VANETs' research over the past decade: overview, credibility, and trends

Elmano Ramalho Cavalcanti
Federal Institute of Pernambuco, Brazil
elmano.cavalcanti@garanhuns.ifpe.edu.br

José Anderson Rodrigues de Souza
Federal University of Campina Grande, Brazil
joseanderson@copin.ufcg.edu.br

Marco Aurélio Spohn
Federal University of Fronteira Sul, Brazil
marco.spohn@uffs.edu.br

Reinaldo Cézar de Morais Gomes
Federal University of Campina Grande, Brazil
reinaldo@computacao.ufcg.edu.br

Anderson Fabiano Batista Ferreira da Costa
Federal Institute of Paraiba, Brazil
anderson@ifpb.edu.br

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ABSTRACT

Since its inception, Vehicular Ad hoc Networks (VANETs) have been attracting much attention from both academia and industry. As for other wireless networking areas, scientific advancements are mainly due to the employment of simulation tools and mathematical models. After surveying 283 papers published in the last decade on vehicular networking, we pinpoint the main studied topics as well as the most employed tools, pointing out the changes in research subject preference over the years. As a key contribution, we also evaluate to what extent the research community has evolved concerning the principles of credibility in simulation-based studies, such as repeatability and replicability, comparing our results with previous studies.

CCS CONCEPTS

• **General and reference** → **Surveys and overviews**; • **Networks** → **Mobile ad hoc networks**;

KEYWORDS

Survey, Vehicular networks, Simulation, Reproducibility

1 INTRODUCTION

Vehicular Ad hoc Networks (VANETs) are one of the most prominent specialization of Mobile Ad hoc Networks (MANETs). In VANETs, vehicles communicate with each other (vehicle-to-vehicle, V2V) or with the infrastructure (vehicle-to-infrastructure, V2I). Currently, the term vehicle-to-everything (V2X) has also been widely adopted.

Since its inception, vehicular networking has been attracting much attention from both academia and industry. Several international industrial and governmental consortia such as the European C2C-CC[1] and the American VII[2] have shown the high relevance and feasibility of V2V and V2I communication for our society.

Figure 1 depicts the total number of publications related to VANETs and MANETs during the last years. We have not plotted 2017 stats since the number of papers that appeared in conferences and journals in the last quarter of the year is not fully available from indexing databases. For VANETs, there is a noticeable increase in the number of published papers, while a reduction is observed for MANETs' publications. Particularly, from 2012 to 2016 the former increased by 50% while the latter decreased by 18%.

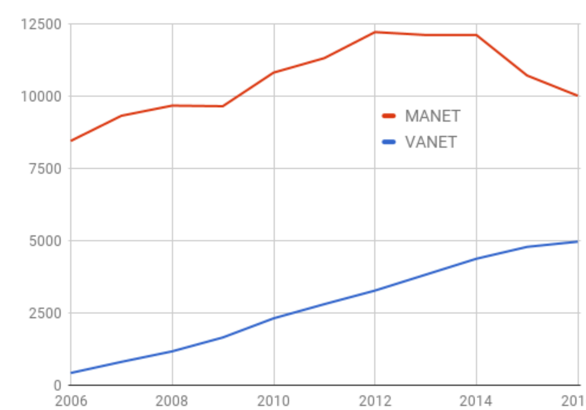


Figure 1: Number of MANET and VANET papers indexed in Google Scholar from 2006 to 2016.

To support the growth of wireless ad hoc networks, researchers have designed a variety of protocols, spanning the main layers of the protocol stack. When it comes to evaluating such protocols,

[1] CAR 2 CAR Communication Consortium, https://www.car-2-car.org
[2] Vehicle Infrastructure Integration, http://www.vehicle-infrastructure.org

analytic modeling, experimentation, and simulation are the three main approaches available to researchers. The first approach usually lacks generalization, by not taking into account the intrinsic high complexity level. The second one provides realistic achievements such as proof of concept, but for large scale scenarios it is financially unfeasible. Therefore, due to its better cost benefit, simulation is by far the leading approach employed by researchers [1].

However, one of the major issues concerning simulation results from its frequently low credibility level. There are likely errors due to the simulation model or from improper data analysis [3]. Unfortunately, there is a widespread bad practice by not describing or omitting information, source code, and datasets, which are crucial for guaranteeing replicability and reproducibility of any published research. Moreover, it is quite common to present statistical results with no information regarding their accuracy in terms of confidence interval, at any given confidence level, including relative statistical errors [27].

In this paper, we analyze the current state of VANETs' research by taking into account hundreds of papers published from 2007 to 2016. The goals of this survey are two-fold: (1) to check to what extent the research community has evolved concerning the principles of credibility in simulation-based studies [17]; (2) to figure out the main research topics investigated as well as the most employed tools (e.g., simulators), models (e.g., mobility, traffic, propagation), and protocols, pointing out several research trends.

This paper is organized as follows: Section 2 describes the related work, Section 3 shows the results of the survey, followed by a critical analysis of the VANET literature (Section 4), and Section 5 concludes the paper.

2 RELATED WORK

The first effort on the evaluation of simulation-based research in computer networks was carried out by Pawlikowski et al. [25]. The authors conducted a survey of over 2, 200 publications related to telecommunications from IEEE INFOCOM (1992 to 1998), and three other computer networking journals, from 1996 to 1998. The survey took into account only two aspects of simulation credibility: the use of appropriate pseudo-random number generators (PRNGs), and the proper analysis of simulation output data. The results revealed that almost 50 percent of all papers did not state the type of simulation employed (i.e., terminating or steady-state), while more than 70 percent did not mention which PRNG was used.

Kotz et al. [16] compared experimentation with simulation of a MANET in order to measure how the available radio propagation models differ from real measurements. The results showed that the usual assumptions considered by the research community (e.g., a radio's transmission area is circular), and adopted by simpler models (e.g., free-space and two-ray ground), are unrealistic. The authors also surveyed a set of MobiCom and MobiHoc articles from 1995 through 2002, showing that about 80% of all papers adopted unrealistic radio models.

In what concerns credibility in MANET simulation-based studies, Kurkowski et al. [17] surveyed 151 papers presented at the International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc) from 2000 to 2005. They focused on measuring how credible the simulation-based papers are, considering four areas of credibility in research: repeatability, rigorous scenario modeling, unbiased results, and proper statistical analysis. General results pointed out that less than 15% of the published papers were found repeatable, only 7.0% addressed initialization bias, and 87.5% did not include confidence intervals in the plots. Later on, we compare their results to ours.

Andel and Yasinsac [3] also discuss the issue of credibility in MANETs' simulation, listing the most common improper simulation practices such as the absence of repeatable simulation requirements, and questionable statistical validity. The former is mainly due to the lack of documentation, whereas the latter is mainly related to inaccurate data collection techniques, or insufficient statistical analysis. In addition to that, another crucial aspect is regarding to the level of details and the model validation employed. As the authors claim, "Omitting detail or oversimplifying the model can lead to ambiguous or erroneous outcomes".

A more recent study [27] presents a comprehensive survey of over 8,300 IEEE publications on telecommunication networks. The authors concluded that, even after ten years of the Pawlikowski et al. study [25], "there is no significant change with respect to quality and credibility of the simulation studies revised and the deep crisis of credibility still remains". Even though a large number of papers were surveyed, only papers published from 2007 to 2009 were taken into account.

Differently of the previous works, in this paper we consider a longer period, from 2007 to 2016, and focus not only on the credibility of simulation-based studies but also on the overall VANETs' research field. To the best of our knowledge, this is the first work to present such kind of review and contribution.

3 SURVEY RESULTS

To conduct the survey we have considered papers containing the words "VANET" or "Vehicular ad hoc Network" in the title, abstract, or index terms (e.g., keywords) on publications from the following conferences and journals for the period from 2007 to 2017:

- The ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc);
- The Annual International Conference on Mobile Computing and Networking (Mobicom) main event and workshops;
- Vehicular Technology Conference (VTC);
- IEEE Transactions on Mobile Computing (TMC).

Mobihoc and Mobicom are well-known highly selective premier conferences on computer networking, whereas TMC is one of the leading journals on mobile computing. In addition to that, VTC was also chosen due to its relevance and the high number of available papers covering overall VANETs' topics (indeed, the conference takes place twice a year).

A total of 283 papers matched this particular selection, of which 147 were published during the first five years (2007-2011), and the other 136 were published during the second period (2012-2017).

We manually inspected the 283 papers, extracting all valuable information required to characterize the research, and to highlight how the authors performed their research. The questionnaire employed for gathering all required information, as well as the data collected, are available at *zenodo* [3].

[3]https://doi.org/10.5281/zenodo.1205633

Table 1: Top-level research categories in VANETs.

CATEGORIES		
Title	**Description**	**Topic examples**
MAC-PHY	MAC and Physical layers issues	Media Access Control Techniques, schemes protocols, or algorithms; Channel modeling, modulating and coding; Adaptive transmit power control
PERF	Performance comparison analysis	Protocol performance/comparison analysis and simulation; Protocol design, testing, and verification analysis
APP	Application layer protocols and services	Safety (e.g., crash prevention); Efficiency (e.g., road congestion avoidance); Entertainment (e.g., multimedia streaming); Environmental (e.g., pollution detection)
DATA	Data management	Data collection and message dissemination methods (e.g., broadcasting)
SERV	Complementary services	Location Tracking, Location Estimate Correction, Integration with Infrastructure Networks, Quality-of-Service Issues, Security issues and countermeasures
ROUT	Routing protocol	Proposal of a new routing procotol
MOB	Mobility issues	Mobility / Connectivity analysis, modelling, management, Clustering Algorithm
TOOL	Tools, testbeds	Tool / Platform / Architecture / Framework proposal Deployment and field testing, Experimental and Prototype Results

3.1 Overview of VANET research in the last decade

Starting from the list of the most common research topics in VANETs (extracted and merged from several 'call for papers' of computer networking conferences and journals), we defined a group of eight research areas (top-level categories), covering a wide range of topics related to vehicular communications (Table 1). For example, if a paper focuses on any aspect related to the link or physical layers, such as a MAC algorithm, channel modeling, network coding, or adaptive transmit power control, the paper is labeled as MAC-PHY. At the other end there is the APP class, containing all papers addressing user applications (e.g., intersection collision avoidance, road congestion notification, and multimedia streaming).

As in other computer networking areas, there are many papers concerning performance evaluation of protocols. A paper is taken as belonging to the PERF class if and only if its main contribution is on the performance evaluation itself. Therefore, if a new MAC or routing protocol was proposed, followed by its performance evaluation, then the paper was labeled as MAC-PHY, or ROUT, instead of PERF.

Papers describing a new tool, platform, framework, or architecture were labeled as TOOL. For the sake of simplicity, all experimental studies, usually concerning deployment and field testing, were also included into that class.

The ROUT class stands for papers proposing a new routing protocol whereas the MOB class relates to mobility issues, such as mobility modeling and clustering algorithms.

We end our classification with the DATA and SERV labels. The former was used for works focusing on data collection/dissemination schemes, while the latter is for what we call 'complementary services', such as Quality of Service (QoS), security, and localization.

Figure 2 depicts the content and temporal distribution for the published papers. Almost a quarter of them was on MAC-PHY issues (23%). During the last decade, both academia and industry have worked in order to enable effective and efficient wireless communication in vehicular environments. The IEEE 802.11p amendment as well as the IEEE 1609 Wireless Access in Vehicular Environments (WAVE) standards result from such an effort. Moreover, our results suggest a slight increase on such issues. The applicability of network coding schemes in VANETs may be considered as one major reason for this trend.[4]

At the second place, we got the SERV class, which includes papers with regard to complementary services, whether it be Quality of Service (QoS), security approaches, or location-based services. In the second period, we noticed more studies associated to the integration between vehicular networks and traditional infrastructure networks (e.g., cellular). There is an expectation for VANETs to be integrated with 5G mobile technology by 2020 [23].

Routing (ROUT label) is still an important topic of research. Firstly, traditional MANET routing protocols were found not suitable for the vast requirements, and unique characteristics of VANETs' scenarios and applications. Tens of routing protocols have been proposed during the last decade, including various taxonomies for classifying them [6]. Rather than the traditional MANETs' routing protocols, which are topology-based (proactive, reactive, or hybrid), the most promising VANETs' alternatives are the geographic and the delay-tolerant approaches. The former is more suitable for

[4] A search for the expression (VANET "NETWORK CODING") in Google scholar results in 478 papers in 2007-2011, and 1570 in 2012-2016.

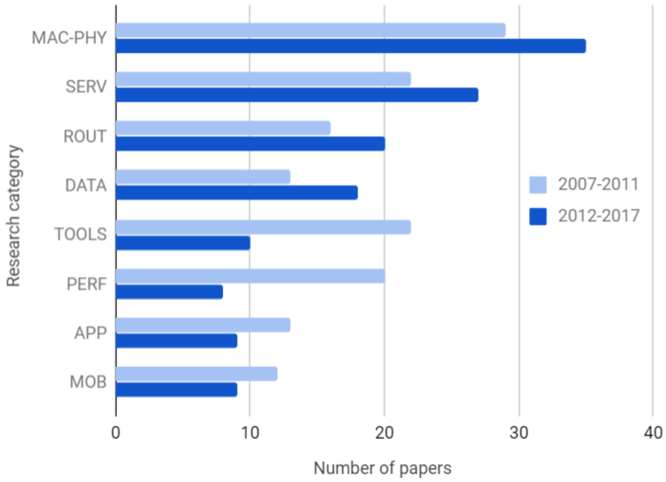


Figure 2: The main research topics in VANETs.

vehicular communication whereas the latter involves the carry-and-forward strategy which is employed to overcome intermittent connectivity, a typical situation in vehicular scenarios.

We noticed a significant increase on the number of works related to dissemination strategies and broadcasting algorithms (DATA label). In fact, it was the one subject with the highest growth among all (38%). As noted by Lee et al. [18], most application protocols rely on variants of the epidemic data dissemination approach so that the appropriate information propagates to nodes in an area where the information is originated. The main challenge in this area is on addressing redundancy and efficiency all together.

Meanwhile, publications in the PERF class dropped from 20 to only 8 papers between the two periods. This result suggests that less effort has been put just on protocol performance comparison and analysis. As the research in VANETs evolves, more attention is given to novel protocols, services, and applications instead of understanding how existing technologies would behave in new environments. Thus, one could take this result somehow predictable.

Table 2: VANET simulation freeware / open source software.

Category	Tool	Release[1]
Integrated framework	TraNS [26]	2007
	MobiREAL [19]	2006
	Veins [28]	2006
Network Simulator	NCTUns [31]	2007
	ns-3 [14]	2008
	OMNET++ [30]	2006
	GrooveNet [20]	2006
Mobility Generator	SUMO [4]	2006
	VanetMobiSim [13]	2006
	MOVE [15]	2007
	CityMob [21]	2008
Scenario Generator	VERGILIUS [10]	2010

[1] Or when it first supported vehicular network simulation.

The class TOOLS was also less addressed, with publications dropping from 22 in the first period to only ten papers in 2012-2017. This might well be due to the fact that, during the first years of research, there is a huge need for tools and frameworks for laying down the groundworks for effective research. For instance, Table 2 shows a list of well-known simulation tools for VANETs, and it is noticeable that all of them were developed during the first period or even earlier. Nevertheless, with the adoption of vehicular communication technology by automobile manufacturers in the following years, it is possible that many new tools and frameworks are going to be introduced.

Lastly, two research categories had shown a slight decrease over the last decade: mobility modeling and analysis, and application layer protocols and services. With regards to the former, as there are already realistic two-dimensional traffic-based vehicular mobility models [4, 13], we foresee future research to be more specific, covering topics like geo-social mobility modeling, and three-dimensional connectivity analysis. On the other hand, concerning the latter topic (i.e., APP class), we were somehow surprised by the decrease on studies concerning the application layer, however, it's understandable that, after an initial period modeling the behavior of existing applications in the new VANETs scenarios, community has moved to more impactful research topics.

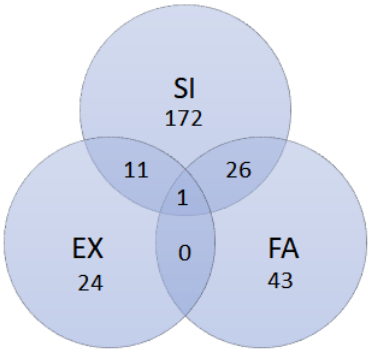
3.2 Has the MANET/VANET research community evolved in conducting simulation-based studies?

First of all, the results corroborate the fact that simulation is still the leading approach for validating and evaluating solutions in MANETs. More outstanding is that the percentage of articles that employed simulation remains basically the same as in 2000-2005: three out of four papers include simulation as the main tool (see Table 4).

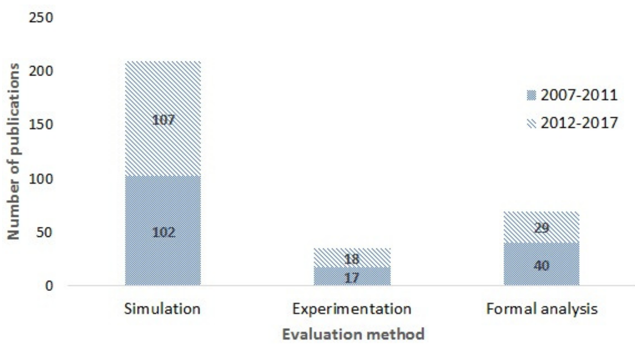
Other research methods, namely experimentation (i.e., real-world measurements), and formal mathematical analysis reached 12.7% and 24.7%, respectively. The sum of the percentages is higher than 100% since 38 works used more than one evaluation technique as presented in Figure 3a. Only six publications employed no method at all, while 277 papers employed at least one out of the three approaches.

Figure 3b depicts the variation on the number of publications by research method over the last two five-year periods. One possible reason for the increase of simulation based works and the reduction of formal analysis studies is the development/availability of more specific and featured simulators for vehicular networking, including tools for realistic road traffic generation. A summarized overview of freeware and open source tools that either have emerged or have added support for VANETs in the last decade is provided in Table 2. Such increase in the number of simulation tools, openly available for the community [22], most likely contributed to the reduction of publications (27.3% to 7.62%, Table 4) based on self-developed or custom simulators.

One astonishing result is that only a single publication made it clear whether the code, or dataset, is publicly available. As code, we mean any piece of software, including scripts, required for repeating the simulations/experiments. Without this resource, no researcher



(a) Number of publications according to the evaluation method employed: Simulation (SI), Experimentation (EX), and Formal Analysis (FA).



(b) Variation over the periods.

Figure 3: On the evaluation method employed.

can reproduce, and eventually validate, one other's research. Indeed, reproducibility is not yet a common approach of neither VANETs' research nor any other computer networks' area [29]. As a matter of fact, the lack of replicability and reproducibility may be a major issue in all sub-areas of computer science [7].

Even though a minority of papers actually include references (i.e, links) to author's web pages for some of the artifacts (e.g., code, dataset), the links are rarely permanent, and often become unavailable after a few months or years. For supporting open science, as well as the need for the 3Rs (repeatability, replicability, and reproducibility), cloud-based platforms have recently emerged aiming at providing a way for researchers to share all kind of data underlying their publications. A comprehensive list of hundreds of repositories is accessible at [24]. We briefly describe nine open research data repositories in Table 3, highlighting the number of datasets and code repositories that are considered as an artifact of at least one publication related to VANETs.

It is noticeable that only a tiny part of research projects get their artifacts actually published. The platforms with more VANETs' registries are Github and CRAWDAD. The focus of the former is on code whereas the latter is on archiving data sets from real networking experiments. In more recent platforms, any type of data may be uploaded, including code, datasets, documents, images, and videos. In most cases, there is DOI support making it possible to cite the resource, also with versioning feature.

Table 3: Research data repositories.

Platform	Launch	Size[1]	Data[2]	Code[3]
codeocean.com	2017	~ 100	0	0
data.mendeley.com	2015	>200	0	0
figshare.com	2011	>10K	5	0
github.com	2008	>10M	0	22
zenodo.org	2013	>8K	1	0
dataverse.harvard.edu	2007	>70K	0	0
Wolfram Repository	2017	~ 600	0	0
crawdad.org	2005	121	14	0
datadryad.org	2008	18K	0	0

[1] Number of research data records.
[2] Number of VANETs' dataset records.
[3] Number of VANETs' code records.

We have also noticed that no paper had included information on the pseudo-random number generator (PRNG) employed along the simulations. The remaining results regarding simulation and environment issues are somewhat similar to MobiHoc's survey [17].

With regard to basic input parameters (Table 4), our findings endorse the claim that there is a low credibility in simulation-based studies. More than one-third of the papers made no statement regarding node transmission range or the size of the simulation area, while only 15.71% cited the traffic pattern (e.g., CBR). In addition to that, nearly one-third of the publications did not mention the number of simulation runs (i.e., trials).

As a direct result of that, only 34.76% of all publications presented the confidence intervals along the plots. Nevertheless, this rate is almost three times higher than the one reported in [17] (12.5%), which suggests some improvement on the credibility of VANETs' simulation-based studies.

3.3 Tools, models, and protocols preferences in VANETs' research

Even though there are several network simulators for a great variety of networks, our focus is on simulators suitable for vehicular networks. In the last years, there have been changes in tools' preferences. Network simulator 2 (NS-2) was the most adopted, reaching 37.9% of the 198 articles citing the application of some sort of network simulator. NS-2 was followed by OMNET++ with 8.6%, MATLAB with 8.1%, and 7.1% for NS-3. Flexible, well-documented, and popular open source frameworks such as Veins [28] enhanced the adoption of OMNET++, mainly for the simulation of V2X networks. It is noticeable that while NS-2 usage dropped 19.5% (41 to 33) since the first five years, OMNET++ adoption has increased more than double (5 to 12).

Figure 5 presents the main vehicle movement pattern generators employed by researchers. The most used mobility simulators are SUMO (31.2%) and VanetMobiSim (11.8%). A high percentage (42.4%) of all simulation-based papers do not report the type of mobility tool employed for the simulations.

Table 4: Survey results comparison for papers published in ACM's MobiHoc conference (2000-2005) and in IEEE's VTC, ACM's MobiCom, and ACM's MobiHoc conferences, and IEEE's TMC journal (2007-2017).

Simulator and Environment				
Our survey's results [1]			**MobiHoc's survey [17]** [2]	
Totals	**Percent**	**Description**	**Totals**	**Percent**
210 of 283	74.20%	Used simulation in the research.	114 of 151	75.5 %
1 of 210	0.47%	Stated the code was available to others.	0 of 114	0%
180 of 210	85.71%	Stated which simulator was used.	80 of 114	70.2%
16 of 210	7.62%	Used self-developed or custom simulators	22 of 80	27.3%
43 of 210	20.48%	Stated which version of the public simulator was used.	7 of 58	12.1%
17 of 210	8.09%	Stated which operating system was used.	3 of 114	2.6%
20 of 210	9.52%	Addressed initialization bias.	8 of 114	7%
52 of 210	24.76%	Addressed the type of simulation.	48 of 114	42.1%
6 of 210	2.86%	Addressed the PRNG used.	0 of 114	0%
Simulation Input Parameters				
Our survey's results [1]			**MobiHoc's survey [17]** [2]	
Totals	**Percent**	**Description**	**Totals**	**Percent**
122 of 210	58.10%	Stated the size of the simulation area.	62 of 109	56.9%
137 of 210	65.23%	Stated the transmission range.	62 of 109	56.9%
88 of 210	41.90%	Stated the simulation duration.	49 of 109	45%
83 of 210	39.52%	Stated the traffic send rate.	41 of 109	37.5%
33 of 210	15.71%	Stated the traffic type (e.g., CBR, VBR, etc.)	31 of 109	28.4%
73 of 210	34.76%	Stated the number of simulation runs (iterations).	39 of 109	35.8%
Plots / Graphs				
Our survey's results [1]			**MobiHoc's survey [17]** [2]	
Totals	**Percent**	**Description**	**Totals**	**Percent**
206 of 210	98.09%	Used plots to illustrate the simulation results.	112 of 114	98.2%
73 of 210	34.76%	Used confidence intervals on the plots.	14 of 112	12.5%
88 of 210	41.90%	Missed labels or units on the data.	28 of 112	25%

[1] **A total of 283 papers published in IEEE's VTC Conference, IEEE's TMC, ACM's MobiCom, and ACM's MobiHoc, from 2007 to 2017.**
[2] **A total of 151 papers published in ACM's MobiHoc conference from 2000 to 2005 [17].**

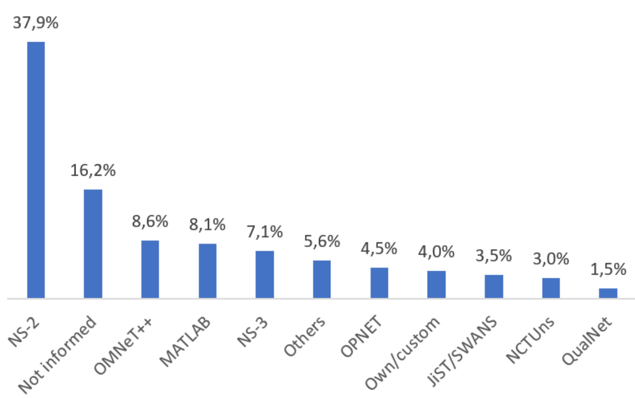


Figure 4: Network simulator preference.

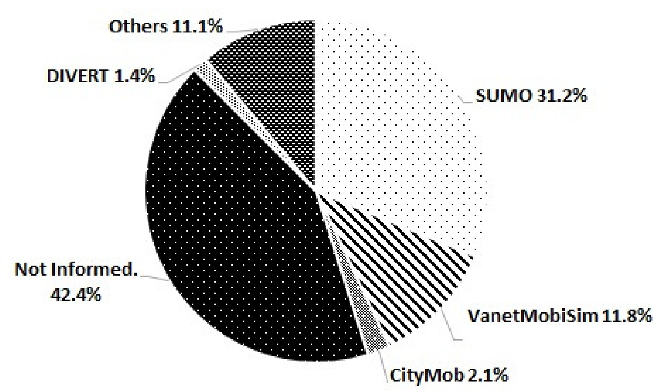


Figure 5: Mobility simulation environment.

When taking into account the papers related to the application layer, we have identified a particular trend: fewer publications regard safety and efficiency issues, while more works deal with entertainment and urban sensing. The former issues are among the original motivations for VANETs' studies and their integration with Intelligent Transport System (ITS). Nevertheless, for either end users or industry players, entertainment integrated services such as multimedia streaming [8] (e.g., geo-located touristic video guide), and urban sensing for a greener environment [2] (e.g., reduction of CO_2 emission), are subjects of current and future research.

It is possible that these four applications' categories are going to be targeted by distinct stakeholders. Vehicles' manufacturers may focus on providing safety and urban sensing applications, whereas public agencies (e.g., the department of transportation) work on developing traffic efficient solutions. Lastly, entertainment applications might well be developed by major software companies.

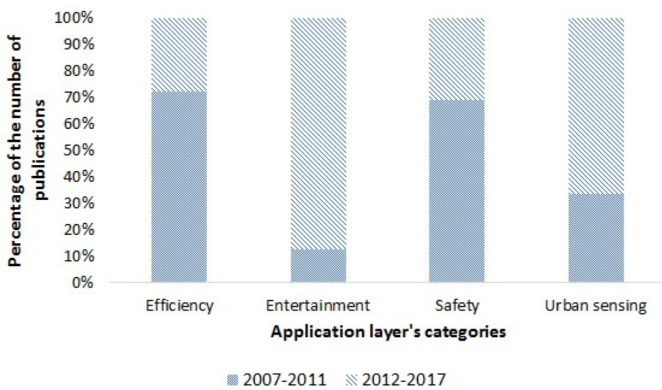


Figure 6: Research trends for VANETs' applications.

While somehow unexpected, the results presented in Figure 7 show that the application of real maps reduced when compared to synthetic maps (i.e., user-defined maps, usually in a Manhattan geographic style). We think that a proper scenario should be based on a realistic mobility model and a real map, which could be easily accomplished with freely available tools such as SUMO and OpenStreeMap [12].

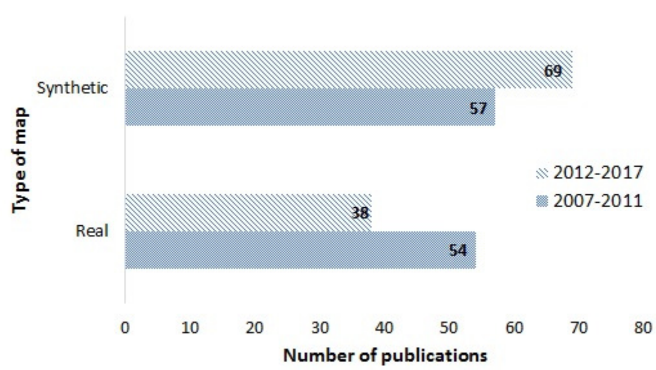


Figure 7: Map type/style.

In addition to the overall analysis of the material and methods presented in the papers (as stated in Table 4), we have also extracted more specific information related to three key components for any wireless network simulation: mobility model, propagation model, and routing protocol. For each one of these components, we present the most chosen options.

The majority of the surveyed papers employed some mobility model: 221 out of 283 (78.10%); however, only 43.44% of them stated which model was used, resulting on a considerable omission rate of 56.56%. As for the propagation model, we observed an even worse result (61.22%).

Propagation models are usually integrated into network simulators, whereas external tools (e.g., SUMO [4]) are frequently chosen for generating realistic vehicle movement patterns. Very often (35.42%) authors cite the adopted mobility tool but they do not mention which model was then selected. Mobility model tools, such as VanetMobiSim [13], have several models available so that it is paramount to mention which specific model was chosen (e.g., Intelligent Driver Model with Lane Changes, IDM-LC).

With regards to propagation models, the Nakagami was the most employed model, reaching a preference rate of 40.96%, followed by the Two-Ray Ground model with 31.32%. Note that these percentages are not exclusive, since more than one model is usually employed in the same study.

Most network simulators have both deterministic and probabilistic models, including all those described in Table 5. However, several solid studies (such as [5]) have shown that a realistic model should consider vehicles as obstacles, because they impact on the LOS obstruction, received signal power, and the packet reception rate.

About one-third of all papers used some routing protocol (97 out of 283, 34.28%), being two-third of them designed by the authors themselves. The geographic GPRS protocol, and the reactive AODV protocol were the most employed ones, with 18.75% and 14.06% respectively. Among the link state protocols, OLSR was the most adopted one, representing 9.38% among all protocols. In several cases (13 out of 64), the authors did not mention which protocol was chosen, but they only cited the publication where the protocol was first introduced.

4 DISCUSSION

Some general remarks can be highlighted from survey results to indicate the trends of researches during the last years such as the increase in the number of published papers related to the physical layer, link layer and routing solutions, and also new services and data management studies. Such increase is directly related to the new demands for solutions from users and manufacturers. The former asked not only for new applications, but mainly for new mechanisms to improve applications in terms of QoS, security, and geographical correlation, in order to enhance users' experience. The latter need new infrastructure technologies to improve data transmission, while supporting new users' services.

On the other hand, investigations regarding users' application behaviour and performance evaluation comparing existing solutions designed for different environments (e.g., MANETs' routing protocols applied in VANETs' scenarios) received less attention from the community. These two topics were extremely important in the initial development of VANETs since they allowed a better understanding of the field and how/when existing solutions could be employed. After that moment, it was expected that new solutions were proposed considering the specific requirements of VANETs, moving efforts to the design of new technologies and protocols.

Table 5: Survey results regarding researchers' preferences on mobility and propagation models, and routing protocols in simulation-based studies.

Mobility Model (MM)		
Totals	**Percent**	**Description**
221 of 283	78.10%	Used MM in the research.
96 of 221	43.44%	Stated which model/tool was used.
34 of 96	35.42%	Only stated the mobility trace generator tool (e.g., VanetMobisim), not specifying the MM.
16 of 96	16.67%	Used Manhattan model.
14 of 96	14.58%	Used own (or proposed) model.
13 of 96	13.54%	Used IDM model.
7 of 96	7.29%	Used Freeway model.
7 of 96	7.29%	Used other models.
4 of 96	4.17%	Used only real traces.
3 of 96	3.13%	Used random waypoint model.
Propagation Model (PM)		
Totals	**Percent**	**Description**
214 of 283	75.62%	Used PM in the research.
83 of 214	38.78%	Stated which model was used.
34 of 83	40.96%	Used Nakagami model.
26 of 83	31.32%	Used Two-Ray Ground model.
8 of 83	9.64%	Used Free Space (Friis) model.
8 of 83	9.64%	Used Rayleigh model.
7 of 83	8.43%	Other models (e.g., CORNER [11]).
6 of 83	7.23%	Used own model.
Routing Protocol (RP)		
Totals	**Percent**	**Description**
97 of 283	34.28%	Used RP in the research.
64 of 97	65.98%	Stated which protocol was used.
33 of 64	51.56%	Used own (or proposed) protocol.
12 of 64	18.75%	Used the GPSR protocol.
9 of 64	14.06%	Used the AODV protocol.
6 of 64	9.38%	Used the OLSR protocol.
4 of 64	6.25%	Other protocols.
3 of 64	4.69%	Used the DSR protocol.
3 of 64	4.69%	Used the DYMO protocol.

Another interesting point is the fact that more works are relying on simulation platforms to conduct their experiments. This happens because more sophisticated simulation platforms, and auxiliary tools (e.g., enhanced models for mobility, radio propagation, and traffic), were developed focusing on VANETs' specific scenarios. The evolution on supporting tools such as SUMO and VanetMobiSim allowed researchers to employ general purpose network simulators (mainly NS2 and OMNet++) instead of developing new simulation tools from scratch.

Nevertheless, reproducibility remains a huge hurdle since authors rarely make available any material (e.g., source code, configuration files, data sets, and mobility traces) to be used by other researchers. In addition to that, a considerable number of papers presented only basic information for understanding the experiments (e.g., the lack of number of runs/trials, radio transmission range, size of the simulation area, traffic pattern, mobility model, propagation model, and routing protocol).

Considering those specific points, when one compares the general results presented by our work to the ones presented by the papers discussed in Section 2, it is possible to see that some research topics switched priorities, with simulation gaining more noteworthiness due to more accurate and reliable tools. However, even though there was some noticeable evolution, most of the problems previously identified remain present in current publications.

5 CONCLUSION

As vehicular networks are expected to be integrated with the 5G mobile technology by 2020, we noted that less research has been done regarding protocol performance evaluation. The focus has moved toward new solutions for services such as location tracking and estimate correction, QoS, cross-layer protocols, and maximization of network resources based on network coding. Moreover, considering the four categories of VANETs' applications as described by Gerla and Kleinrock [9], our results indicate that fewer publications concern safety and efficiency issues, while a growing number are related to entertainment and environmental urban sensing.

The results of our survey show that VANETs' simulation-based studies still lack credibility due to issues similar to those reported in previous studies published in 2002 [25], 2005 [17], and 2014 [27]. Besides omitting technical information, such as the implied models (e.g., mobility, propagation), and input/configuration parameters, we could not identify a single repository for code or dataset resulting from any of the surveyed papers. Nevertheless, with the advent of open science principles and the recent development of cloud-based platforms for research data sharing (Table 3), we expect this reality to change in the next years.

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