Vehicular Communications 11 (2018) 12–19

Contents lists available at ScienceDirect

Vehicular Communications

www.elsevier.com/locate/vehcom

Effect of non-cooperative vehicles on path connectivity in vehicular networks: A theoretical analysis and UAV-based remedy

Wissam Fawaz

Department of Electrical and Computer Engineering, School of Engineering, Lebanese American University, Lebanon

ARTICLE INFO

Article history:
Received 15 August 2017
Received in revised form 18 January 2018
Accepted 27 January 2018
Available online 3 February 2018

Keywords:
Unmanned Aerial Vehicles
Path connectivity
Vehicular Ad-hoc Networks
Performance analysis

ABSTRACT

A fully-connected Vehicular Ad-hoc Network (VANET) contributes tremendously to the improvement of the travel experience of commuting passengers. However, the existence of an end-to-end multi-hop path across VANET highly depends on the willingness of vehicles to cooperate with one another when it comes to data forwarding. Unlike the existing VANET connectivity studies that focused solely on fully-cooperative vehicular environments, this paper develops a mathematical model to explain the effect of non-cooperative vehicles on the end-to-end connectivity through the roadway segments of a VANET.

First, this work characterizes some of the fundamental traffic-theoretic properties of VANETs in the presence of non-cooperative vehicles. Then, it proposes to alleviate the detrimental effect of non-cooperation on end-to-end path connectivity by exploiting Unmanned Aerial Vehicles (UAVs) as store-carry-and-forward nodes in a VANET. Through both mathematical analysis and extensive simulations, the role that UAVs can play in enhancing end-to-end path connectivity is quantified in the context of a hybrid, UAV-assisted VANET architecture.

1. Introduction

Vehicular Ad-hoc Networks (VANETs) have attracted, over the past years, a great deal of attention owing to their ability to support a myriad of applications, ranging from traffic management to infotainment [1]. Newly manufactured vehicles are being equipped with sensors, computerized modules, and wireless communication devices with a view to actively participating in modern Intelligent Transportation Systems (ITSs). Through Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, vehicles will constitute an integral part of the constantly expanding Internet of Things (IoT) paradigm [2], which is one of the key enabling technologies for 5G wireless networks. However, an essential challenge in establishing an operational ITS continues to be the frequent disruption of connections among vehicles in a VANET, due to its highly dynamic topological nature. Therefore, the characterization of connectivity in a VANET drew the attention of numerous studies [3–12]. However, in all of these studies, path connectivity was analyzed solely under the assumption of a fully-cooperative VANET environment. Consequently, the exact dependence of connectivity on the willingness of vehicles to participate in data forwarding was not addressed analytically. According to [13], some vehicles may choose not to cooperate and such an uncooperative behavior may be driven by a malicious intent or a desire to reduce energy consumption. The latter case is of particular interest especially with the renewed worldwide political push for electric vehicles (EV) deployment in a bid to abate climate change. However, one of the major inconveniences of EVs lies in their limited travel range on a single charge. So, it is safe to assume that not all EVs deployed in a VANET would be ready to waste precious battery power resources given the large amount of time (in the order of hours) required to recharge an EV's battery [14].

As a result, it becomes necessary to supplement the multitude of existing VANET connectivity studies with a study that provides answers to the following essential questions: *a)* How do non-cooperative vehicles affect end-to-end path connectivity in a VANET?; *b)* What are the possible means for alleviating such an effect? This paper addresses the former question by developing a mathematical framework that evaluates connectivity in the presence of non-cooperative vehicles. Moreover, the paper tackles the latter question by investigating the role that factors, external to vehicular networks, may play towards the end of enhancing path connectivity across a VANET, counterbalancing thus the negative effect of selfish vehicles. It is worthwhile noting in this regard that the adjectives uncooperative, selfish, and greedy will be used interchangeably to qualify the vehicles that are not contributing to data redistribution, as per the guidelines given in [15].

E-mail address: wissam.fawaz@lau.edu.lb.

https://doi.org/10.1016/j.vehcom.2018.01.005

This paper proposes to improve the path connectivity in the context of a vehicular network that is plagued with the arrival of uncooperative vehicles by incorporating cooperative external players privileged with store-carry-and-forward capability into the system. Particularly, the paper contemplates utilizing Unmanned Aerial Vehicles (UAVs), also known as drones, as cooperative airborne nodes to assist ground vehicles in delivering data to a remote infrastructure RoadSide Unit (RSU). This has the advantage of reinforcing two of the main pillars underlying connectivity in a VANET, namely the end-to-end path availability as well as the average end-to-end data delivery delay. The proposed UAV-based solution is motivated by the following fundamental observations: *a)* the mechanisms proposed in the literature for stimulating the cooperation of greedy vehicles do not guarantee full compliance of such vehicles. The reader is referred to [13] for a comprehensive survey of the so-called reputation-based and credit-based mechanisms; *b)* the research industry is witnessing a spike of interest in flying platforms such as UAVs. As a matter of fact, the drone production market is likely to reach $2.3 billion in value by 2027 [16]. Furthermore, a recent Amazon U.S. patent [17] enumerates possible use-cases and applications of UAVs, citing store-carry-and-forward as a potential functionality for UAVs.

The rest of the paper is organized as follows. In section 2, the relation of this study to the open literature is discussed. Section 3 describes a sample VANET subnetwork scenario that serves as a basis for our mathematical analysis. Then, section 4 delineates the logic governing the behavior of both vehicles and UAVs, in the context of the considered VANET scenario. Section 5 presents an analytical study analyzing connectivity, in the context of the UAV-assisted VANET scenario in the presence of uncooperative vehicles. Section 6 introduces a simulation framework confirming the accuracy of the mathematical models. Finally, section 7 concludes this paper.

2. Related studies

The contributions of this paper are twofold:

- The paper mathematically analyzes connectivity in a VANET comprising selfish vehicles that do not assist in data forwarding.
- A UAV-based solution is proposed to mitigate the effect of non-cooperation on VANET connectivity.

This section highlights, in what follows, the novelty of each one of these contributions.

2.1. Connectivity analysis

The authors of [3] characterized the distribution of the distance headway between consecutive vehicles, considering three different conditions of vehicular density. In [4], the authors introduced a new equivalent speed parameter that they used to derive a closed-form analytical expression for path connectivity in a VANET. A comprehensive mobility model is defined in [5] for the purpose of evaluating VANET connectivity in the context of a highway having predefined entry and exit points. The connectivity in both one-way and two-way highway scenarios is examined in [6], whose results are extended to the case of multi-hop connectivity in [7]. Connectivity results are also reported for a VANET in [8] under more realistic mobility models, where vehicle speeds were assumed to be normally distributed and vehicles were allowed to overtake one another. Connectivity bounds were derived for both sparse and dense VANETs in [9]. The authors of [10] developed analytical models for deriving both uplink and downlink connectivity probabilities. Therein, uplink connectivity probability is defined as the probability of possible delivery of messages from vehicles to the infrastructure, while the downlink connectivity probability is concerned with the downstream direction. The authors of [11] studied the impact that a non-exponential inter-vehicle spacing distribution may have on the connectivity of a VANET. Finally, a comprehensive analytical framework for analyzing the network connectivity of an urban VANET was presented in [12]. A major limitation of all of the previously surveyed studies is related to the following fact. None of these studies evaluated connectivity in a partially-cooperative VANET. More specifically, the effect of uncooperative vehicles on end-to-end path availability and end-to-end delay in a VANET has not been assessed, making thus a study like this one necessary.

2.2. UAV-assisted VANET

As far as the UAV-assisted VANET architecture defined in this paper is concerned, it is important to note the following. UAVs are a rising technology that was originally founded for supporting military missions. With time, the usage of UAVs evolved into supporting civilian applications, such as crop spraying, remote sensing, and so on [18]. Nowadays, UAVs are capable of revolutionizing many of the existing network architectures. Nonetheless, their enormous potential is not fully tapped into yet. The authors of [19] surveyed a plethora of applications that might benefit from the deployment of UAVs with an emphasis on the communication and networking aspects underlying such a deployment. In the same spirit, the authors of [20] investigated the use of UAVs in offloading the existing cellular infrastructures. The work in [21] defined the optimal trajectory and derived the heading of UAVs serving static ground users, in the context of a ground-to-air uplink scenario. Mozaffari et al. [22] explored the deployment of a UAV as a base station providing wireless access to a predefined geographical area. In addition, the utility of UAVs in maintaining wireless connectivity under emergency conditions has drawn some attention in the literature. In this respect, the work in [23] considered a load balancing application of UAVs that is based on a game-theoretic strategy. The latter was utilized to achieve load balancing between LTE-unlicensed Unmanned Aerial Base stations (UABs) and Wi-Fi access points. The authors of [24] proposed the establishment of a multi-UAV aerial subnetwork when the vehicular network operates under extreme conditions. In this case, the authors argued that UAVs can be used to gather information about the environment and then relay it to ground vehicles through make-shift control centers. Similarly, the authors in [25] introduced a UAV-aided routing protocol that is tailored to urban VANET environments. In [26], we studied the effect of the deployment of UAVs on the performance of a fully-collaborative VANET. The authors of [27] studied mathematically the problem of interconnecting several disconnected clusters of cars using a stationary UAV located at an altitude h. The system was viewed as a single server queueing system for the purpose of determining the maximum number of cars that can be serviced while satisfying predefined quality of service measures. In [28], the authors proposed to use UAVs for VANET security improvement through the detection of intelligent malicious and selfish nodes. In [29], the authors proposed routing protocols for urban vehicular environments where stationary UAVs are used to help ground vehicles with data routing. Specifically, the UAVs are deployed to assist ground vehicles in finding communication routes for their data.

To the best of the author's knowledge, none of the surveyed existing studies has looked into the possibility of coupling partially-collaborative VANETs with store-carry-and-forward UAVs, in an attempt to improve connectivity in the presence of greedy vehicles. This paper thus provides the *first performance analysis* of a partially-collaborative UAV-assisted VANET scenario. This scenario is introduced in the next section.

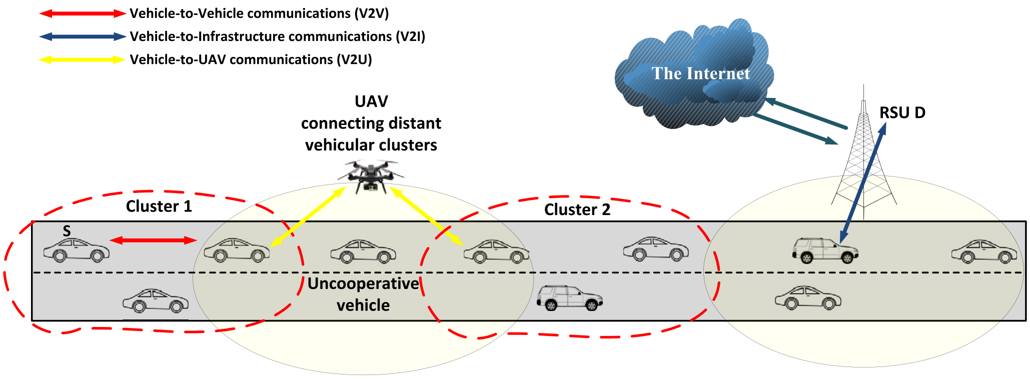


Fig. 1. Partially-collaborative UAV-assisted VANET scenario.

3. Motivating scenario

The connectivity analysis carried out in this paper revolves around the typical VANET scenario [30] depicted in Fig. 1. However, unlike [30] where a fully-collaborative VANET environment was assumed, this paper considers a partially-collaborative one, as illustrated previously. The rationale for adopting the scenario given in Fig. 1 is as follows. In point of fact, a vehicle *S* can exploit the variety of ITS services for as long as it resides within the transmission range of an RSU. However, once *S* exits the transmission range of the RSU, it is said to join a dark area. Within the dark area, the only means facilitating communication between *S* and the infrastructure RSU are the intermediate cooperative vehicles existing between *S* and the RSU. Fig. 1 depicts a similar scenario as the leftmost vehicle *S* is striving to establish an end-to-end connectivity path to the remote RSU *D*. Even though the setup of such a path between *S* and *D* can be realized through cooperative V2V communication with the intermediate cooperative vehicles residing between *S* and *D*, the task is made challenging by the uncooperative vehicles that might be present between *S* and *D*. Packets emanating from *S*'s OnBoard Unit (OBU) buffer are forwarded, on a hop-by-hop basis, by multiple intermediate cooperative vehicles until they reach *D*.

In this context, inter-vehicle communication is orchestrated by the Wireless Access in Vehicular Environment (WAVE) protocol suite [32]. A transmitting vehicle can either deliver its packets to the RSU if the latter happens to be within its coverage range or alternatively, rely on the cooperative vehicles within its transmission range to ultimately transmit the packets to the RSU. So, a transmitted packet would traverse multiple cooperative vehicles' buffers until either getting to *D* or reaching an intermediate cooperative vehicle that cannot transfer the packet any further. In this case, the packet waits in the buffer of that vehicle until a new contact opportunity arises following a favorable change in the vehicular network's topology. Obviously, the end-to-end multi-hop communication path between *S* and *D* may be fragmented at multiple places along the considered roadway segment. This fragmentation is caused, mainly, by two phenomena, namely the non-cooperation and clustering phenomena. The non-cooperation phenomenon is rooted in the unwillingness of some vehicles to assist in the packet forwarding process. It is assumed in this paper that a well defined portion of the vehicles arriving at the considered roadway segment are non-cooperative and as such do not contribute to the packet delivery process. As for the clustering phenomenon, it is very much related to cooperative vehicles. In fact, the cooperative vehicles navigating along the roadway segment considered in Fig. 1 are grouped into several disconnected clusters. A cluster represents a set of cooperative vehicles that can communicate directly with one another. While data packets can travel freely within a cluster by means of intra-cluster V2V communication, they cannot cross the boundary of a cluster moving to another cluster until their carrying vehicle becomes a member of that other cluster. The non-cooperation and clustering phenomena are clearly shown in Fig. 1. For instance, packets from cluster 1 cannot benefit from the uncooperative ground vehicle residing between clusters 1 and 2 to move to cluster 2. These packets have to wait in cluster 1 until the network topology evolves in a way that enables such inter-cluster data communication. Clearly, in the VANET topology depicted in Fig. 1, both clustering and non-cooperation disrupted the end-to-end path between the source vehicle *S* and the destination RSU *D*. This is considered, according to the terminology introduced in [30], as a case of path unavailability for the source vehicle *S*.

Had the uncooperative vehicle residing between clusters 1 and 2 in Fig. 1 exhibited a cooperative behavior, it would have been possible for packets to flow from the vehicles of cluster 1 to those of cluster 2. This is particularly true since in that case, the two clusters would have been merged into one aggregate cluster. This paper argues that this problem can be circumvented by having a store-carry-and-forward UAV (or multiple ones) fly above the roadway segment illustrated in Fig. 1. This can increase the likelihood of inter-cluster data transfer. Fig. 1 shows a UAV that happened to be located between clusters 1 and 2. As such, the vehicles from cluster 1 can leverage the UAV's store-carry-and-forward capability to transmit data packets to the vehicles of cluster 2 and potentially to the destination RSU *D*. Such inter-cluster communication is possible if and only if: *a)* the UAV happens to be within the transmission range of the rightmost cooperative vehicle from cluster 1, and *b)* the UAV can transmit data to at least the leftmost cooperative vehicle from cluster 2. If the latter condition *(b)* is not satisfied, then the "carry" portion of the store-carry-and-forward feature kicks in to enable UAV-assisted data packets transport to cluster 2. In this context, if the vehicles of cluster 2 are already connected to *D*, then in the final analysis, the UAV would have contributed to establishing a fully-connected path between *S* and *D*. This is a direct consequence of the UAV's ability to mend any partitioning that might arise in the network topology. Consequently, it is expected that the presence of such UAV(s) help alleviate the detrimental effect of uncooperative vehicles, improving in the process the performance of VANETs in terms of path availability and end-to-end delay.

The next section discusses: *a)* the roles of both the vehicles and the UAVs in the context of the considered VANET scenario; *b)* the enabling technology required to fulfill that role.

4. Enabling technology and roles of vehicles/UAVs

In the context of the considered partially-collaborative VANET scenario, there are three types of nodes, namely, cooperative vehicles, uncooperative ones, and the UAVs. While both cooperative vehicles and UAVs act as store-carry-and-forward nodes, actively

Algorithm 1 Algorithm executed by a UAV/cooperative vehicle when interacting with a transmitting vehicle V.

```
function PROCESSINCOMINGPACKETS($V$)
    while (Buffer not full AND $V$ has more packets) do
        $Pkt$ = receive packet from $V$
        if (no transmission opportunity available) then
            Insert $Pkt$ into Buffer                          ▷ store and carry
        else
            if (RSU is in range) then
                deliver $Pkt$ to RSU
            else
                relay $Pkt$ to in-range cooperative vehicle   ▷ forward
            end if
        end if
    end while
end function
```

participating in data packets forwarding, uncooperative vehicles behave greedily by not contributing to the data delivery process. An algorithmic description of the way both UAVs and cooperative vehicles would actively engage in the data delivery process in the vehicular network scenario discussed earlier is provided in Algorithm 1. To support communication with ground nodes, a steerable antenna is assumed to be mounted onto the UAV and oriented towards the ground nodes [31].

As far as the technology enabling communication among the different nodes involved in the VANET scenario, the nodes are assumed to be equipped with Dedicated Short Range Communication (DSRC) modules and hence communicate with cooperative vehicles/UAVs/RSUs according to the rules dictated by the WAVE protocol suite [32]. The WAVE communication spectrum is divided into one Control CHannel (CCH) and multiple Service CHannels (SCH). In this context, the process of establishing a connection between two nodes is carried out as follows. Each node in the network periodically broadcasts beacon messages over the CCH announcing its offered services (in the case of an RSU) or information about its speed, location, buffer size, and direction of travel (in the case of a vehicle or a UAV). A vehicle wishing to communicate would simply monitor the CCH, coordinate with the RSU, neighboring vehicles or UAVs, and then switch to an SCH to establish a communication link.

Next, the performance of the considered partially-collaborative UAV-aided vehicular networking architecture is evaluated both mathematically as well as via simulation.

5. Connectivity modeling

5.1. Traffic model

Based on the scenario depicted in Fig. 1, this section analyzes mathematically two of the main pillars underlying path connectivity in a partially-collaborative UAV-assisted VANET, namely, the end-to-end path availability and the self descriptive average packet end-to-end delay to D. End-to-end path availability represents the percentage of incoming vehicles seeing a fully connected multi-hop path to D. In other words, it corresponds to the probability with which a newly arriving vehicle would observe an end-to-end fully connected path to D. The assumptions underlying the analysis are somewhat aligned with the ones adopted by the authors in [30]. More specifically, a multi-lane unidirectional roadway segment is considered. The length of the roadway segment is denoted by d_{SD}, which represents the distance between a source vehicle S at the beginning of the segment and a destination RSU D. The segment is assumed to be operating under Free-Flow traffic conditions and therefore is subject to Poisson vehicle arrivals with a parameter of λ vehicle arrivals per unit of time (also known as the flow rate). However, unlike [30], arriving vehicles are categorized into being uncooperative with a probability denoted by P and cooperative with a probability equal to $1 - P$. This is equivalent to saying that the roadway segment is subject to two independent arrival processes [33]: *a)* a Poisson cooperative vehicle arrival process with a parameter of $(1 - P)\lambda$; *b)* a Poisson uncooperative vehicle arrival process with a parameter of $P\lambda$. The individual vehicle speeds are independent and identically distributed random variables assuming values in the range of $[V_{min}; V_{max}]$. Vehicles' speeds are drawn from a truncated normal distribution and remain constant for the entire duration of the navigation to the RSU D. All vehicles have a transmission range of R meters and are supposed to arrive at the considered roadway segment with one packet in their buffer [30].

In the context of the UAV-aided vehicular network, a periodical UAV arrival process is emulated in each direction of the roadway segment by having two UAVs navigate at an altitude of 100 m with constant speeds, denoted by V_{UAV}, in opposite directions above the considered roadway segment. Each of the two UAVs flies back and forth between S and D, but when one is plying from S to D, the other would be flying from D to S (in the opposite direction). In this way, by the time the UAV flying in the direction of D reaches D, the other UAV would have reached S and can, as such, start navigating in the direction of D. This ensures that at any given moment, there will always be a single UAV flying from S to D and acting as a store-carry-and-forward node for the ground vehicles navigating in that same direction. Note that a UAV is required to assist only those cars that are navigating in the same direction as the UAV. Considering a fixed geographical point on the roadway segment, for instance the entry point S, the UAV inter-arrival time at S would be $I_{UAV} = \frac{d_{SD}}{V_{UAV}}$.

As far as the UAV's altitude is concerned, it would be relevant to mention in this context that the Federal Aviation Authority [31] recommends that UAVs be flown below 120 meters above ground level. Furthermore, Ref. [34] reported a maximum UAV speed value of 100 m/s. This paper uses a reasonable value of 50 m/s for V_{UAV} but adopts the speed value of 100 m/s as a theoretical speed upper-bound for benchmarking purposes. So, in the context of the investigated UAV-aided solution, the UAVs are required to move along a well-defined path to provide assistance for the ground vehicles. According to [35], the UAVs that satisfy these requirements include long endurance UAVs as well as short range small UAVs. It is worthwhile noting in this regard though that there are still some challenges in the deployment of UAVs in VANETs, such as the regulation of the operation of UAVs as well as energy limitations, to cite a few. The reader is kindly referred to [36] for a comprehensive treatment of these challenges and constraints.

5.2. Path availability

5.2.1. UAV-free VANET

As illustrated in Fig. 1, vehicles navigating along the considered roadway segment form several clusters. Each cluster consists of a group of cooperative vehicles that can communicate with one another through one-hop/multi-hop communication. The distance separating two adjacent cooperative vehicles within the same cluster is less than or equal to R, allowing thus for inter-vehicle communication among the cooperative vehicles that make up the cluster. Building on this observation, a newly arriving vehicle S would enjoy a fully connected path to the RSU D if and only if, all the cooperative vehicles residing between S and D form a single cluster. More precisely, if we consider the entry point to be the distance origin, then a multi-hop path would be available from S to D if there exists a single cluster of cooperative vehicles having a length of $d_{SD} - R$ between S and D with S being the leftmost member of the cluster. This is particularly true since it is sufficient that the rightmost member of the said cluster be at a distance R from D for packet delivery to be possible. Therefore, the probability of having an available end-to-end path from S to D, which we denote by

P_{SD}, is equivalent to the probability of having a single cluster of cooperative vehicles extending from the entry point of the roadway segment through the distance $d_{SD} - R$.

Cluster formation is strongly dependent on the so-called parameter P_e; this parameter being the probability that the forwarding of a packet stops. In other words, a packet stored in a vehicle's buffer can be forwarded to an immediate cooperative next hop with a probability $1 - P_e$; otherwise, forwarding stops with a probability P_e due to the nonexistence of another cooperative vehicle within the transmission range. It was established in [5] that $P_e = e^{-\rho R}$, where $\rho = \frac{\lambda}{E[V]}$ represents the vehicular density in vehicles per meter and E[V] is the space mean speed [37]. However, some adjustment must be made to the formulation of P_e since [5] did not account for the existence of uncooperative vehicles. Given that the only vehicles contributing to data forwarding are cooperative vehicles and that cooperative vehicles arrive at a rate of $(1 - P)\lambda$ arrivals per unit of time, it follows that in our case, $P_e = e^{-(1-P)\rho R}$.

Moreover, it was proven in [5] that $\overline{W} = E[V] \times \frac{1-P_e(1+\rho R)}{\rho(1-P_e)}$. By following the same reasoning as before, $\overline{W}$ can be rewritten as follows:

$$\overline{W} = \frac{1 - P_e(1 + (1 - P)\rho R)}{(1 - P)\rho(1 - P_e)} \tag{1}$$

When a single cluster connects S to D resulting in a path availability instance for S, the length of the cluster would be $d_{SD} - R$, as indicated earlier. The average size of such cluster in terms of intermediary cooperative vehicles between S and D can thus be obtained by dividing $d_{SD} - R$ by the mean intra-cluster distance $\overline{W}$. Now, given that the probability of a successful one-hop forwarding is equal to P_e, it follows that the probability of successful multi-hop forwarding of a packet from S to D over $\left\lceil \frac{d_{SD}-R}{\overline{W}} \right\rceil$ hops, namely path availability, is given by:

$$P_{SD} = \left(1 - P_e\right)^{\left\lceil \frac{d_{SD}-R}{\overline{W}} \right\rceil} \tag{2}$$

5.2.2. UAV-aided VANET

In the context of the considered UAV-aided scenario, there is always a single UAV flying from S to D, as discussed earlier. As the UAV is linearly moving at a constant velocity between S and D and following the guidelines given in [38], the probability density function (p.d.f.) of the distance along the x-axis between S and the UAV can be obtained as:

$$f_X(x) = \frac{1}{d_{SD}} \tag{3}$$

This translates into an increase of the density along the considered roadway segment by a value of $\frac{1}{d_{SD}}$ [37]. As such, the modified value of the density in the presence of a single UAV constantly navigating between S and D can be expressed as: $\rho' = (1 - P)\rho + \frac{1}{d_{SD}}$. The change of the density value to ρ' causes a change of P_e to $P'_e = e^{-\rho' R}$. Consequently, the path availability, denoted by P'_{SD}, in the considered UAV-aided vehicular networking scenario can be rewritten as:

$$P'_{SD} = \left(1 - P'_e\right)^{\left\lceil \frac{d_{SD}-R}{\overline{W}'} \right\rceil} \tag{4}$$

where $\overline{W}'$ is the modified intra-cluster distance in the presence of the UAV and is given by:

$$\overline{W}' = \frac{1 - P'_e(1 + \rho' R)}{\rho'(1 - P_e)} \tag{5}$$

5.3. Delay analysis

5.3.1. UAV-free VANET

As proven earlier, an end-to-end path would only be probabilistically available between a source vehicle S at the beginning of the roadway segment and the destination RSU D. Specifically, such a path is unavailable when there are several disconnected clusters of cooperative vehicles residing between S and D. In this case, the path between S and D is said to be broken at multiple locations along the roadway segment. Under this condition, a packet carried by a newly arriving vehicle experiences two types of delays as it travels towards D: *a)* the *communication delay* is the amount of time required to push all the bits that make up the packet onto the wireless channel, and *b)* the *carry delay* is the amount of time that a packet spends being carried by a vehicle within a road segment. It is important to note in this regard that the carry delay is significantly longer than the communication delay [40]. Therefore, the rest of the delay-related discussion will revolve solely around the carry delay, ignoring the communication delay. This means that the delay experienced by a packet as it is forwarded from one hop to another within the same cluster will be considered to be equal to 0. The only delay component that will be considered is the one that corresponds to the case where the carrier vehicle does not encounter another cooperative vehicle within its transmission range, forcing thus the packet to wait in the vehicle's buffer until a communication opportunity arises.

The approach adopted in this paper for calculating the incurred carry delay is inspired by the one presented in [40]. Therein, the authors introduced the concept of *carry distance* and defined it as "the physical distance a packet is carried by a vehicle within a road segment". The authors then proposed a somewhat accurate approximation of the carry delay by dividing the so-called carry distance by the vehicle's average speed. Nonetheless, their approximation method can be further improved as follows. In fact, the authors of [40] made the restrictive assumption that there is only one cluster along the roadway segment. Herein, this assumption is relaxed by considering the more realistic case of multiple clusters along the roadway segment. This is particularly true since a newly arriving vehicle will see upon its arrival an average number of clusters spanning the roadway segment.

So, it is sufficient to determine that average number of clusters, multiply it by the average cluster length, and then subtract the obtained quantity from $d_{SD} - R$ to get a more accurate value for the carry distance. In order to compute the average number of clusters, we need first to derive the average cluster size in terms of cooperative vehicles, denoted by $\overline{C}$. Considering the equation proposed in [40] for the average cluster length, denoted by $E[L]$, for a road having a finite length and after making the adjustment discussed earlier, $E[L]$ can be expressed as follows:

$$E[L] = \frac{\alpha((N-1)\beta^N - N\beta^{N-1} + 1)}{(1-\beta)^2} + (d_{SD} - R) \times \beta^N \tag{6}$$

where, $\alpha = E[V]P_e(\frac{1}{(1-P)\lambda} - (R + \frac{1}{(1-P)\lambda})P_e)$, $N = \left\lceil \frac{\beta(1-\beta)}{\alpha} \times (d_{SD} - R) \right\rceil$, and $\beta = 1 - P_e$.

Armed with $E[L]$, $\overline{C}$ can be obtained as follows:

$$\overline{C} = \frac{E[L]}{\overline{W}} \tag{7}$$

This is justified by the fact that the ratio between the average cluster length $E[L]$ and the average intra-cluster distance $\overline{W}$ yields the average cluster size $\overline{C}$. Given $\overline{C}$, it becomes possible to find the average number of clusters as seen by a newly arriving vehicle along the roadway segment. As a matter of fact, the latter is equal to the

Table 1
List of symbols.

Symbol	Description
d_{SD}	Length of the considered roadway segment
P	Probability of receiving an uncooperative vehicle
I_C	Cooperative vehicle inter-arrival time
R	Vehicle transmission range
X	Distance along the x-axis between S and the UAV
V_{UAV}, I_{UAV}	Speed of the UAV and UAV inter-arrival time
λ, λ'	Flow rate for UAV-free VANET and UAV-aided one, respectively
ρ, ρ'	Vehicular density for UAV-free VANET and UAV-aided one, respectively
$E[V]$, $E[V']$	Space mean speed for UAV-free VANET and UAV-aided one, respectively
P_e, P'_e	Probability that forwarding stops for UAV-free VANET and UAV-aided one, respectively
$\overline{W}$, $\overline{W}'$	Mean intra-cluster distance for UAV-free VANET and UAV-aided one, respectively
P_{SD}, P'_{SD}	Path availability for UAV-free VANET and UAV-aided one, respectively
$\overline{C}$, $\overline{C}'$	Average cluster size for UAV-free VANET and UAV-aided one, respectively
$E[d]$, $E[d']$	Carry distance for UAV-free VANET and UAV-aided one, respectively
$E[T]$, $E[T']$	Average end-to-end delay for UAV-free VANET and UAV-aided one, respectively

ratio between the average number of cooperative vehicles on the roadway segment and $\overline{C}$, namely $\frac{(1-P)\rho(d_{SD}-R)}{\overline{C}}$. Having found the average number of clusters, the carry distance, denoted by $E[d]$, can be determined as follows:

$$E[d]=(d_{SD}-R)-E[L]\times\frac{\rho(d_{SD}-R)}{\overline{C}} \tag{8}$$

This more accurate characterization of the carry distance makes it possible to obtain the average carry delay, denoted by $E[T]$, as follows:

$$E[T]=\frac{E[d]}{E[V]} \tag{9}$$

5.3.2. UAV-aided VANET

In the context of the UAV-aided vehicular network scenario, there will be new values for the traffic flow, vehicle density, and space mean speed. The new values of the traffic flow, vehicle density, and space mean speed are designated by λ', ρ', $E[V']$, respectively. Note that λ' is the new flow rate value resulting from the aggregation of both the cooperative vehicle arrival as well as the UAV arrival processes. As previously highlighted, the considered roadway segment is now subject to several independent arrival processes, including: *a)* a Poisson cooperative vehicle arrival process with a parameter $(1-P)\lambda$ vehicles per unit of time, and *b)* a periodic UAV arrival process with a constant inter-arrival time of $I_{UAV}=\frac{d_{SD}}{V_{UAV}}$. As a result, the overall arrival process of cooperative nodes offered to the roadway segment can be characterized as follows. Consider a fixed geographical point on the roadway segment, say S, the time separating two cooperative arrivals at S is governed by both cooperative vehicle and UAV arrivals. Given that the cooperative vehicle inter-arrival time is exponential with an average of $I_C=\frac{1}{(1-P)\lambda}$ and that the UAV inter-arrival time is constant with a value of $I_{UAV}=\frac{d_{SD}}{V_{UAV}}$, it follows that the resulting overall inter-arrival time for cooperative nodes follows a truncated exponential distribution upper-bounded by I_{UAV}. Building on this observation and as per the guidelines presented in [39], the new aggregate flow rate λ' would be related to the old flow rate $(1-P)\lambda$, where UAV arrivals are excluded, as follows:

$$\lambda'=(1-P)\lambda\times\frac{1-e^{-(1-P)\lambda I_{UAV}}}{1-(1+(1-P)\lambda I_{UAV})e^{-(1-P)\lambda I_{UAV}}} \tag{10}$$

Moreover, as per the guidelines given in [37], $E[V']$, the new average space mean speed in the presence of the UAV, can be obtained as follows:

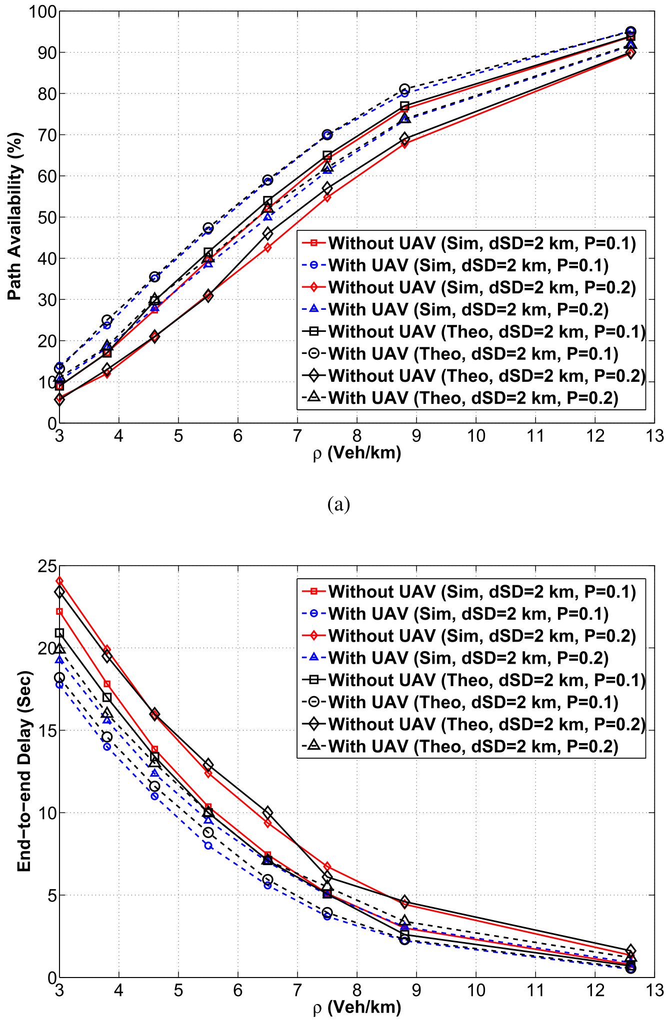
$$E[V']=\frac{\frac{1}{I_C}+\frac{1}{I_{UAV}}}{\frac{1}{I_C\times E[V]}+\frac{1}{I_{UAV}\times V_{UAV}}} \tag{11}$$

The average carry delay in the presence of the UAV, denoted by $E[T']$, can be derived in a way that is analogous to the one delineated in the previous subsection. The only difference lies in the need to replace in Eq. (9) every occurrence of λ, ρ, and $E[V]$ with λ', ρ', and $E[V']$, respectively.

6. Numerical results

To validate the mathematical models introduced earlier, discrete event simulations were performed. In particular, realistic mobility traces were collected via SUMO [41] and used as input simulation parameters, with the purpose of evaluating the impact of uncooperative vehicles in the presence of real-world traffic conditions. The simulator's input parameter values are as follows (see Table 1): *a)* Vehicle density: $\rho\in[3;12]$ (veh/km) and *b)* $R=500$ (m). The adopted performance metrics, namely end-to-end path availability and delay, were evaluated over a total of 10^7 time slots in order to realize the highest level of accuracy.

Fig. 2(a) plots simultaneously the simulation and mathematical results corresponding to the path availability metric as a function of ρ, considering both a UAV-free as well as a UAV-assisted VANET scenario, where $d_{SD}=2$ km. Two different values of P are considered, namely $P=0.1$ and $P=0.2$. Similarly, Fig. 2(b) plots concurrently the simulation and mathematical results pertaining to the end-to-end delay metric as a function of ρ under the same conditions. The following conclusions can be extracted from the reported results: *a)* the mathematical results match to a great extent the simulation ones, confirming thus the validity of the models developed in this paper; *b)* the path availability and end-to-end delay measures are affected negatively by the arrival of uncooperative vehicles; *c)* the deployment of a single UAV helped enhance path availability and reduce the end-to-end delay across the VANET, mitigating to some degree the detrimental effect of uncooperative vehicles. For example, for $\rho=4.6$ veh/km and $P=0.1$, a path availability of approximately 27% was recorded for the UAV-free VANET scenario while a value of approximately 35% was observed for the UAV-assisted scenario. This translates into an 8% improvement in terms of path availability when a UAV is deployed to grant an alternative connectivity option to ground vehicles. Nevertheless, for high vehicular densities, the improvement achieved by the UAV becomes less pronounced. This observation is due mainly to the fact that at high vehicular density values, VANET would be operating at a high degree of path connectivity to the RSU D. In the remainder of this section, the mathematical results will be omitted to maximize the readability of the plots.



(a)

(b)

Fig. 2. Theoretical vs. simulation results for UAV-free/UAV-assisted VANET, where $d_{SD} = 2$ km and $P = 0.1$ & 0.2: a) Path availability, and b) Delay.

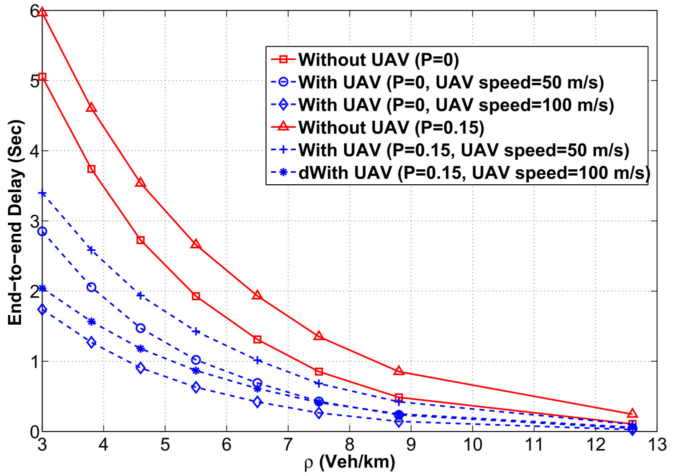


Fig. 3. Delay performance of VANET with/without UAVs, where $d_{SD} = 1$ km, $V_{UAV} =$ 50 & 100 m/s, and $P = 0$ & 0.15.

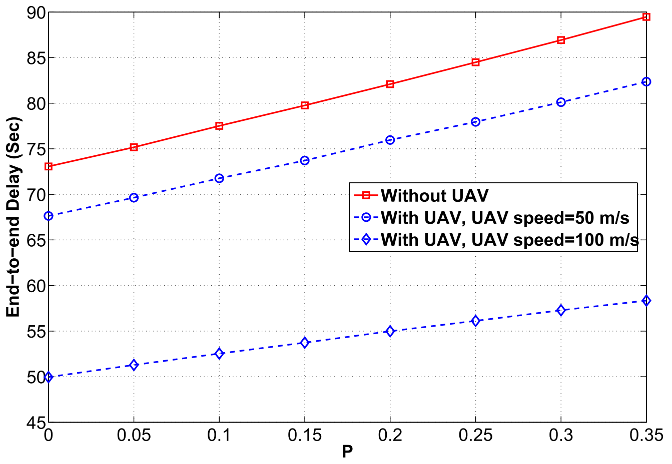


Fig. 4. Delay performance of VANET with/without UAVs, where $\rho = 3.4$ veh/km, $d_{SD} = 5$ km, and V_{UAV} of 50 & 100 m/s.

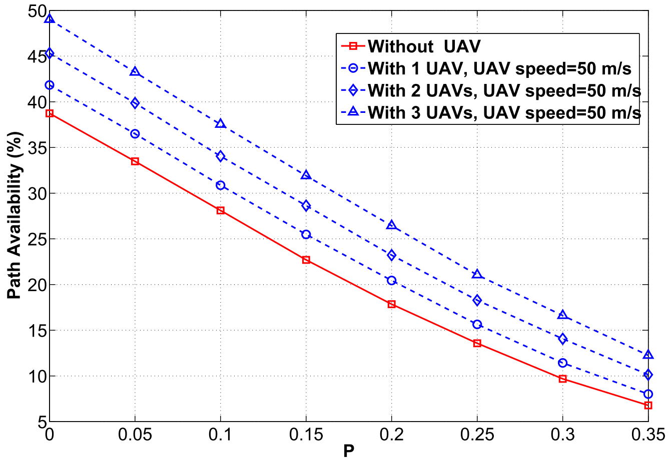


Fig. 5. Path availability performance of VANET with/without UAVs without/with 1, 2, or 3 UAVs, where $\rho = 3.4$ veh/km, $d_{SD} = 5$ km and $V_{UAV} = 50$ m/s.

Next, the impact of an increase of the drone speed V_{UAV} from 50 m/s to 100 m/s is studied. Fig. 3 compares the performance of a UAV-free VANET to that of a UAV-assisted VANET for different values of V_{UAV}. First, a fully-cooperative scenario ($P = 0$) was considered. Then, a scenario where 15% of the arriving vehicles are uncooperative ($P = 0.15$). For both scenarios, d_{SD} was set to 1 km. Once again, the presence of uncooperative vehicles degraded the performance of VANET increasing the end-to-end delay relative to the fully-cooperative VANET scenario. For instance, for $\rho = 3$ veh/km, the delay observed in the context of the UAV-free scenario increased from 5 sec in the fully-collaborative scenario to 6 sec in the partially-collaborative one. In this case, the injection of a UAV having a speed of 50 m/s into the system helped reduce the end-to-end delay to 3 sec. Then, the increase of the UAV's speed to the benchmark speed value of 100 m/s decreased the delay by an additional 40% to approximately 1.8 sec. This is justified by the fact that a rise in the UAV speed value ensures faster inter-cluster communication as well as shorter delivery delays to D. Similar conclusions can be drawn based on the results given in Fig. 4, where the evolution of the end-to-end delay as a function of P is captured for different speed values. In this case, a longer distance of 5 km is considered with a fixed $\rho = 3.4$ veh/km. The patterns are the same as before. That is, the end-to-end delay is an increasing function of P. The less vehicles are willing to cooperate, the longer the observed end-to-end delays would be. Moreover, the UAV-assisted scenarios outperform the UAV-free one with a more significant improvement recorded for higher UAV speed values.

Finally, Fig. 5 illustrates the impact of UAV count on the path availability in the presence of uncooperative vehicles, for $d_{SD} =$

5 km and $\rho = 7.5$ veh/km. Two/three UAVs are considered in each direction with an individual constant speed of 50 m/s. The UAVs are assumed to be separated by a distance of $\frac{d_{SD}}{2}$ when 2 UAVs are used and $\frac{d_{SD}}{3}$ when 3 are employed. It is clear from the reported results that the presence of the additional UAVs helped improve the path availability slightly. The reason for this slight improvement is as follows. For a relatively long distance between the entry point of vehicles and D, it takes more than 3 UAVs to substantially increase the likelihood that an isolated newly arriving vehicle finds a UAV within its transmission range to establish connectivity to D.

7. Conclusion

This paper aimed at filling a gap in the open literature that is related to the following. The existing connectivity analysis studies were built upon the assumption that all vehicles are willing to participate in data forwarding. This study relaxed this assumption by considering a partially-collaborative VANET environment and analyzed analytically the effect of non-cooperation on the connectivity performance of a VANET. A UAV-based solution was then proposed to enhance the connectivity performance in the presence of uncooperative vehicles. A UAV-assisted VANET environment like the one introduced in this paper is a small yet important step in the ongoing journey towards achieving the objective of developing a fully-connected VANET environment.

References

[1] S. Al-Sultan, M.M. Al-Doori, A.H. Al-Bayatti, H. Zedan, A comprehensive survey on vehicular ad hoc networks, J. Netw. Comput. Appl. 37 (2014).

[2] L. Davidson, How Connected Cars are Driving the Internet of Things, Technical report, The Telegraph, 2015.

[3] K. Abboud, W. Zhuang, Stochastic analysis of a single-hop communication link in vehicular ad hoc networks, IEEE Trans. Intell. Transp. Syst. 15 (5) (2014).

[4] S. Durrani, X. Zhou, A. Chandra, Effect of vehicle mobility on connectivity of vehicular ad hoc networks, in: Proc. IEEE Vehicular Technology Conference, 2010.

[5] M. Khabazian, M. Ali, A performance modeling of connectivity in vehicular ad hoc networks, IEEE Trans. Veh. Technol. 57 (4) (2008).

[6] S. Panichpapiboon, W. Pattara-atikom, Connectivity requirements for self-organising traffic information systems, IEEE Trans. Veh. Technol. 57 (6) (2008).

[7] W.-L. Jin, W. Recker, An analytical model of multihop connectivity of inter-vehicle communication systems, IEEE Trans. Wirel. Commun. 9 (1) (2010).

[8] S. Yousefi, E. Altman, R. El-Azouzi, M. Fathy, Analytical model for connectivity in vehicular ad hoc networks, IEEE Trans. Veh. Technol. 57 (6) (2008).

[9] G.H. Mohimani, F. Ashtiani, A. Javanmard, M. Hamdi, Mobility modeling, spatial traffic distribution, and probability of connectivity for sparse and dense vehicular ad hoc networks, IEEE Trans. Veh. Technol. 58 (4) (2009).

[10] W. Zhang, et al., Multi-hop connectivity probability in infrastructure-based vehicular networks, IEEE J. Sel. Areas Commun. 30 (4) (2012).

[11] L. Cheng, S. Panichpapiboon, Effects of intervehicle spacing distributions on connectivity of VANET: a case study from measured highway traffic, IEEE Commun. Mag. 50 (10) (2012).

[12] W. Viriyasitavat, et al., Dynamics of network connectivity in urban vehicular networks, IEEE J. Sel. Areas Commun. 29 (3) (2011).

[13] J. Dias, et al., Cooperation advances on vehicular communications: a survey, Veh. Commun. 1 (1) (2014).

[14] A. Poullikkas, Sustainable options for electric vehicle technologies, Renew. Sustain. Energy Rev. 41 (2015).

[15] H. Hasrouni, et al., VANET security challenges and solutions: a survey, Veh. Commun. 7 (2017) 7–20.

[16] SmarTech Markets Publishing LLC, Additive Manufacturing for the Drone/UAV Industry: An Opportunity Analysis and Ten-Year Forecast, Report, 2017.

[17] D. Dupray, F. Leblanc, Unmanned aerial vehicles, U.S. Patent Application No. 15/224,497, 2016.

[18] I. Bekmezci, et al., Flying ad-hoc networks (FANETs): a survey, Ad Hoc Netw. 11 (3) (2013).

[19] S. Hayat, E. Yanmaz, R. Muzaffar, Survey on unmanned aerial vehicle networks for civil applications: a communications viewpoint, IEEE Commun. Surv. Tutor. 18 (4) (2016) 2624–2661.

[20] S. Rhode, C. Wietfeld, Interference aware positioning of aerial relays for cell overload and outage compensation, in: Proc. IEEE Vehicular Technology Conference, 2012.

[21] F. Jiang, A. Swindlehurst, Optimization of UAV heading for the ground-to-air uplink, IEEE J. Sel. Areas Commun. 30 (5) (2012).

[22] M. Mozaffari, et al., Unmanned aerial vehicle with underlaid device-to-device communications: performance and tradeoffs, IEEE Trans. Wirel. Commun. 15 (6) (2016).

[23] D. Athukoralage, et al., Regret based learning for UAV assisted LTE-U/WiFi public safety networks, in: Proc. IEEE Global Communications Conference, 2016.

[24] Y. Zhou, et al., Multi-UAV-aided networks: aerial-ground cooperative vehicular networking architecture, IEEE Veh. Technol. Mag. 10 (4) (2015).

[25] O. Oubbati, et al., UVAR: an intersection UAV-assisted VANET routing protocol, in: Proc. IEEE Wireless Communications and Networking Conference, 2016.

[26] W. Fawaz, et al., Unmanned aerial vehicles as store-carry-forward nodes for vehicular networks, IEEE Access 5 (2017).

[27] P. Shilin, et al., Connectivity of VANET segments using UAVs, in: Proc. International Conference on Next Generation Wired/Wireless Networking, Springer International Publishing, 2016.

[28] C.A. Kerrache, et al., UAV-assisted technique for the detection of malicious and selfish nodes in VANETs, Veh. Commun. 11 (2018) 1–11.

[29] O. Oubbati, et al., Intelligent UAV-assisted routing protocol for urban VANETs, Comput. Commun. 107 (2017).

[30] R. Atallah, et al., Multi-hop vehicle-to-infrastructure communications: a feasibility study, modelling and performance analysis, IEEE Trans. Veh. Technol. 99 (2016).

[31] E. Frew, T. Brown, Airborne communication networks for small unmanned aircraft systems, Proc. IEEE 96 (12) (2008).

[32] ITS Standards Fact Sheets, IEEE 1609 – family of standards for wireless access in vehicular environments (wave), available online: https://www.standards.its.dot.gov/factsheets/factsheet/80.

[33] L. Kleinrock, Queueing Systems, Volume 2: Computer Applications, Wiley, 1976.

[34] L. Gupta, R. Jain, G. Vaszkun, Survey of important issues in UAV communication networks, IEEE Commun. Surv. Tutor. 18 (2) (2016).

[35] W. Jingjing, et al., Taking drones to the next level: cooperative distributed unmanned-aerial-vehicular networks for small and mini drones, IEEE Veh. Technol. Mag. 12 (3) (2017).

[36] H. Menouar, et al., UAV-enabled intelligent transportation systems for the smart city: applications and challenges, IEEE Commun. Mag. 55 (3) (2017).

[37] F. Mannering, S. Washburn, Principles of Highway Engineering and Traffic Analysis, 5th ed., John Wiley and Sons, NJ, USA, 2013.

[38] A. Zafar, et al., Capacity gains of buffer-aided moving relays, in: Proc. IEEE International Conference on Computing, Networking, and Communications, 2017.

[39] D. Olive, Applied robust statistics, Preprint M-02-006, 2008.

[40] J. Lee, et al., Two-way traffic link delay modeling in vehicular networks, Comput. Netw. 110 (2016).

[41] M. Behrisch, et al., Sumo-simulation of urban mobility: an overview, in: Proc. Conference on Advances in System Simulation, 2011.