustering areas. However, these clustering areas are not assigned with a fixed length value. Their size varies depending on the average speed of the vehicles within them. If the average speed is small then the cluster size is smaller, otherwise bigger. However, it is not mathematically described what smaller or bigger means. If an RSU is inside a cluster, then this is elected as CH. Otherwise, CH election is based on a single metric that is the velocity. As the clusters are static, the vehicle with the lowest speed in the cluster is going to spend the more time inside the cluster. Thus this vehicle is elected as CH. However, although the CHCR is reduced, is not clear how the fact that the position of CH related to the other cluster members is not taken into consideration is affecting the communication between CH and cluster members.

Performance assessment is done via topology metrics only, which are quite different than the ones typically used. Instead of measuring directly the rate of changes in CH or clusters, the times of creation of clusters or the time of electing CH is measured. However, these are not good measurements of the stability in clusters; instead these assess the initial performance of clustering.

There are some clustering solutions that represents a bridge between the two main identified types or a combination. Such is for instance the solution proposed by **Tung et al. (2013)**. This is a clustering algorithm designed in the context of an intersection collision avoidance service. This clustering algorithm is employed in the design of a novel VANET WLAN-cellular architecture. This architecture is based on a heterogeneous network: LTE and WiFi. The communication messages inside the cluster are done via WiFi and they are called beacons, while CHs only are using the LTE interface for communicating with the base stations. As aforementioned, the proposed algorithm uses both static and mobile approach. On one hand, the clustering is bounded by the so called service region, region that is placed in the nearby of the intersection, but on the other hand it follows the mobility of the vehicles taking into account their direction. The proposed clustering algorithm is very specific to the solution built within. However, it indicates an efficient modality of bringing LTE in the vehicular networking context, as at this moment it appears to be more likely that LTE cannot handle the multiple messages that can be generated in VANET, especially during rush hours and in the traffic collision related applications when a huge number of messages can be generated. This solution was preceded by (Sivaraj et al., 2011) that employed a clustering algorithm to design a LTE-WAVE network architecture dedicated to multimedia delivery. This latest work uses a similar principle as in (Taleb & Benslimane, 2010; Benslimane et al., 2011), where a generic VANET UMTS-WAVE architecture based on clustering is designed, but instead of 3G brings 4G in the VANET context. The principle of these three works differ from (Tung et al., 2013) by delegating the responsibility of communicating to infrastructure (via 3G or 4G) to another node, a gateway node, while CH is the main forwarder of messages inside the cluster. Multiple metrics are involved in both selection procedures: CH and gateway node as both states are of great importance. Independently of the type of node that has the responsibility of communicating with the infrastructure, CH or gateway, there is a single node in each cluster that is accessing the cellular network interface. This leads to an optimized architecture that it is also proven to be reliable even for applications that require a rich content such as multimedia applications.

In (Tung et al., 2013), the procedure of selecting the CH is based on a single metric: the proximity to the base station. The algorithm is evaluated in the context of the overall solution using solution-dependent metrics. Although WiFi standard is chosen for the inter-vehicle communications, the authors suggest that this can be replaced with V2V communication (IEEE 802.11p). Such architecture is used in the clustering solution proposed by Harikrishnan & He (2013): IEEE 802.11p – V2V communication – for intra-cluster communication and LTE for the communication between CH and base station. This algorithm is a general CH-based clustering algorithm for VANETs. The clustering metrics are not clearly stated, but the CH is selected following the same policy as above: minimum distance to the base station. The algorithm is evaluated in terms of both network-specific performance metrics and topology-based performance metrics, namely: $\overline{CHL}$, $\overline{CS}$ and $\overline{NoC}$. Another clustering approach where clusters are bounded to an intersection region was proposed in **(Chen et al., 2016)**. Unlike (Tung et al., 2013) the architecture of the clustered network is a pure ad-hoc architecture, based on V2V communication only. The clustering is done on the geographical location basis only, but the novelty of the approach is the employment of game theory in order to determine the CHs to decide on the aggregated transmission power and packet generation rate. Game theory has a secondary role in the context of the cluster-based solution proposed for congestion control. However, game theory started to be considered as the main decisional framework in the context of clustering algorithms. Some of these approaches will be discussed in the next chapter.

Mobile Clustering Algorithms

Su & Zhang (2007) proposed a CH-based clustering algorithm in the design of a dedicated VANET MAC protocol. The cluster formation is based on beaconing messages (an initial message periodically broadcast in the network either by a vehicle recently entered in the network, either by CHs) and other cluster messages among the same-direction neighbours. Thus in cluster formation the main criterion considered is the direction of the vehicles based on the assumption that vehicles flowing in the same direction have similar speeds and moving patterns that are regulated by the traffic rules. Another criterion considered in cluster formation is signal strength and its role is revealed in the next paragraph.

The possible states of a vehicle-node in this clustering algorithm are: CH, quasi-CH, cluster member and quasi-cluster member. Each vehicle is seen from the moment of entering on the road a potential CH, so it receives the quasi-CH state. If after a predefined period of time it does not receive any valid *invite-to-join* beaconing message from a CH, the vehicle elects himself as a CH, otherwise the vehicle joins the cluster and its state changes to cluster member. Note that valid *invite-to-join* message must have the signal strength greater than a predefined threshold. Thus the size of the cluster is determined by the signal strength threshold.

This algorithm is among the first mobile VANETs clustering algorithms. Its principle is simple, the only clustering metrics considered are direction and signal strength and the CH election is very simple, no decision process based on multiple metrics is involved. However, it is the first that considered direction metric in clustering the vehicles. In addition, this is the first approach in the literature that thoroughly defined some of the most popular general topology metrics in VANETs: $\overline{CHL}$ and $\overline{CS}$. Also, they defined 2 relative topology metrics, previously discussed: $\overline{RSWC}$ and $\overline{RSCH}$. These metrics are used to illustrate the performances of the clustering algorithm, but no other clustering algorithm is used as reference. The focus of the authors is on testing the MAC protocol where the clustering solution has been integrated. Tests show that this MAC protocol outperforms the standard IEEE 802.11p.

Kuklinski & Wolny (2009) propose a mobile clustering algorithm where mobile clusters are formed by the neighbouring vehicles through beaconing and other messages exchange. Multiple clustering metrics are considered in creating stable clusters such as: connectivity level that is actually measuring the density, link quality estimated by SNR, relative nodes position and the prediction of this position in the future (based on speed and position) and nodes reputation built upon the history of node connections. The prediction of vehicle positions aims on one hand to avoid situations like clustering the vehicles that are moving in different directions with high speed. On the other hand, it allows for clustering the vehicles that are moving in different directions but with a low speed (e.g. vehicles in traffic jam). This approach leads to a greater stability of the clusters. Moreover, in order to avoid a high rate of re-clusterings, a node is given three possible states, excepting the CH state: member, candidate and visitor. Vehicles must prove they are potentially stable members of the clusters before they can join. First, a vehicle is in the visitor change, then after a time threshold is given the candidate state and only after applying the other clustering metric (connectivity, future position, etc), its state is changed into a member. Candidate and visitor nodes do not have the same rights as members do. They are not provided with the services that are provided in the cluster and they only have the right to exchange clustering messages. CH election algorithm is not described, although in each cluster a vehicle is assigned with this role. In addition, it is not clear what the CH responsibilities are.

The proposed solution is compared against the state-of-the-art algorithm, Highest Degree and proves better performances in terms of $\overline{CS}$ and $\overline{CHCR}$ topology metrics.

Almalag & Weigle (2010) introduced a CH-based clustering algorithm designed mainly for urban scenarios that uses traffic flow in cluster formation. The authors focus on the CH election algorithm as it is a well-known fact that stable CHs conduct to stable clusters. This algorithm is based on multiple clustering parameters: density, distance between vehicles, speed and the lane of travelling. This last parameter is a new parameter considered so far in the clustering schemes and the key novelty of the algorithm. The rationale behind considering this parameter is that CH should be selected from a lane that the majority of vehicles are travelling in. Each vehicle first determines its own lane. Then each lane, referred as traffic flow, is given a weight. It is not explained what is the rationale behind weights' assignment for each traffic flow. Then for each vehicle it is determined on one hand the number of vehicles it is connected to (density), the comparison of its speed compared to others within its range and the comparison of its distance from all other vehicles within its range and on the other hand all these parameters but within their own traffic flows. The first group of parameters are multiplied with the traffic flow weights and then added to the second group in order to obtain the CH level of each vehicle. The vehicle with the highest CHL is selected as CH. The proposed algorithm is compared against other three algorithms: the well-known Lowest Id, Highest Degree and against what authors generic named the Utility Function algorithm for VANETs. The latter clustering approach was proposed by Fan et al. (2005) having as models Lowest Id and Highest Degree and it is probably the first clustering scheme proposed for VANETs. The focus in this scheme is fully on the CH election that is suggested to be chosen for VANETs as the vehicle having the speed closest to the average and the distance between vehicles closest to the average. Although the authors do not provide details about what closest to the average means, they state that simulation results show better performance of their approach compared to Lowest-Id and Highest Degree. In the performance assessment of the traffic flow based algorithm, the authors use their own understanding of what closest to the average means for both speed and distance parameters. This is the same understanding that they used for implementing their own algorithm with respect to speed and distance metrics. The traffic flow-based algorithm outperforms all three algorithms (i.e. Lowest Id, Highest Degree and Utility Function) in terms of the topology metric used, $\overline{CHCR}$.

Shea et al. (2009) proposed another mobility-based clustering algorithm for VANETs with focus on the stability of the resulted clustered network. The novelty of the algorithm consists in employing affinity propagation (Frey & Dueck, 2007), a clustering technique that is borrowed from data clustering field. Same pattern for clustering formation is followed as in the other structure-free discussed algorithms: exchange of clustering messages between vehicles in 1-hop neighbourhood. Direction is the first parameter considered in clustering formation: the vehicles form clusters with their 1-hop same-direction neighbours. The focus is again on the CH election algorithm where the affinity propagation technique applies. This technique is based upon a similarity function that is tailored for VANETs. Thus it is based on the Euclidean distance between the position of the node and the positions of its same-direction neighbours and the Euclidean distance between the next position of the node and the next positions of its same-direction neighbours. The efficiency of the algorithm is demonstrated against the previously discussed clustering algorithm proposed by Su & Zhang (2007) by applying the most popular topology-based metrics: $\overline{CHL}$, $\overline{CML}$, $\overline{NoC}$ and $\overline{CHCR}$.

Goonewardene et al. (2009) proposed a mobile clustering algorithm based on exchange of clustering messages between 1-hop neighbours designed with a robust adaptability to mobility – RMAC (i.e .robust mobility adaptive clustering). The algorithm is designed to support geographic routing, although no routing protocol is proposed. An unclusterd node first makes a list of its 1-hop neighbours that answer to its beaconing messages with a message containing their speed, location and direction of travelling. Based on these metrics, the list is then sorted so that the most appropriate neighbour of the unclustered node to be selected as its CH. The appropriateness is decided as follows. First the position parameter is considered. Based on this the Euclidean distance is computed between the node and its neighbours. If the distances are comparable, then the next parameters, speed and location are considered. Based on these two parameters the next locations of the node and its neighbours are computed. The first neighbour in the list, the most appropriate to become the CH, is the one closer in the current moment of time and in the next one. This is quite a new approach in the literature, as usually a CH is elected in the cluster based on some values (id, computed weight using different techniques) that applies globally. The clustering algorithm proposed here is node-oriented – node precedence algorithm – as each node elects its own CH. If the first node in its 1-hop neighbours list is already a CH then the unclustered node becomes a member of its CH cluster. Otherwise, the vehicle selects this node as its CH and e new cluster is formed. Thus, beside cluster member and CH, a node can be in a dual state that is when it is a CH of a cluster and a member of another cluster. This leads to overlapping neighbouring clusters and no message overhead in case of a cluster member transition to a neighbouring cluster.

Another novel concept introduced by this algorithm is the zone of interest that enables each vehicle to keep an updated table of its neighbours that goes beyond their transmission range. Zone of interest' radius is established as two times their transmission range. Thus vehicles have prior knowledge about the network while they are travelling into the neighbourhood which it's translated into an optimized and smoother process of re-clustering.

The algorithm is compared against an algorithm proposed by Basagni (1999) that is shortly called DMAC (**Distributed and Mobility Adaptive Clustering**). DMAC is a generalised clustering algorithm designed for MANETs where the CH election is done globally and is not node-oriented. Each vehicle has a weight associated. The clustering process begins with each node examining the weights of all nodes within its own transmission range. The node with the highest weight becomes the CH. This algorithm can be tailored for VANETS where the weight of a vehicle is calculated using metrics such as distance/speed/acceleration. RMAC outperforms DMAC in terms of $\overline{CML}$, and in terms of another topology metric: node re-clustering time.

Fuzzy Logic was employed in the decision making process in the context of several clustering approaches (**Hafeez et al., 2011; Tal & Muntean, 2013a; Arkian, Atani, Diyanat & Pourkhalili, 2015; El Mouna, Tabbane, Labiod & Tabbane, 2015, Sharma & Kaul, 2018**). Fuzzy Logic is an excellent mathematical framework for dealing with imprecision and multiple parameters. This is what needs to be modelled in VANET clustering: imprecision – it is impossible to define precisely how each of the clustering metrics influences the stability of CH in particular and clusters in general – and multiple clustering metrics that are imposed by the dynamicity and complex vehicular networking environment (Tal&Muntean, 2017). Moreover, Fuzzy Logic is widely used in prediction and detection systems.

Hafeez et al. (2011) introduced a clustering algorithm in the context of a new MAC protocol. Vehicles are organized in clusters on the basis of the beaconing and clustering messages they exchange in their neighbourhood. The focus is again on the CH election as CH is assigned with the main organizing and communication roles inside its cluster. The vehicles can have 5 different states: lone (not clustered), member, temporal CH, backup CH and CH. Temporal CH and backup CH roles aim to provide on one hand a stable CH in the cluster, a temporal CH must prove that it is the most stable selection, and on the other hand to ensure a smoother CH re-election, backup CH is ready to take over the CH role. CH election algorithm is based on a weighted stability factor that is built upon the exponential-weighted moving average of the previous stability factors. Stability factor is computed for each vehicle and it is based on the relative movement between the neighbouring vehicles reflected in the average speed difference between the vehicle speed and its neighbours' speed. The novelty of this clustering scheme consists in the technique implemented in order to provide a smoother CH re-election and consequently to improve the cluster stability. Basically, this technique states how backup CH is taking over the CH role. The implementation of this technique is based on a Fuzzy Logic system that aims to predict and learn driver's behaviour. Based on this the next position and speed of the vehicles are computed. If in this next moment of time if not all the member of its cluster are in its range anymore, but they are still in the range of the backup CH, then CH hands over its role to the backup CH.

The proposed clustering solution is assessed using a large variety of metrics from all the classes presented. Thus, the MAC protocol integrating the clustering solution is assessed as well. However as our interest relays in the clustering schemes we mention the topology-based metrics employed in assessment: $\overline{CHL}$, $\overline{CS}$, $\overline{CML}$. The proposed clustering algorithm is demonstrated to overcome the performances of another cluster algorithm designed for a VANETs MAC protocol that was previously discussed (Su & Zhang, 2007). Moreover, the MAC protocol based on the proposed clustering solution proves better performances than the protocol used as comparison.

Tal & Muntean (2013a) proposed a new CH-based scheme that has as main novelty the employment of Fuzzy Logic as decisional framework in selecting the CH. The clustering metrics considered are the average relative distance, average relative velocity, direction of travelling and the average relative compatibility. This later parameter was introduced as a novelty by Tal & Muntean (2012) and measures the compatibility in the users (vehicles' drivers/passengers) preferences in certain data/content. The aim is to increase the probability of users being provided with data/content of their interest inside the cluster. Thus both clustering

schemes aim to provide a cluster-based architecture for disseminating data/content of users' interest inside the cluster. In addition, these two approaches emphasize on the capability of clustering of designing efficient and optimized VANET architectures where the communication with infrastructure is limited (only CH is communicating with RSU) and in the same time the communication range can be extended via multi-hop communication inside the cluster in case of a multi-hop clustering.
In an assessment that compares these both algorithms and in addition the Lowest Id it is shown that the Fuzzy Logic-based clustering algorithm performs better than others two. The performance metrics used were $\overline{CHL}$, $\overline{CS}$ and a solution–dependent relative topology metric.
Arkian, Atani, Diyanat & Pourkhalili (2015) introduced a new cluster-based vehicular cloud architecture. The purpose of this architecture is to provide a better management of the limited resources in vehicular networks. Fuzzy Logic is employed in the CH selection algorithm that is proven to perform better than the one proposed in (Tal & Muntean, 2013a) in terms of $\overline{CHL}$ performance metric and other solution-dependent performance metrics. The clustering metrics used in the algorithm are: neighborhood degree, average speed, and RSU link quality. The selection of the CH subscribes to the following policy: a CH should have a high neighborhood degree and the RSU link quality should also be high.
A newer trend in VN clustering is the employment of clustering algorithms in designing reliable and efficient VN architectures that bring together multiple access technologies. Such cluster-based hybrid architectures were proposed in some of the aforementioned clustering solutions (Sivaraj et al., 2011; Taleb & Benslimane, 2010; Benslimane et al., 2011, Tung et al., 2013). El Mouna, Tabbane, Labiod & Tabbane, 2015 proposed such an architecture, with Fuzzy Logic playing a central role. The vehicles in the cluster communicate via V2V communications based on the IEEE 802.11p standard, while a GW in the cluster is chosen for connection to the LTE Advanced infrastructure. Fuzzy Logic is employed in the GW selection. The selection takes into consideration multiple criteria: QoS classes, connectivity strength between the vehicle and infrastructure, connectivity strength between the CH and infrastructure, CH load and link connectivity between the vehicle and CH that encompasses the mobility of the vehicle. The algorithm is demonstrated to perform better than other clustering algorithms, and also the benefits of the clustered network are demonstrated against the non-clustered/flat network. The performance metrics were mainly network-specific metrics, including the overhead imposed by the clustering messages/control.
Security is a hot research topic in the context of 5G and VANET. Sharma & Kaul (2018) proposed a Fuzzy Logic cluster-based swarm optimized intrusion detection system for VANET, where Fuzzy Logic is employed as the main player in the CH selection. The main role of the clustering in the context of the proposed solution is to deal with the stability of the ever-changing VANET network.
Wahab et al. (2013) is a two-hop CH-based clustering scheme for VANETs that is also incorporating computational intelligence. This is one of the proposed clustering algorithm novelties: the employment of Ant Colony Optimization in selecting the nodes having a state called multi point relay. These nodes are selected by CH for inter-cluster communication. The other novelty of this approach consist in building 5 new clustering metrics models with the focus on QoS. The most complex one combines bandwidth, connectivity and mobility metrics specific to VANETs (i.e. relative speed and distance). The output of the model is a QoS factor that is computed for each vehicle. Each of these models can be employed in further QoS-oriented clustering algorithms for VANETs, the authors describing each model's recommended scenario. This QoS factor is used to elect the most suitable CH and the multi point relays, while the clustering formation is done only on the basis of 2-hop neighbouring.
The clustering algorithm is designed in the context of a new routing protocol dedicated for VANETs that derivates from a MANET routing protocol designed to improve QoS, QoS-OLSR that on its turns derives from the state-of-the-art routing protocol for MANETs, QLSR (Optimized Link State Routing). Thus the performance assessment aims to demonstrate on one hand the efficiency of the clustering algorithm in terms of network stability and on the other hand to prove the efficiency of this algorithm in the designed routing protocol. In the first case, the performance is tested using a solution-dependent topology metric defined by the authors that is generic entitled stability. The metric is highly dependent on the clustering parameters. The authors show the performances of the algorithm in terms of stability and network metrics (e.g. packet delivery ratio) in 5 different cases corresponding to the 5 different clustering metrics models. No

comparison is done with other clustering schemes. The comparison-based assessment is done only when showing the performances of the overall solution. The cluster-based routing protocol outperforms QoS-OLSR and OLSR both.

Game theory started to be explored as a decision making tool in the context of clustering approaches in the more generic context of mobile networks (Massin, Le Martret & Ciblat, 2017), but also in the specific context of VANET clustering (Khan, Abolhasan & Ni, 2018). In **(Khan, Abolhasan & Ni, 2018)** game theory is employed in the decision making process for both cluster head selection and vehicle clustering. An Evolutionary Game Theoretic (EGT) framework aiming to create stable clusters and to select stable CHs is proposed. The decision criteria are throughput, link capacity between the RSU and CH and cluster size. Initially, the vehicles are randomly clustered and the cluster reformation and CH selection is triggered through the EGT framework. The clustering algorithm is evaluated in terms of both network-specific performance metrics and topology-based performance metrics, namely: $\overline{CHCR}$. The latter metric is the one used for measuring the stability of the proposed approach. Game theory was employed in another VANET clustering algorithm, but not as a decisional tool (**Ahmad et al., 2018**). In this V2X-LTE cluster-based solution, clustering is used in order to minimize LTE usage, while game theory is used to enforce a cooperation policy between the cluster members in order to avoid bottlenecks in sharing data.

FUTURE RESEARCH DIRECTIONS

In a roadmap of clustering algorithms in the VANET research area, its start is recorded in 2005 when the first studies have been performed by employing Lowest Id and Highest Degree in VANETs scenarios and by suggesting new approaches that relate to these (e.g. Fan et al. (2005)). Actually, most of the VANET mobile clustering algorithms are using the basic principles that fundament Lowest Id and Highest Degree algorithms. Back in 2005 some of the main clustering challenges in VANETs have been outlined as well: rapidly changing topology of VANETs, scalability, multiple services to be provided with different requirements (real-time traffic, non-real time traffic) (Reumerman, Roggero & Ruffini, 2005).

Since then, the clustering algorithms evolved, many approaches have been proposed to tackle especially the rapidly changing topology of VANETs. More and more mobility parameters have been considered in clustering: direction, lanes, speed, position, predicted speed and position and combined with other parameters such bandwidth, connectivity (or density of the vehicles) and signal strength. These parameters are mainly considered in selecting the nodes with extra-responsibilities in the cluster, especially CH. CH election algorithms are of high importance and some of the researchers are actually focusing on this aspect of clustering only. Usually CH has the main responsibilities in the cluster and therefore a stable CH is required. In addition, the stability of CH is highly influencing the stability of the cluster itself, as most of the times when CH is re-elected a cluster reconfiguration is required, too. Therefore, researchers employed all kind of techniques to combine the clustering parameters and to decide which is the most suitable CH. The predominant techniques are utility functions and weight-based techniques, but the more these algorithms evolved, more and more innovatory techniques such as Affinity Propagation, Fuzzy Logic, game theory, etc. have been employed. As a matter of fact, one of the latest trends in VANET clustering algorithms is the employment of computational intelligence. Initially, these techniques were employed in secondary roles, but afterwards they were employed as main players in CH selection/clustering algorithms. As such, Fuzzy Logic (Hafeez et al., 2011) and Ant Colony Optimization (Wahab et al., 2013) were employed for instance in some secondary roles in clustering such as predicting the future positions of the vehicles. Fuzzy Logic decisional systems, known as very powerful decisional systems, have started to be employed as main players in the context of CH selection algorithms (Tal & Muntean, 2013a; Arkian, Atani, Diyanat & Pourkhalili, 2015; El Mouna, Tabbane, Labiod & Tabbane, 2015). Fuzzy Logic is the perfect mathematical framework for dealing with imprecise information such as the one used in clustering (it is impossible to precisely define how each of the clustering parameters influence the stability of CH) and with multiple parameters. Similarly, game theory was employed as the main decision making tool in the context of another clustering scheme for both CH selection and clustering algorithms.

Another trend in VANET clustering is the employment of clustering algorithms in designing reliable and efficient VANET architectures that bring together multiple access technologies. The need to converge multiple types of technologies in VANET context in order to enable the diversity of vehicular applications is underlined more and more in the literature and is also enforced by the low penetration rate of the WAVE technology. Moreover, 5G will be characterized by a heterogeneous network environment. Thus, design techniques of VANET architectures that bring together multiple access technologies are of high interest. First, VANET cluster-based 3G-WAVE architectures were envisioned and more recently, VANET cluster-based architectures using 4G together with other technologies (WLAN or WAVE) were proposed. Very recently, an SDN enabled 5G-VANET clustered architecture was proposed (Duan, Liu & Wang, 2017), where the one of the main role of clustering is again to optimize cellular communication – reduce from the communication burden: every CM would communicate with the BS via CH only, while the intra-cluster communication would rely on another type of communication (e.g. IEEE802.11p).

As a conclusion to the aforementioned aspects, the future directions in this research area of clustering in VANETs can be summarized as follows:

- More mathematical frameworks incorporating computational intelligence should be experimented in trying to find the most appropriate method of combining the clustering parameters in order to obtain stable CHs and stable networks. Machine learning techniques and their application are gaining momentum in the context of VANET (Ye et al., 2018) and we argue that this would be a research direction to explore in the specific context of VANET clustering as well considering that clustering algorithms in general have their own particular role in the context of machine learning.
- Although this chapter does some significant steps forward in the context of performance assessment of clustering algorithms in VANETs, this remains still an open challenge. The analysis of the VANET clustering algorithms conducted in this work, leads to the idea that there is a need of standardizing clustering performance metrics, especially the general topology metrics. In addition, there is a huge need of traffic and mobility models for performing the testing of VANETs clustering algorithms.
- A direction to be followed is the one that relates to clustering capabilities of conducting to a reliable and optimized design of VANET architecture based on multiple access technologies that is able to support the diversity of VANET applications. As 5G will be characterized by a heterogeneous network environment this research direction is of particular interest.
- Moreover, VANET security in particular and 5G security in general is a hot research topic (Hussein, Elhajj, Chehab, & Kayssi, 2017; Hasrouny, Samhat, Bassil & Laouiti, 2017; Sharma & Kaul, 2018b). The potential of clustering to be used in the context of security solutions was highlighted in (Sharma & Kaul, 2018a; Sharma & Kaul, 2018b) where clustering is suggested to have an important role in overcoming security issues that relate to the network scalability and stability control. As clustering is a well-known solution to these later issues, this potential should be further exploited in future security solutions.

CONCLUSION

This chapter has emphasized the high importance of VANETs in the context of future 5G-enabled smart cities and roads. Initially, VANET was mainly associated with WAVE/DSRC technologies, but this work has underlined the need for the convergence of multiple wireless technologies for support of a reliable VANET architecture that is able to provide a variety of services and to cope with the multiple challenges of VANETs. Clustering can be employed in designing such a VANET architecture that successfully uses different wireless communications technologies in an optimal manner. Thus, clustering algorithms may play an important role in the future 5G heterogeneous networks. Moreover, clustering addresses some of VANETs major challenges such as scalability and stability.

This work presents a comprehensive survey of clustering schemes in the VANET research area covering aspects that were not really addressed before in a structured manner. The survey presented in this chapter provides a general classification of the clustering algorithms, presents some of the most advanced and latest algorithms in VANETs, and in addition, this is among the few works in the literature that also reviewed the performance assessment of clustering algorithms. In this chapter, we discussed the performance assessment metrics used in clustering in VANETs, provided a classification, identified and defined general performance metrics to be used in the evaluation of clustering algorithms in VANETs.

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KEY TERMS & DEFINITIONS

Smart Cites: cities of the future that provide increased comfort to their citizens while creating a sustainable environment.
VANET: vehicular ad-hoc networks
Clustering: technique of grouping similar objects used mainly to deal with scalability, but its aim depends on the context it is applied in.
Performance assessment: evaluation – in the context of this chapter, the evaluation of clustering algorithms in VANETs
V2X communications: the main enabling technology of VANETs
WAVE: Wireless Access Vehicular Environment – V2X communications standardization
3G/4G/5G – 3rd/4th/5th Generation of mobile cellular communications
WLAN – Wireless Local Area Network