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Unmanned Aerial Vehicles as Store-Carry-Forward Nodes for Vehicular Networks

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ABSTRACT A fully connected vehicular *ad hoc* network (VANET) establishes a strong foundation for the development of smart cities, where one of the main objectives is the improvement of the welfare of commuting passengers. The availability of a multi-hop path across a VANET system, through vehicle-to-vehicle communication, depends mainly on the vehicular density and the willingness of vehicles to cooperate with one another. This paper proposes to minimize the path availability's dependence on vehicular density and cooperation, by utilizing unmanned aerial vehicles (UAVs). Particularly, this paper explores, both mathematically as well as through an extensive simulation study, the advantages of exploiting UAVs as store-carry-forward nodes so as to enhance the availability of a connectivity path as well as to reduce the end-to-end packet delivery delay. The obtained results shed clear light on the benefits emanating from the coupling of UAVs with vehicles in the context of a highly promising, innovative, and hybrid vehicular networking architecture.

INDEX TERMS Unmanned aerial vehicles, store-carry-forward, vehicular networks, connectivity.

I. INTRODUCTION

Vehicular Networks have been proven to promote a safer and more pleasant traveling experience for passengers. Through both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication support, the promise of an Intelligent Transportation System (ITS) became a reality, allowing for the deployment of a multitude of different applications ranging from traffic management to Internet access [1]. However, vehicular networks are plagued by a number of challenging inherent aspects such as frequent disruption of connections resulting from highly dynamic network topologies, to cite a few, which render the development of solutions addressing these challenges obligatory. In particular, connectivity in the context of a V2V communication system emerged as a fundamental problem and hence attracted a lot of attention in the literature [2]–[4]. Understandably, the existence of an always-on multi-hop connectivity path through vehicles is and will always remain an elusive objective that vehicular networks still cannot fully guarantee. This is particularly true since the existence of such ideal paths depends on a variety of factors, including for instance the traffic flow and vehicular density. Owing to the tremendous impact that connectivity improvement may have on the dynamics of V2V communications, it is necessary to investigate the role that factors, external to vehicular networks, may play towards this end. It is in this context that proposals like the one presented herein become required.

This paper proposes to enhance the connectivity of vehicles in the context of vehicular networks through the incorporation of external players privileged with store-carry-forward (SCF) capability into the system. Specifically, the paper envisages utilizing Unmanned Aerial Vehicles (UAVs), also known as drones, as SCF-enabled airborne nodes to assist ground vehicles in the process of data delivery to a remote infrastructure RoadSide Unit (RSU). This shall help consolidate two of the main pillars underlying connectivity, namely the end-to-end path availability as well as the average end-to-end data delivery delay. Now, there exists several incentives that motivate exploiting UAVs in vehicular environments [5]. In fact, currently, the research industry is witnessing high interests and investments in the drone production and application market. Subsequently, the overall drone production market is expected to top $ 2.3 billion in value by 2027 [6]. Furthermore, a recent U.S. patent [7], filed by Amazon, elaborates on use-cases and possible applications of UAVs. For example, UAVs are projected to provide an infrastructure for, among other things, delivering goods that will be so pervasive to a point that virtually, every smart device can be the target of UAV-supplied value-added services [8]. In the context of vehicular networks, SCF-enabled UAVs like the ones investigated in this paper can be augmented with the capability of delivering advertisements to ground vehicles. In this manner, SCF service providers or network operators running these UAVs can turn them into lucrative entities, counterbalancing as such the cost associated with their operation. The possibilities are obviously endless for making the use of SCF-enabled UAVs economically feasible. Such a discussion is, however, beyond the scope of the paper.

The contributions of this paper are threefold:

- The paper introduces a novel UAV-assisted networking architecture that aims at improving path connectivity and reducing packet delivery delay in the context of vehicular networks.
- Mathematical models are developed for the purpose of evaluating the benefits of the UAV-assisted vehicular network.
- Insightful guidelines are provided regarding the traffic-theoretic characterization of vehicular networks in the presence of UAVs.

The rest of the paper is organized as follows. In section II, the main contribution of the paper is highlighted by positioning it relative to the relevant open literature. Section III describes a sample scenario that provides insight into the environment, in which UAVs are proposed to be deployed. Then, in section IV, the proposed hybrid UAV-aided vehicular network architecture is described in details. Section V presents both an analytical and simulation studies evaluating the benefits of the proposal. Finally, concluding remarks are given in section VI.

II. RELATED STUDIES

UAVs are an emerging technology that was initially harnessed for military applications. Over time, advancement in electronics and sensor technology expanded the scope of UAV applications to support applications as diverse as traffic monitoring and remote sensing [9]. Nowadays, UAVs have the ability to revolutionize many of the state-of-the-art network architectures. Nonetheless, the enormous potential of UAVs is not fully exploited yet. Gupta *et al.* [8] reviewed some of the research efforts aiming at turning multi-UAV systems into robust context-specific networks. In the same spirit, the authors in [10] explored the use of UAVs for the purpose of assisting the existing cellular infrastructure in reducing cell overload and outage. The work in [11] derived the optimal trajectory and heading of UAVs serving static ground users, in the context of a ground-to-air uplink scenario. Mozaffari *et al.* [12] investigated the deployment of an UAV as a base station for providing on the fly wireless access to a given geographical area. Moreover, the use of UAVs to maintain wireless connectivity under emergency scenarios has attracted some attention in the literature. In this particular regard, the work in [13] considered a load balancing use case of UAVs that is based on a game-theoretic approach. The latter was employed to perform load balancing between LTE-unlicensed Unmanned Aerial Base stations (UABs) and WiFi access points. The authors in [14] proposed the establishment of a multi-UAV aerial subnetwork when a vehicular network operates in an extreme environment. Under such circumstances, the authors argued that UAVs can be used to collect information about the environment and relay it to ground vehicles through make-shift control centers. By the same token, the authors in [15] introduced a UAV-assisted routing protocol that is designed for urban Vehicular Ad-hoc Network (VANET) environments. The authors of [16] mathematically investigated the problem of interconnecting several disconnected groups of cars using a stationary UAV hovering at an altitude h. The overall system was modelled as a single server queueing system with the purpose of determining the maximum number of car groups that can be serviced while satisfying well-defined quality of service measures. In [17], the authors proposed routing protocols for urban vehicular environments where stationary UAVs are deployed to assist ground vehicles with data routing. Specifically, the UAVs are deployed to help ground vehicles find 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 integrating UAVs as SCF-enabled nodes with vehicular networks, in a bid to improve connectivity under normal operation of the network. This paper thus provides the *first performance analysis* of a vehicular subnetwork scenario in the presence of SCF-enabled UAV nodes. This scenario is presented in the next section.

III. MOTIVATING SCENARIO

To demonstrate the benefits that might result from an UAV-assisted vehicular network, this paper adopts the typical vehicular subnetwork scenario [18] depicted in Fig. 1. As a matter of fact, a vehicle can take advantage of the diverse ITS services for the entire duration of its residence within the transmission range of an RSU. Once the vehicle goes

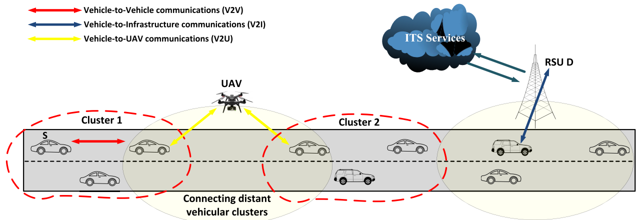

FIGURE 1. Enhanced Connectivity via store-carry-forward UAVs.

out of the coverage region of the RSU, it is said to enter a dark area where the only means of communication with the RSU becomes the intermediate vehicles residing between the source vehicle and the RSU. Fig. 1 illustrates such a situation, with the leftmost vehicle S striving to communicate with the remote RSU D. The setup of a connectivity path between S and D can be realized through cooperative V2V communication with the intermediate vehicles separating S from D. In this way, packets originating from S's buffer traverse multiple intermediate vehicle's buffers en route to D. In this context, communication among the vehicles is coordinated by means of the Wireless Access in Vehicular Environment (WAVE) protocol suite [19]. A transmitting vehicle would either initiate a connection to the RSU if the latter happens to be within its communication range or rely on vehicles within its coverage range to assist with the packets delivery process. It is well established in this regard that the selection of the farthest in-range vehicle by a transmitting vehicle yields the minimum data delivery delay [20]. So, a transmitted packet would travel along a multi-hop path until it either reaches D or gets to an intermediate vehicle that cannot forward the packet any further, in which case the packet resides in the buffer of that vehicle until a contact opportunity arises following a change in the vehicular network's topology. With this mode of operation, vehicles are said to be performing SCF routing, under which a data message is moved from its source to its intended destination one hop at a time. It is clear that the communication between S and D through an end-to-end multi-hop path consisting of intermediate vehicles may be disrupted at multiple locations along the roadway. In fact, the vehicles navigating along the road segment considered in Fig. 1 would form several clusters, with a cluster being a group of vehicles that can communicate directly with one another. While data packets can flow freely within a cluster through intra-cluster V2V communication, they cannot move to another cluster until the carrying vehicle joins that other cluster. For instance, packets from cluster 1 cannot benefit from the existing ground vehicles to move to cluster 2 until the network topology evolves in a way that would enable such inter-cluster data transfer. Given the current state of the network topology depicted in Fig. 1, there is no end-to-end path consisting of ground vehicles connecting the source vehicle S to the destination RSU D. This is considered, according to the terminology introduced in [18], as a case of path unavailability for the source vehicle S.

The discussion has thus far assumed that a traditional vehicular communication system is considered in Fig. 1. This paper argues that the presence of an SCF-enabled UAV (or multiple ones) moving along the roadway illustrated in Fig. 1 can increase the likelihood of inter-cluster data transfer. Fig. 1 portrays a UAV that happens to be navigating between cluster 1 and cluster 2. As such, the vehicles from cluster 1 can leverage the UAV's SCF capability to send data packets to the vehicles of cluster 2 and potentially to the destination RSU D. This inter-cluster communication is possible only if:

Algorithm 1 Packet Routing Algorithm Employed by a Vehicle/UAV

```
function routePacket(P)
    V ← current vehicle/UAV;
    S_v ← the set of one-hop neighbors of V;
    if (RSU ∈ S_v) then
        Deliver P to RSU;
    else
        if (∃ vehicle/UAV ∈ S_v) then
            Forward P to farthest in-range vehicle/UAV;
        else
            Store, carry, and wait for neighbors;
        end if
    end if
end function
```

a) at least the rightmost vehicle from cluster 1 can transmit its data packets to the UAV, and *b)* at least the leftmost vehicle from cluster 2 is within the transmission range of the UAV. If the latter condition *(b)* is not satisfied, then the "carry" portion of the "SCF" feature would come into play to enable UAV-assisted data packets transport to cluster 2. If the vehicles of cluster 2 are privileged with a multi-hop path connectivity to D, then the UAV, in this context, will contribute to establishing a fully-connected path between S and D. This is especially true since the existence of such a UAV can help mend any partitioning that might arise in the network topology. Consequently, improvements in terms of the path availability and packet end-to-end delivery delay metrics can be observed. The proposed hybrid vehicular networking architecture as well as its enabling technology are delineated in the next section.

IV. PROPOSED UAV-AIDED NETWORK SYSTEM

A. SYSTEM ARCHITECTURE

As shown in Fig. 1, the proposed system architecture consists of ground vehicles navigating along a roadway segment coupled with UAVs flying above the segment. In the context of the proposed hybrid architecture, UAVs are assumed to be equipped with batteries benefiting from harvested solar energy. This is especially true since recent advances in battery technologies like enhanced lithium-ion batteries and hydrogen fuel cells augmented with the use energy sources such as solar energy enable the maximization of UAV flight times [21]. In addition, vehicles and UAVs are assumed to be equipped with OnBoard Units (OBUs) through which they communicate with one another as well as with the remote RSU. The following types of wireless communications are possible in the context of the proposed hybrid architecture: *a)* Vehicle-to-Vehicle (V2V), *b)* Vehicle-to-UAV (V2U), *c)* UAV-to-Vehicle (U2V), *c)* UAV-to-UAV (U2U), *d)* Vehicle-to-RSU (V2R), and *d)* UAV-to-RSU (U2R). Particularly, a vehicle/UAV can transmit the packets that reside in its OBU's buffer to the farthest in-range vehicle/UAV. Furthermore, a vehicle/UAV can deliver its packets to the RSU if the latter is found to be within its communication range.

B. MEDIUM ACCESS CONTROL (MAC) PROTOCOL

The communication technology that UAVs will support depends on the target application. To ensure a seamless integration of the SCF-enabled UAVs with vehicular networks, UAVs need to be configured to supply services cooperatively. This can be achieved by equipping UAVs with Dedicated Short Range Communication (DSRC) modules and hence, enabling them to infiltrate vehicular networks and communicate with vehicles/RSUs according to the rules dictated by the WAVE protocol suite [19]. Moreover, to support communication with ground nodes, a steerable antenna needs to be mounted onto the UAV and oriented towards the ground nodes [22]. Armed with these essential building blocks, UAVs would have the ability to fulfill their role as SCF-enabled nodes and as a result, help alleviate the negative effects of frequent topology partitioning on the overall performance of vehicular networks.

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.

C. ROUTING PROTOCOL

An essential component in the process of packet delivery to the RSU is the routing protocol employed by both UAVs as well as ground vehicles. In this context, packets carried by vehicles/UAVs are routed on a hop by hop basis through in-range vehicles/UAVs until the packets ultimately reach the RSU. A vehicle/UAV manages to forward the packets residing in its OBU if another vehicle/UAV is within its communication range. Otherwise, packet forwarding would stop and the vehicle/UAV is forced to carry the packets until a contact opportunity with a vehicle/UAV arises. An algorithmic description of the way both an SCF-enabled UAV and a ground vehicle would actively engage in the data delivery process in the proposed hybrid network architecture is provided in Algorithm 1.

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

V. MODELING AND PERFORMANCE ANALYSIS

A. TRAFFIC MODEL

This section gauges the benefits that can be reaped from the deployment of UAVs as SCF-enabled nodes. In particular, the performance analysis revolves around the scenario depicted in Fig. 1. The assumptions underlying the analysis are aligned with the ones adopted by the authors in [18]. 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 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). 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. Hence, the number of vehicles N present on the roadway segment between S and D is Poisson distributed with a probability mass function given as follows [4]:

$$Pr[N = n] = \frac{(\rho d_{SD})^n}{n!} e^{-\rho d_{SD}} \quad (1)$$

where $\rho = \frac{\lambda}{E[V]}$ represents the vehicular density in vehicles per meter and E[V] is the space mean speed [23]. 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 [18]. The performance of a UAV-aided vehicular network is compared to that of a UAV-free one. The following performance measures are adopted: *a)* Path availability, which represents the percentage of incoming vehicles observing a fully connected multi-hop path to D, and *b)* the self-descriptive packet end-to-end delay to D.

In the context of the UAV-aided vehicular network, a total of $2 \times k$ UAVs having constant speeds, denoted by V_{UAV}, are assumed to be flying back and forth at an altitude of 100 m between S and D. To emulate a periodical UAV arrival process at the roadway segment with a constant inter-arrival time of I_{UAV}, the $2 \times k$ UAVs are divided into two groups of k UAVs each. The UAVs of each group are separated by a constant distance of $\frac{d_{SD}}{k}$. These two groups fly in opposite directions above the roadway segment. That is, when one group is flying from S to D, the other group would be flying in the opposite direction, namely from D to S. In this way, by the time one of the UAVs flying in the direction of D reaches D, a UAV from the group navigating in the opposite direction 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 exactly k UAVs flying from S to D and acting as SCF-enabled nodes 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 in the context of the considered UAV mobility model $I_{UAV} = \frac{d_{SD}}{k \times V_{UAV}}$.

As far as the UAV's altitude is concerned, it would be relevant to mention in this context that the Federal Aviation Authority recommends that UAVs be flown below 120 meters above ground level. Furthermore, the authors of [8], [24]

TABLE 1. List of symbols.

Symbol	Description
d_{SD}	Length of the considered roadway segment
I	Vehicle inter-arrival time
R	Vehicle transmission range
k	Total number of UAVs navigating, at any given moment, in each direction of the roadway segment
V_{UAV}, I_{UAV}	Speed of the UAV and UAV inter-arrival time
λ, λ'	Flow rate for UAV-free vehicular network and UAV-aided one, respectively
ρ, ρ'	Vehicular density for UAV-free vehicular network and UAV-aided one, respectively
$E[V]$, $E[V']$	Space mean speed for UAV-free vehicular network and UAV-aided one, respectively
$E[N]$, $E[N']$	Average number of nodes between S and D for UAV-free vehicular network and UAV-aided one, respectively
P_e, P'_e	Probability that forwarding stops for UAV-free vehicular network and UAV-aided one, respectively
$\overline{W}$, $\overline{W}'$	Mean intra-cluster distance for UAV-free vehicular network and UAV-aided one, respectively
P_{SD}, P'_{SD}	Path availability for UAV-free vehicular network and UAV-aided one, respectively
$\overline{C}$, $\overline{C}'$	Average cluster size for UAV-free vehicular network and UAV-aided one, respectively
$E[d]$, $E[d']$	Carry distance for UAV-free vehicular network and UAV-aided one, respectively
$E[T]$, $E[T']$	Average end-to-end delay for UAV-free vehicular network and UAV-aided one, respectively

reported a maximum UAV speed value of 100 m/s. In light of this observation, 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. Under free-flow traffic conditions, the space mean speed values of ground vehicles would be relatively high [25]. This allows the UAV to reside within the transmission range of a ground vehicle for a longer period of time since the relative speed between the UAV and a ground vehicle will be relatively small. Consequently, the delivery of the packets emanating from the ground vehicles to the UAV is mostly guaranteed, owing to the relatively small communication delay as compared to the UAV's residence time within the transmission range of a ground vehicle.

B. PATH AVAILABILITY

1) UAV-FREE VEHICULAR NETWORK

As illustrated in Fig. 1, vehicles navigating along the considered roadway segment form several clusters. Each cluster consists of a group of vehicles that can communicate with one another through one-hop/multi-hop communication. The distance separating two adjacent vehicles within the same cluster is less than or equal to R, allowing thus for inter-vehicle communication among the 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 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 length $d_{SD} - R$ 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 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 next hop with a probability $1 - P_e$; otherwise, forwarding stops with a probability P_e due to the nonexistence of another vehicle within the transmission range. It was established in [4] that $P_e = e^{-\rho R}$. Moreover, it was proven therein that P_e can be used to obtain $\overline{W}$, the mean intra-cluster distance separating two consecutive vehicles within the same cluster, as follows:

$$\overline{W} = \frac{1 - P_e(1 + \rho R)}{\rho(1 - P_e)} \tag{2}$$

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 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 $\lceil \frac{d_{SD}-R}{\overline{W}} \rceil$ hops, namely path availability, is given by:

$$P_{SD} = \Big(1 - P_e\Big)^{\left\lceil \frac{d_{SD}-R}{\overline{W}} \right\rceil} \tag{3}$$

2) UAV-AIDED VEHICULAR NETWORK

In the context of the considered UAV-aided scenario, there are always k UAVs flying from S to D, as discussed earlier. This translates into an increase of the density along the considered roadway segment by a value of $\frac{k}{d_{SD}}$. In point of fact, in the absence of UAVs, the average number of vehicles per unit length of the roadway segment is given by: $\rho = \frac{E[N]}{d_{SD}}$ [23], where $E[N]$ is the average number of vehicles present on the roadway segment. In the presence of k UAVs constantly navigating between S and D, the average number of nodes present on the roadway segment becomes $E[N'] = E[N + k] = E[N] + k$. As such, the modified value of the density would be: $\rho' = \frac{E[N']}{d_{SD}} = \rho + \frac{k}{d_{SD}}$. 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

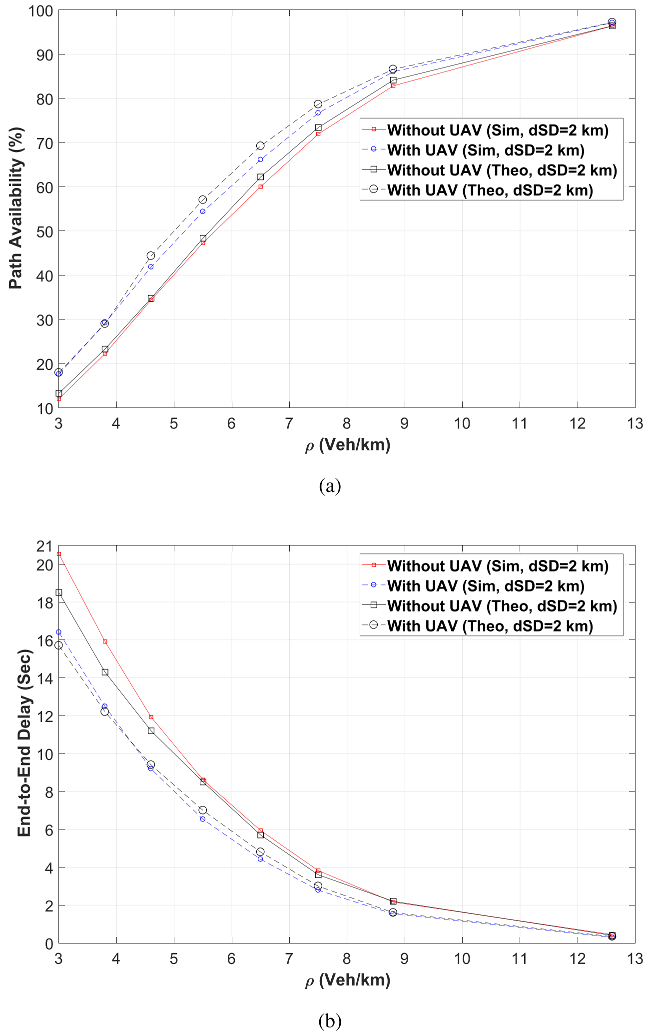

FIGURE 2. Theoretical vs. simulation results for vehicular network with/without UAV, where $k = 1$, V_{UAV}=50 m/s and d_{SD}=2 km: a) Path availability, and b) Delay.

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:

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

C. DELAY ANALYSIS

1) UAV-FREE VEHICULAR NETWORK

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 vehicles residing between S and D. In this case, the path between S and D is said to be broken

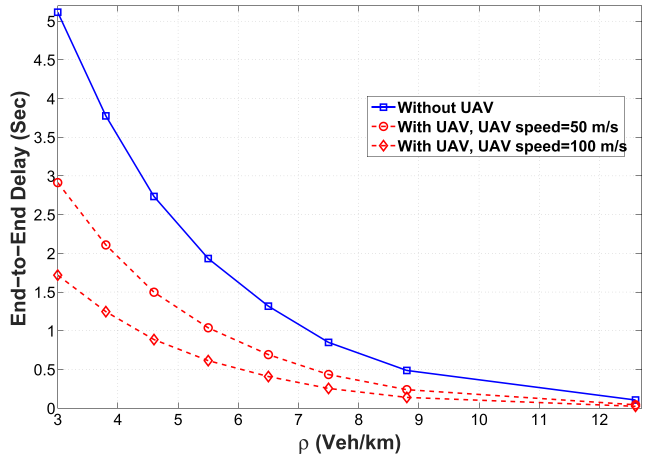

FIGURE 3. Delay performance of vehicular network with/without UAVs for $k = 1$, d_{SD} of 1 km and V_{UAV} of 50 & 100 m/s.

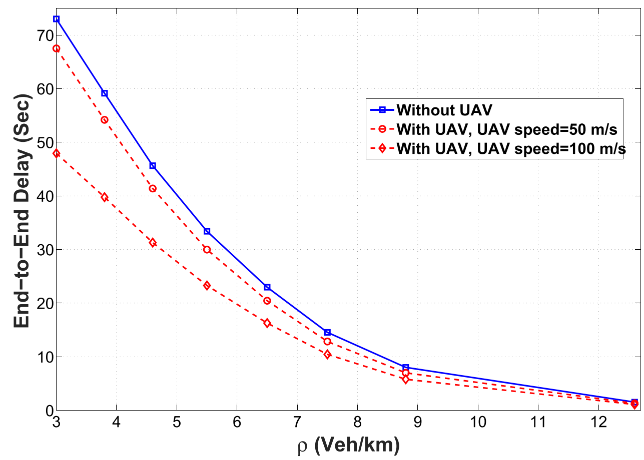

FIGURE 4. Delay performance of vehicular network with/without UAVs for $k = 1$, d_{SD} of 5 km and V_{UAV} of 50 & 100 m/s.

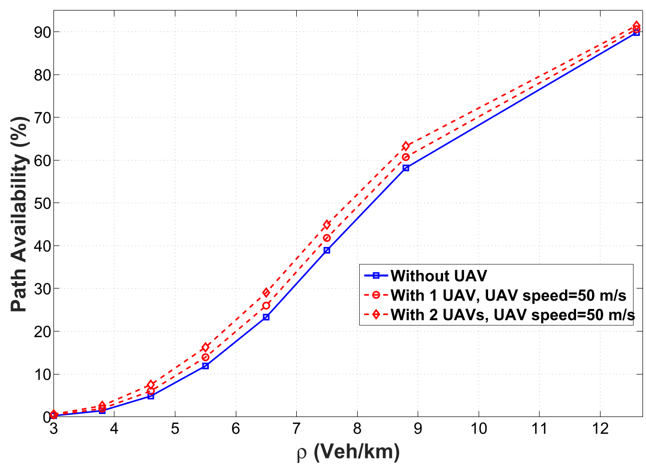

FIGURE 5. Path availability performance of vehicular network with/without UAVs for k of 1 & 2 UAVs, d_{SD} of 5 km and V_{UAV} of 50 m/s.

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 [26]. 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 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 [26]. 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 point of fact, the authors of [26] made the restrictive assumption that there is only one cluster along the roadway segment. Herein, this assumption is fixed 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, as confirmed by [18] and the many references therein. It is worthwhile noting in this regard that the method proposed by the authors of [26] overestimates the value of the carry distance. As such, it is safe to state that their method provides an upper-bound for the carry delay value.

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 vehicles, denoted by $\overline{C}$. The authors of [26] proved that the average cluster length, denoted by $E[L]$, for a road having a finite length is given by:

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

where, $\alpha = E[V]P_e(\frac{1}{\lambda} - (R + \frac{1}{\lambda})P_e)$, $N = \left\lceil \frac{\beta\,(1-\beta)}{\alpha} \times (d_{SD} - R) \right\rceil$, 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 ratio between the average number of vehicles on the roadway segment and $\overline{C}$, namely $\frac{\rho(d_{SD}-R)}{\overline{C}}$. 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:

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

2) UAV-AIDED VEHICULAR NETWORK

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, vehicular density, and space mean speed are designated by λ', ρ', and $E[V']$, respectively. Note that λ' is the new flow rate value resulting from the aggregation of both the vehicle arrival as well as the UAV arrival processes. As previously highlighted, the considered roadway segment is now subject to two independent arrival processes: *a)* a Poisson vehicle arrival process with a parameter λ vehicles per unit of time, and *b)* a periodic UAV arrival process with a constant inter-arrival time of $I_{UAV} = \frac{d_{SD}}{k \times V_{UAV}}$. As a result, the overall arrival process 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 arrivals at S is governed by both ground vehicle and UAV arrivals. Given that the vehicle inter-arrival time is exponential with an average of $I = \frac{1}{\lambda}$ and that the UAV inter-arrival time is constant with a value of $I_{UAV} = \frac{d_{SD}}{k \times V_{UAV}}$, it follows that the resulting overall inter-arrival time follows a truncated exponential distribution upper-bounded by I_{UAV}. Building on this observation and as per the guidelines presented in [27], the new aggregate flow rate λ' would be related to the old flow rate λ, where UAV arrivals are excluded, as follows:

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

The carry distance in the presence of the UAV, denoted by $E[d']$, 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. (8) every occurrence of λ and ρ with λ' and ρ', respectively. However, the average carry delay, denoted by $E[T']$, cannot be derived until the new space mean speed value, denoted by $E[V']$, is determined. As per the guidelines given in [23], $E[V']$ can be obtained as follows:

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

Knowing both $E[d']$ and $E[V']$ enables us to express $E[T']$ as follows:

$$E[T'] = \frac{E[d']}{E[V']} \tag{12}$$

D. NUMERICAL RESULTS

To confirm the accuracy of the analysis introduced in the previous subsections, discrete event simulations were carried out. Particularly, realistic mobility traces were obtained via SUMO [28] and used as input simulation parameters, with the objective of evaluating the impact of UAVs 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).

Figs. 2(a) and 2(b) plot concurrently the simulation and mathematical results pertaining to the path availability and delay as a function of ρ for a UAV-assisted vehicular network (where, $k = 1$ and $V_{UAV} = 50$ m/s) and a UAV-free vehicular network. The results highlight: *a)* the accuracy of the mathematical formulation delineated in the previous subsections and *b)* the superiority of the UAV-assisted vehicular network scenario, where enhanced path availability and reduced delays are observed for all vehicle densities. For example, for ρ =5.5 veh/km, a path availability of approximately 57% was observed for the UAV-aided scenario while a value of 48% was recorded for the UAV-free scenario. This translates into approximately a 19% improvement in terms of path availability when an SCF-enabled UAV is used to grant an alternative connectivity option to ground vehicles. Nevertheless, for high vehicle densities, the presence of the SCF-enabled UAV becomes less advantageous, since, under this condition, the vehicular network will be operating at a relatively high degree of path connectivity to D. In what follows, mathematical results will be omitted for clarity of presentation.

Figs. 3 and 4 show the effect of speed increase on the performance in terms of delay for d_{SD} values of 1 and 5 km, respectively. In this case, the benchmark speed value of 100 m/s is considered along with the speed value of 50 m/s. $k = 1$ UAV is considered to be navigating in each direction of the roadway segment. While an improvement of 40% can be achieved, for example, at $\rho = 3$ veh/km when $V_{UAV} = 50$ m/s and $d_S D = 1$ km, that delay enhancement increases to 60% in the case of $V_{UAV} = 100$ m/s. In point of fact, a rise in the UAV speed translates into a faster delivery of packets to D, justifying thus the obtained results. Fig. 5 illustrates the impact of k, the number of UAVs flying in each direction of the roadway segment, on the path availability for newly arriving vehicles for $d_{SD} = 5$ km. $k = 2$ UAVs are considered in each direction with an individual constant speed of $V_{UAV} = 50$ m/s. The UAVs are assumed to be separated by a distance of $d_{SD}/2$. It is clear from the reported results that the presence of the second UAV helps improve the path availability slightly. The reason for the slight improvement is as follows. For a relatively long distance between the entry point of vehicles and D, it takes more than 2 UAVs to substantially increase the likelihood that an isolated newly arriving vehicle find a UAV within its transmission range to establish connectivity to D.

VI. CONCLUSION

The future of the data communication landscape will be dominated by the need for heterogeneous smart things to exchange data. This paper supplements the plethora of research efforts seeking to collect all the missing pieces to complete the overall puzzle. One of the fundamental smart pieces identified in this paper is the SCF-enabled UAV. Through a proper deployment of the latter in the context of a vehicular network, path connectivity was proven to be improved. This makes a hybrid vehicular networking architecture like the one introduced in this paper an essential step in the ongoing journey towards the development of fully interconnected Internet of Things (IoT) architectures.

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