Opportunistic UAV Relaying for Urban Vehicular Networks

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***Abstract*—We study the impact of employing Unmanned Aerial Vehicles (UAVs) flying random, arbitrary missions as purely-opportunistic relays for cooperative awareness applications in vehicular networks. We do not require that opportunistically relaying UAVs alter trajectory nor speed, so that the additional relaying task can be executed with close-to-zero impact on the execution of the primary mission. Based on extensive computer simulations we demonstrate that, within a wide band of acceptable speeds, flight routes (up to a standard deviation of 300 m from the optimum), as well as altitudes, opportunistic relaying of transmissions via UAVs can yield a benefit to system performance that is on the same order of magnitude as that of optimally deployed UAVs. Moreover, much of the reduction in impact due to suboptimal missions can be recovered simply by moderately increasing the number of UAVs.**

I. Introduction

Especially in research on Smart Cities and the Internet of Things (IoT), new civilian use cases are continuously emerging for Unmanned Aerial Vehicles (UAVs), that is, drones [1]. Such use cases include UAVs flying various types of different missions, for example, infrastructure inspection [2], delivery of medical supplies [3], or parcel delivery [4]. Thus, we hypothesize a trend towards a high number of UAVs being in the air in future smart cities.

A separate trend is cooperative driving to improve today's traffic problems like congestion, environmental pollution, and safety. By enabling vehicles to communicate wirelessly with each other, decisions can be taken cooperatively, e.g., to avoid collisions at intersections [5]. To make this possible, reliable communication between road users is a prerequisite.

Communication between road users is usually based on Radio Frequency (RF) technology such as IEEE 802.11p or 5G sidelink communication. However, especially in urban scenarios, buildings and other obstacles have a substantial impact on radio propagation [6].

There are several approaches to address the problem of unreliable communication, such as simultaneous use of several communication technologies [7], adaptive protocols [8], or the installation of additional infrastructure. Considering, however, that both aforementioned trends coincide – that is, *(i)* many UAVs will be in the air performing monitoring tasks or will be used for last-mile package delivery while *(ii)* road traffic becomes more efficient and safer as vehicles move cooperatively within the city – we explore an orthogonal option: Because UAVs are equipped with communication capabilities for mission planning and coordination, we investigate to which degree UAVs can be used opportunistically for IoT data – specifically as relays for communicating road vehicles. Based on extensive computer simulations, we show that randomly passing UAVs lead to an increased awareness of other road users on the same order of magnitude compared to the case where UAVs are deployed specifically for supporting vehicles. For this, we use an approach for UAVs that exploits overhearing of cooperative awareness broadcasts from vehicles and re-transmits an aggregated packet (containing information about its surrounding) to support any vehicle that might receive it. We consider two scenarios: an artificial urban intersection and a realistic scenario that uses an intersection in Luxembourg.

In brief, the key contributions of this paper are:

- We study the effects of opportunistic relaying of Vehicle to Everything (V2X) communication by UAVs (that is, exploiting them as relays without altering their mission parameters such as flight direction, speed, or altitude).
- We investigate the impact of four different characteristics of UAVs – speed, altitude, number of UAVs, and flight route – on the performance of such opportunistic relaying.
- We show that a larger number of UAVs has a predominant effect on cooperative awareness, whereas characteristics such as speed or flight route have little to no influence.

II. Related Work

There is a broad range of related work in the field of utilization of UAVs in wireless networks [9]. Many works are proposing strategies to predict positions and flight trajectories of UAVs to enable ground nodes to exploit UAVs as repeaters or data storage [10]–[12]. Some also explore opportunistic utilization of UAVs [1]. Few explore road traffic use cases:

Hadiwardoyo et al. [13] propose a positioning technique to optimize the position of a UAV for a vehicular environment. The authors take into account irregularities in the terrain that can affect link quality. Using simulations, they show that the position techniques ensure that the UAV keeps a Line Of Sight (LOS) to all cars and thus maintains a successful communication link. Yet, the study considers a limited scenario and deploys UAVs explicitly for the support of V2X communication, whereas in our approach, a dedicated use of UAVs is not necessary.

Further work by Hadiwardoyo et al. [14] proposes a three-dimensional mobility model for UAVs. This model defines the movement of UAVs in a way such that it maintains good coverage (in terms of communications) with moving ground vehicles. The approach then appropriately adjusts the mission parameters of a UAV to function solely in support of the vehicles. Accordingly, this is a dedicated mission or a strong influence on mission parameters, which is unnecessary for our approach. Moreover, the evaluation considers only a small scenario with three vehicles.

Weisen et al. [15] propose a UAV-assisted framework to connect UAVs with vehicular networks on the road. The framework supports different communication technologies like IEEE 802.11p or 3gpp LTE and is evaluated using a highway simulation. Dedicated UAVs are used to relay packets between multiple vehicles. The authors show that use of the proposed framework decreases average delay while increasing throughput. However, the work requires a dedicated deployment of UAVs and it does not use already existing UAVs in the air.

Summing up, the use of UAVs to support communication between other (mobile) nodes in a network, particularly of road users, is an important topic that is currently being investigated in many directions. A lot of the approaches show a clear positive impact on different metrics used when UAVs are deployed for a specific use case. However, in such works, purely opportunistic relaying for road users has only been considered in very simple settings or, indeed, not at all.

In this paper, we close this gap by investigating the impact of UAVs on vehicular networking applications using detailed computer simulations with realistic communication and mobility patterns for vehicles. We analyze four different UAV properties in two different scenarios and assume no more than a purely random, immutable flight route for UAVs.

III. Opportunistic Relaying

In preliminary work [16] we investigated the effects of exploiting randomly passing UAVs at an urban intersection to improve awareness of vehicles on the ground. We showed that such a system can increase the number of perceived vehicles by about 5 percentage points (% points). However, we considered only a very limited parameter range. The chosen parameters resulted essentially from the characteristics of commercially available UAVs (e.g., speed) and the currently applicable legal regulations (e.g., altitude). Our evaluation did, however, indicate that various parameters such as speed, altitude, flight routes, or the total number of UAVs might have a strong impact on the increase in the number of perceived vehicles.

To investigate the impact of the parameters mentioned above, we consider so-called point-to-point flying UAVs [1] that are following a predefined trajectory to fulfill a predefined goal (e.g., parcel delivery services). Thus, a UAV does not adjust the current flight route, altitude, or speed to accomplish secondary missions (e.g., data relaying). In addition to a predefined trajectory, we also assume a predefined speed and altitude.

We further suppose that vehicles transmit wireless broadcasts at regular intervals. Such broadcasts contain information about the position of a vehicle or its speed. Received broadcasts are used by other vehicles to build a neighbor table of vehicles in their surroundings. This table could be used (for example) for awareness or to prevent vehicle collisions at an intersection.

Table I
Simulation scenario

Parameter	Value
Road traffic simulator	Sumo 1.8
V2X simulation models	Veins 5.1 & INET 4.2.1
Simulated area	3000 m x 3000 m
Intersection legs	4
Intersection leg length (artificial)	500 m
Intersection leg length (LuST)	approx. 550 m to 1000 m
Road traffic update interval	0.01 s
Vehicle length	4 m
Desired speed $v_d = v_{\max}$	13.9 m/s (approx. 50 km/h)
Min speed $v_{\min}$	0 km/h
Krauss driver imperfection σ	0.5
Krauss desired headway	0.5 s with 5 m minimum
Spawn position of vehicles	random (north,east,south,west)
Spawn rate of vehicles	$0.25\,\mathrm{veh/s}$
Turn direction	random (1:3:1 left:straight:right)
Traffic light scheduling	Non-adaptive
GN / YL phase duration (artificial)	15 s or 5 s / 3 s
GN / YL phase duration (LuST)	30 s or 10 s / 4 s
Cycle time (artificial)	$52\,\mathrm{s} = 2 \times (15\,\mathrm{s} + 2 \cdot 3\,\mathrm{s} + 5\,\mathrm{s})$
Cycle time (LuST)	$96\,\mathrm{s} = 2 \times (30\,\mathrm{s} + 2 \cdot 4\,\mathrm{s} + 10\,\mathrm{s})$

We then enable UAVs to support this wireless communication of vehicles on the ground. This is realized by UAVs receiving and storing broadcast transmissions from the vehicles. The received data is then aggregated and transmitted as a broadcast to all vehicles in the environment.

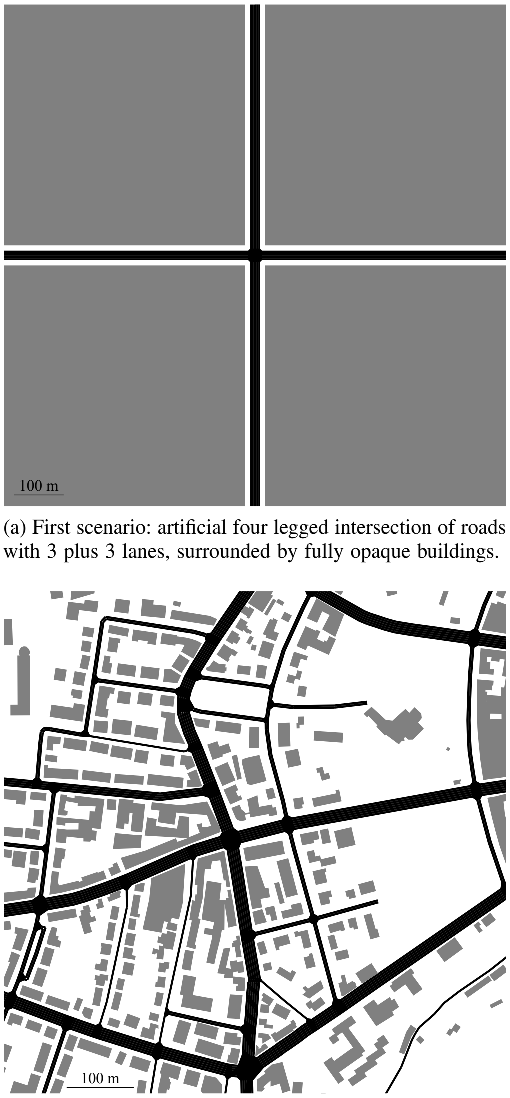
In this work, we investigate the following four parameters concerning the flight behavior of UAVs to investigate to what degree they might matter:

- Flight speed of a UAV: The flight speed is identical for all UAVs and constant during the flight.
- Flight altitude of a UAV: The flight altitude is identical for all UAVs and constant during the flight.
- Number of UAVs: UAVs are spawned at the outer edge of the scenario. The number of UAVs is either fixed to 10 or their inter-arrival time is exponentially distributed.
- Flight route: UAVs are flying in a straight line that passes by the center of the intersection at a normally distributed distance. We vary its standard deviation.

IV. Experimental Setup

We investigate the impact of opportunistic UAV relaying on cooperative awareness using computer simulations based on the popular open-source vehicular network simulator Veins [17], coupling the OMNeT++ INET Framework for modeling wireless networking with SUMO [18] for modeling road traffic.

We are using two different scenarios to evaluate the impact of opportunistic UAV relaying on vehicular networks. Both scenarios have a simulated area of 3000 m x 3000 m. The UAVs always start at the edge of the area and then move towards the



(a) First scenario: artificial four legged intersection of roads with 3 plus 3 lanes, surrounded by fully opaque buildings.

(b) Second scenario: intersection of Boulevard Grande-Duchesse Charlotte and Avenue Monterey in the center of Luxembourg.

Figure 1. Our evaluation includes two scenarios. The first scenario is an artificial, symmetric intersection, which minimizes side effects in the simulation. The evaluation thus explicitly shows the consequences of the opportunistic relaying. The second scenario is a realistic scenario from the real world.

intersection. Thus, transmissions from vehicles partly already reach UAVs and vice versa.

The first scenario is an artificial intersection with four arms (500 m each) that is surrounded by buildings, sketched in Figure 1a. It is the same scenario we used in our preliminary work [16]. All buildings have a height of 20 m and a distance of approx. 10 m to the roads. We consider a free-space path loss model for radio propagation but treat buildings as fully opaque to radio transmissions. Vehicles are not blocking radio transmissions. Vehicles are spawning at a rate of 0.25 veh/s at the end of each arm of the intersection, taking random trajectories through the intersection. The spawn rate of Poisson arrival of road vehicles was chosen in a way that the simulation reaches a steady state, that is, repeatedly some vehicles temporarily accumulate at the intersection, but are also completely released again after some time. Turn directions at the intersection are chosen with weights of 1:3:1 (left:straight:right). The intersection is controlled by a static traffic light program.

Table II
WIRELESS NETWORK SIMULATION PARAMETERS

Parameter	Value
Technology	IEEE 802.11p
Carrier Frequency	5.89 GHz
Bit rate	6 Mbit/s
Transmit power	20 mW
Beacon interval (vehicles)	0.1 s
Beacon interval (UAVs)	0.5 s
Path loss (Friis model)	$\alpha = 2$
Shadowing	fully opaque buildings

The second scenario is a section of the city of Luxembourg, extracted from the SUMO LuST scenario [19]. This scenario provides an accurate representation of the city in terms of the street topology, but also regarding buildings. We consider the intersection of the streets Boulevard Grande-Duchesse Charlotte and Avenue Monterey in the center of Luxembourg sketched in Figure 1b. The configuration of radio shadowing, traffic volume, and turn directions are identical to the first scenario.

Table I summarizes the most important parameters regarding road networks in the simulation study.

Vehicles are transmitting wireless broadcasts (here: IEEE 802.11p beacons containing status information for cooperative awareness) at a frequency of 10 Hz. Received broadcasts are used by each vehicle to build a neighbor table of vehicles in their surroundings. We remove an entry from the neighbor table for which no transmission from a certain vehicle has been received for over 1 s. Transmissions received by UAVs are aggregated during a period of 0.5 s and transmitted back as a broadcast.

Table II summarizes the most important parameters for wireless communication in our simulation study.

We perform 10 independent runs for statistical confidence and collect data for 600 s after the transient phase at the beginning of each simulation. Since the confidence intervals are negligibly small, they are not shown in the plots.

To quantify awareness in our scenario, we consider, for each vehicle, the fraction of perceived neighbors (that is, those having an entry in the neighbor table) within an area of 90 m around the center of the intersection (i.e., those which might be relevant for realizing an intersection collision avoidance application). Figure 2 illustrates this principle.

Unless otherwise specified, there is a constant number of 10 UAVs in a scenario of 3000 m x 3000 m. If a UAV leaves the simulation playground, a new one is scheduled uniformly distributed between the next 15 s to 30 s. The additional variable spawn time ensures that the UAVs are not simultaneously above the intersection, but are distributed within the transient phase. A constant number of UAVs eliminates side effects due to the

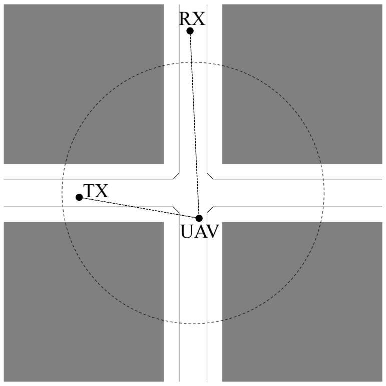


Figure 2. Experimental setup: receivers of cooperative awareness broadcasts are interested in the presence of transmitters within a 90 m region of interest around an intersection. UAVs help aggregate and relay cooperative awareness broadcasts.

Table III
UAV SIMULATION PARAMETERS
(UNLESS OTHERWISE SPECIFIED FOR EXPERIMENTS)

Parameter	Value
UAV speed	20 m/s
UAV height	70 m
Mean UAV flight distance to intersection	0 m
UAV spawn interval	Uniform (15 s, 30 s)
Number of UAVs simultaneously in scenario	10
UAV mobility model	Linear mobility

random occurrence of UAVs according to a defined spawn distribution.

Table III summarizes the most important parameters for UAVs in the simulation study.

V. INFLUENCES ON OPPORTUNISTIC RELAY SUCCESS

Our preliminary work [16] investigated the influence regarding the awareness of the vehicles on the ground for a single parameter combination. However, different properties of a UAV like altitude, speed, or flight route will typically vary in a relatively wide range. In the following, we investigate these changes and their impact on the relay success.

A. UAV altitude

In urban areas, radio shadowing by buildings is often a problem for both road traffic [20] and UAVs [21]. Figure 3 shows the effects of the flight altitude on the LOS to vehicles on the ground. If the altitude of a UAV is too low, buildings have a strong influence on radio propagation, making communication unreliable.

A solution to this problem cannot be to place UAVs as high as possible to avoid radio blockage due to Non Line Of Sight (NLOS) conditions: Considering path loss only, it becomes apparent that, the received power decreases with the square of the distance. It is therefore not possible to let a UAV fly at an arbitrary altitude to reach as many vehicles as possible in an urban area [22]. We, therefore, study the effect of the UAV

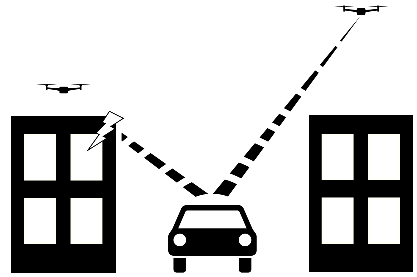
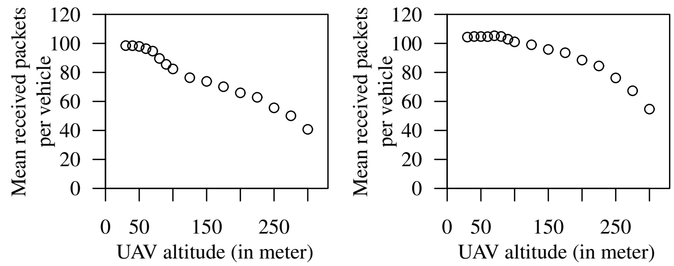


Figure 3. Illustration of shadowing effects by buildings: With a change in altitude, the angle with respect to the vehicles changes. A higher flight altitude increases the visibility range on the road. At the same time, an increase in flight altitude also has an effect on the received signal strength of transmissions from vehicles and vice versa.



(a) artificial scenario (b) Luxembourg scenario

Figure 4. Number of packets received by vehicles from an UAV that is statically hovering above the center of the intersection. As the altitude increases, the number of packets received decreases. The reason for this is the path loss, which increases quadratically with distance.

altitude on the success that a packet from a UAV is received by a vehicle on the ground.

As an initial step, we consider the impact of a single and static UAV placed directly over the center of the intersection. Importantly, this is not a system realization we are proposing; our goal in this step is simply to ignore the dynamics caused by the flyover of UAVs and focus on only the influence of the altitude. We conduct a parameter study with a static UAV, starting at 30 m altitude and increasing up to 300 m in 30 m steps.

Figures 4a and 4b show the mean number of overall received packets per vehicle for the artificial scenario and the Luxembourg scenario respectively. Both scenarios show an almost constant behavior at low flight altitudes. The number of received packets then decreases with increasing flight altitude. This can be attributed to signal attenuation due to the free space path loss. With an increasing distance, the received signal strength on the receiver side decreases, and thus fewer transmissions from the UAV can be successfully decoded by vehicles on the ground. Our data also shows that even at an altitude of 300 m, packets continue to be received successfully by vehicles and thus the UAV still supports communication between vehicles on the ground.

Figure 5, however, shows that a lower raw number of received packets does not directly translate into a lower awareness: Our data for the artificial scenario shows that the fraction of known

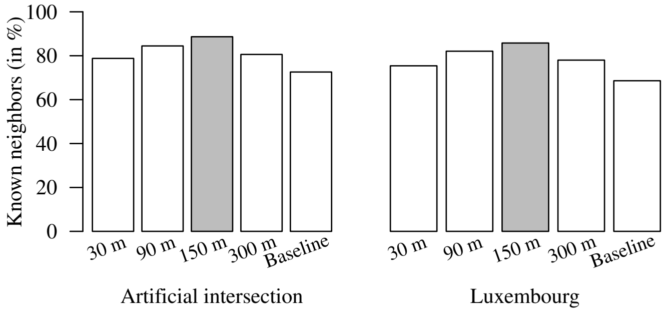


Figure 5. Relative proportion of known vehicles (located within 90 m of the intersection) depending on UAV altitude. The proportion of known neighbors shows an optimum at a flight altitude of about 150 m to 175 m (data not shown). The visibility decreases with a further increasing flight altitude. Still, even a high flight altitude (here 300 m) leads to a better result than the baseline scenario without any UAV.

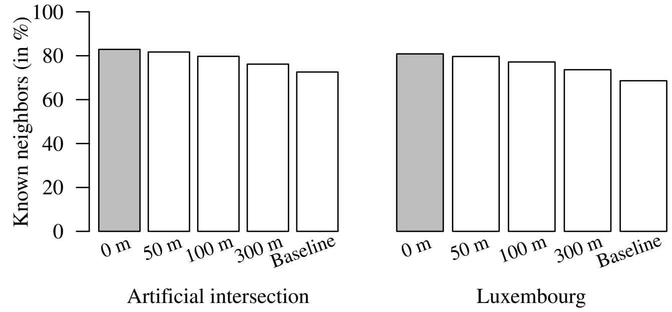


Figure 6. Relative proportion of known vehicles (located within 90 m of the intersection) depending on standard deviation of flight paths from optimum. The relaying success of packets of vehicles on the ground decreases with an increasing deviation (regarding the flight route) from the center of the intersection for both the artificial and the Luxembourg scenario. A strong deviation of 300 m still has a positive influence on the awareness and thus leads to an improvement compared to the baseline scenario without any UAV.

vehicles is steadily increasing up to a height between 150 m and 175 m (data not shown) before subsequently dropping off with a further increase of the height. The improvement (compared to the baseline scenario with no UAV) at 90 m towards the center of the intersection is approx. 16 % points.

Summing up: Although the total number of received packets decreases (Figure 4), the positive influence of these packets is greater at a higher altitude. The reason for this is the increasing number of LOS connections that the UAV establishes with increasing altitude. This results in packets being received by more vehicles. Since a higher flight altitude is again accompanied by stronger signal attenuation, this trend reverses: the proportion of known vehicles decreases again with increasing altitude. With this, fewer transmissions from the UAV can be successfully decoded by vehicles on the ground. However, if we compare the highest flight altitude (300 m), we can observe that a sporadic flyover of a UAV still leads to an improvement, although small, compared to the case without any UAV. Even in this case, the improvement (compared to the baseline scenario) at 90 m towards the center of the intersection is approx. 8 % points.

The right part of Figure 5 shows the relative number of known neighbors as a function of the distance towards the center of the intersection for the Luxembourg scenario. Due to the different geometry of the roads and the buildings, the course of the data is slightly different. Here again, shadowing effects by buildings influence the signal propagation and the awareness of vehicles first improves with an increasing height of the UAV. Analogous to the first scenario, this decreases as the altitude continues to rise. An optimum is also reached here at 150 m to 175 m. The improvement (compared to the baseline scenario) at 90 m towards the center of the intersection is approx. 18 % points. Again, this is due to signal attenuation due to path loss, but even the scenario with the highest altitude (300 m) achieves better results (approx. 9 % points) compared to the scenario without any UAV.

Based on our data, it cannot be concluded that a UAV should fly as high as possible to get a better LOS on the roads. Rather, the optimum is a medium flight altitude.

B. *UAV flight route*

The flight route of a UAV impacts on how well the UAV can be spotted by vehicles on the ground. If a UAV is permanently moving directly above the road, the UAV maintains a permanent LOS with vehicles on the road. Therefore, the communication is not negatively influenced due to buildings or other obstacles (assuming the attenuation is only affected by the free space path loss without multipath radio propagation properties). Since we assume that UAVs do not change their primary mission, a realistic assumption is that UAVs pass the intersection with a suboptimal distance to the center of the intersection.

For this and the following experiments, we thus let UAVs fly over the scenario at a normally distributed random distance from the center of the intersection. We perform a parameter study regarding the standard deviation of the distance towards the center of the intersection, starting at 0 m distance and increasing up to 300 m in 25 m steps.

The left part of Figure 6 shows the results for the artificial scenario. The data for a perfect flyover over the center of the intersection (0 m) and the flyovers with a standard deviation of 50 m are almost identical. The reason for this is the size of the crossing area. A standard deviation of up to 50 m around the center of the intersection still allows many UAVs a flyover that allows a LOS connection with many vehicles on the ground. Accordingly, a high proportion of known road users is achieved due to the UAV support that is close to the perfect flyover. This is no longer the case for flyovers at a greater distance from the center of the intersection. Since UAVs are not necessarily directly above the area of the intersection, but perhaps only fly over one arm of the intersection, such a trajectory can only detect a fraction of the vehicles on the ground. Consequently, the relative number of perceived neighbors per vehicle is lower. Our simulation results show that this effect becomes stronger when the distance to the center of the intersection is increased. The improvement (compared to the baseline scenario) at 90 m towards the center of the intersection is approx. 10 % points for the best-case configuration with 0 m deviation.

The right part of Figure 6 shows the results for the Luxembourg scenario. The trend is similar to the artificial scenario. The small deviations between the scenarios can be explained by the different shape of buildings and roads. Yet again a perfect flyover is of the greatest added value for vehicles on the road. This configuration leads to an improvement (compared to the baseline scenario) at 90 m towards the center of the intersection of approx. 12 % points.

Based on our experiments, it can be said that a UAV does not necessarily have to fly perfectly over the intersection. It is already sufficient (for our proposed use cases) if a UAV crosses the intersection area so that a LOS connection to the arms of the intersection (and thus to vehicles) is achieved. There is only a negligible difference between a synthetic and a realistic environment.

Considering Figure 6 it can further be concluded that even in the worst case with a standard deviation of 300 m towards the center of the intersection, a substantial improvement is still achieved compared to the baseline scenario with no UAV. Our simulations revealed an improvement of approx. 4 % points and approx. 5 % points for the artificial and Luxembourg scenario respectively. Related work often controls the position of a UAV with comparatively high accuracy so that vehicles on the ground are supported optimally. Based on our data, however, it can be said that this is not necessarily required. Since the benefit is still provided even with a large standard deviation, the distance to the optimal case might also be compensated by a larger number of UAVs and complex algorithms and protocols might not necessarily be required to achieve this. We come back to this hypothesis later in this study.

C. *UAV speed*

Since the UAVs collect data during the flyover and send it back after a time, flight speed affects this store-carry-forward approach.

We thus carry out a parameter study for the speed of a UAV as well to measure the influence of this property on the fraction of perceived neighbors. The parameter study includes very low speeds of, for example, 1 m/s, but also very high speeds that are already reached by current delivery UAVs. We use a maximum speed of 35 m/s for this study.

For the speed property, it is important that the number of UAVs is constant during the simulation (see Section IV). If a spawn interval is used for UAVs and UAVs are configured to move with a very small speed, this will lead to an extreme increase regarding the total number of UAVs in the scenario. Thus, after an appropriate simulation time, there would permanently be several UAVs above the intersection. This can result in very good visibility (if communication is still possible at all due to the channel load), but this is not a realistic scenario. Therefore, the number of UAVs is kept constant (to 10 UAVs) for this parameter study.

Figure 7 shows the relative amount of perceived vehicles as a function of distance towards the center of the intersection for both the artificial and the Luxembourg scenario.

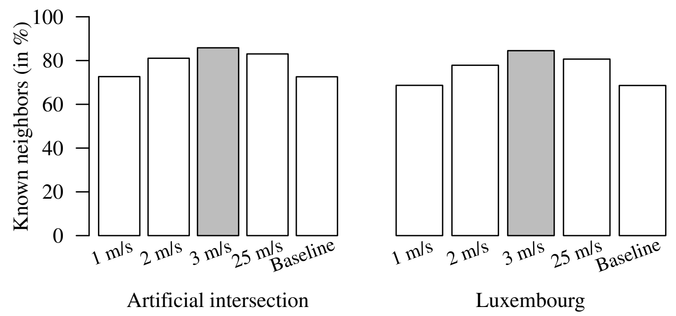


Figure 7. Relative proportion of known vehicles (located within 90 m of the intersection) depending on UAV speed. The relay success is low at low speeds and identical to the baseline scenario. With increasing speed, however, the relative number of known neighbors reaches an optimum at 3 m/s in both scenarios. However, this advantage is comparatively small, so that the speed of a UAV has practically a negligible effect on the relay success (after reaching a minimum speed).

Our data shows that the lowest speed (1 m/s) has the smallest effect on the chosen metric. Simulations show that at this speed, there is only a negligible effect on the used metric and it behaves exactly like the baseline scenario. At a very low speed, the UAV moves slowly over the center of the intersection. However, it also spends a huge fraction of the flight duration above buildings, where it cannot establish a LOS connection with vehicles on the ground. Consequently, the UAV cannot support the transmissions of vehicles on the ground by relaying transmissions. However, when the UAV is finally close to the intersection, it can support the communication of vehicles again. Due to the low speed, the UAV stays for quite a while within the area of the intersection where it can perceive other vehicles. With this, the UAV is able to collect wireless broadcasts for quite a while and transmits the aggregated information more than once during its flyover. However, the aggregated packets usually contain redundant information after it has been received once by a vehicle. Thus, it does not provide any benefit with additional transmissions for the road traffic.

As the speed increases, the proportion of known vehicles first increases. Beyond a speed of 3 m/s (data not shown), the proportion of known vehicles drops slightly, but then remains constant even at high speeds. The improvement (compared to the baseline scenario) at 90 m towards the center of the intersection for a speed of 3 m/s is approx. 13 % points and 15 % points in the artificial and Luxembourg scenario, respectively.

This can be attributed to the fact that although the UAV moves faster over the intersection, the duration is sufficient to collect all the necessary information from vehicles and transmit the aggregated packet back. Since the total number of UAVs in both scenarios is constant, a new UAV spawns right after one finishes its trip and quickly reaches the intersection due to its high speed. Accordingly, the time of the flyover above the buildings (where no communication is possible) is minimized.

The slightly lower proportion of detected vehicles at high speed can be explained by the fact that a UAV can only rarely transmit a message during the flyover before it reaches the

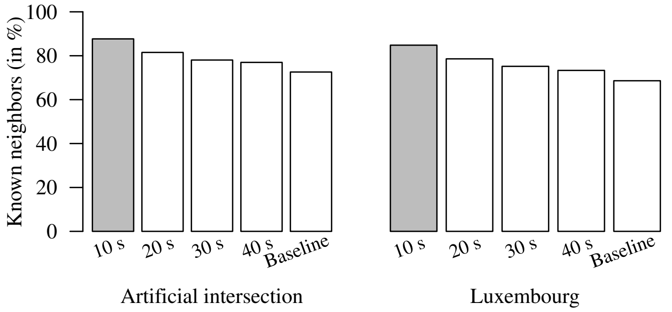


Figure 8. Relative proportion of known vehicles (located within 90 m of the intersection) depending on UAV density (expressed as the mean of exponential inter-arrival time). The proportion of known neighbors shows an optimum at a mean interval of 10 s – the lowest interval in our study. The data from this study shows that the relative proportion of known neighbors increases with the number of UAVs. Since the wireless broadcasts of UAVs are transmitted much less frequently, the number of UAVs can increase substantially before a problem regarding the channel load occurs. However, it is questionable whether such extreme scenarios are realistic.

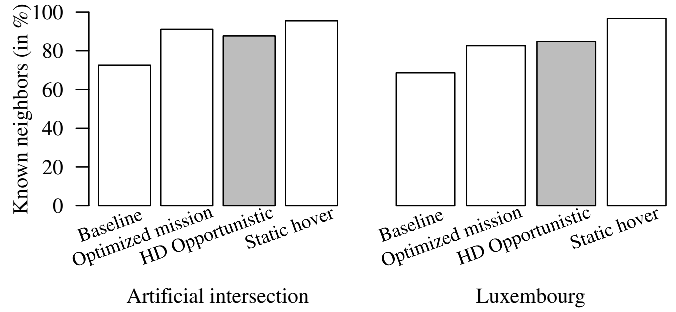


Figure 9. Relative proportion of known vehicles (located within 90 m of the intersection) depending on mission. Deploying UAVs for *optimized missions* yields comparable performance to purely opportunistic relaying (albeit at moderately higher UAV density).

buildings on the other side of the road that completely shields the signal propagation. Thus, a very fast flyover of a UAV has a slightly lower advantage for road traffic.

In the end, the data for the artificial and the realistic scenario shows that the speed has no substantial influence on the awareness, provided it has reached a certain minimum. At high speeds (35 m/s, data not shown), the difference to the optimal case in our experiments is only approx. 3 % points lower in both scenarios. Yet, the minimum in our scenario is sufficiently low that it is reached (or exceeded) even by delivery UAVs.

D. UAV density

Increasing the number of UAVs leads to more opportunities to support the relay of transmissions from vehicles on the ground. This raises the question of the number of required UAVs to achieve a noticeable advantage compared to the scenario with no UAVs.

In this study, the number of UAVs is flexible and no longer static, as in the previous experiments. We change the spawn frequency of UAV flyovers and investigate the effects on awareness regarding vehicles. The inter-arrival rate follows an exponential distribution. We configure the mean to be between 10 s and 50 s in steps of 10 s. Further reducing the spawn interval would increase the number of UAVs until a state is reached where more UAVs would be in the scenario than vehicles. Thus, we take a mean of 10 s as the minimum.

Figure 8 shows the result of this study for both scenarios. Our data shows that as the frequency of flyovers increases, the relative proportion of known nodes on the ground increases as well. This is the case for both scenarios. Accordingly, as the frequency of the flyovers reduced, data becomes more similar to that of the baseline scenario without any UAV. The improvement with a high occurrence of UAVs is approx. 15 % points for the artificial scenario (approx. 16 % points for the Luxembourg scenario) compared to the baseline scenario.

From the point of view regarding our metric, it would be desirable if as many UAVs as possible are active in the scenario, as long as the wireless channel is not too heavily loaded. In our case, the average channel busy ratio in the center of the intersection is approx. 17 % on average. Accordingly, there is still the possibility of using more UAVs to optimize the metric without overloading the wireless channel.

These results show, however, that with a higher number of UAVs, the relative proportion of known vehicles can increase correspondingly with the number of available UAVs. Compared to the static hover scenario (Figure 5), a mean interval of 10 s only achieves a result that is 7 % points lower for the artificial scenario and 10 % points lower for the Luxembourg scenario. With a value of 10 s, there are on average about 5 UAVs in the intersection area (1000 m x 1000 m).

VI. Optimized Missions vs. Opportunistic Relaying

Even though UAVs are only opportunistically available as relays, it is evident from the previous experiments that characteristics such as altitude, etc., affect relaying success. For a further experiment, we now use an additional *optimized mission* configuration of UAVs using the values that proved most beneficial in the aforementioned experiments regarding the speed (3 m/s), altitude (150 m), and deviation from the center of the intersection (0 m). As an alternative to optimized mission planning, we investigate simply increasing the number of UAVs to the most beneficial value of the aforementioned experiments (a mean interval of 10 s); we call this deployment *High Density (HD) Opportunistic*. HD Opportunistic deployment uses an average of 15 (artificial scenario) to 17 (Luxembourg scenario) UAVs in the air (compared to 10 UAVs for the alternatives). We compare the performance of these alternatives with that achievable with an idealized mission of a UAV: hovering statically and permanently at an optimal altitude right in the center of the intersection; we call this alternative *static hover*.

The left part of Figure 9 shows the simulation results of the artificial scenario, whereas the right part shows the simulation results for the Luxembourg scenario. The data shows that optimized mission planning yields an approx. 18 % points (artificial scenario) and approx. 14 % points (Luxembourg scenario) improvement compared to the baseline. Compared with the performance achievable by static hovering, performance is only approx. 5 % points (artificial scenario) and approx. 14 % points (Luxembourg scenario) lower. The same performance, however, is also achievable in the *HD Opportunistic* deployment: almost the same proportion of known neighbors is reached (−3 % points for the artificial scenario) or it is even exceeded (+2 % points for the Luxembourg scenario).

Thus, we can conclude that purely opportunistic relaying can be an alternative to optimizing mission planning if it can instead rely on a moderately higher number of UAVs.

VII. Conclusion

In this work, we have studied the impact of employing Unmanned Aerial Vehicles (UAVs) flying random, arbitrary missions as opportunistic relays for cooperative awareness applications in vehicular networks. We did not require that UAVs alter either trajectory or speed for opportunistic relaying so that the additional relaying task could be executed with zero impact on the execution of the primary mission, aside from the energy impact of relaying messages. Because of the public nature of cooperative awareness data, the system also demands no additional privacy considerations. To gauge the benefit of opportunistic relaying, we compared it to three baselines: no relays, an idealized mission profile, and an optimized mission profile. We were particularly interested in the question of to what degree a simple increase in the number of UAVs employed for opportunistic relaying can approximate the performance obtainable from statically positioned UAVs or UAVs flying optimized missions.

We performed simulations in two urban scenarios. The scenarios represented an artificial, symmetrical intersection and a realistic scenario extracted from the city of Luxembourg. Our experiments showed that neither suboptimal speed (as long as speed remains above 2 m/s) nor suboptimal flight routes (up to a standard deviation of 300 m from the optimum) sacrifice a substantial amount of achievable performance. Suboptimal altitudes of opportunistic relays, on the other hand, can substantially impact system performance – though there is a wide band of acceptable altitudes.

In summary, our results showed that an opportunistic relaying of transmissions via UAVs can lead to an improvement on the same order of magnitude as static deployed UAVs serving a primary mission of supporting Vehicle to Everything (V2X) communication. Since this improvement also improves awareness and thus safety on the roads (while not introducing additional costs or effort), the proposed approach is worthwhile. Moreover, the impact of suboptimally-positioned relays on system performance can be recovered simply by moderately increasing the number of UAVs flying arbitrary missions while acting as opportunistic relays.

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