Opportunistic Airborne Virtual Network Infrastructure for Urban Wireless Networks*

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Abstract

We study the suitability of Unmanned Aerial Vehicles (UAVs) as purely opportunistic airborne virtual network infrastructure to support urban wireless networks, specifically in two Vehicle-to-Everything (V2X) use cases: First, UAVs being used as relays for cooperative awareness applications; second, UAVs being used to coordinate channel access for platooning in urban areas. We do not require that these UAVs alter trajectory nor speed from those of their random, unrelated primary missions, so that these additional tasks can be executed with close-to-zero impact on the execution of their primary missions. Based on extensive computer simulations we show 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. We further show that an opportunistic channel access control can reduce the total number of packet collisions by approx. 86 % compared to a scenario without any UAVs. Moreover, much of the reduction in impact due to suboptimal missions can be recovered simply by moderately increasing the number of UAVs.

Keywords: vehicular networking, UAV, drones, simulation

1. Introduction

With increasing urbanization, various challenges are arising in cities, which the trend toward Smart Cities aims to tackle. One of the leading problems in these cities is the increasing traffic that is going to be more than doubled by 2045 [2]. The steep increase in traffic volumes has always been associated with traffic problems such as congestion and an increased risk of accidents but also increased emissions (e.g., greenhouse gas and noise) [3].

Cooperative vehicles are widely considered to play an essential role in alleviating traffic problems. The underlying idea is that vehicles exchange information wirelessly to generate decisions cooperatively [3]. An example is the exchange of current status information about the respective vehicle for cooperative awareness. With this, an accurate data set of the current traffic situation can be generated and used for (cooperative) decision making; for example, to avoid collisions at intersections. Another very common application that promises to address the problems mentioned above is platooning. The idea of platooning is to form a convoy of vehicles, each driven by a Cooperative Adaptive Cruise Controller (CACC). Vehicles in a platoon are connected wirelessly and can thus exchange information in the form of platooning beacons, containing data about their position, speed, or the desired acceleration [4]. The CACC uses the received data to maintain a distance of only a few meters between vehicles at freeway speed while keeping the entire platoon in a stable configuration without vehicle collisions. This small inter-vehicle distance leads to better road utilization and reduced fuel consumption. Another positive effect is the improvement in traffic flow, as all vehicles in the platoon move synchronously due to the constant exchange of information. Platooning is often an application for freeway scenarios. However, recent research demonstrates the potential of platooning also in urban areas [5, 6].

Besides road traffic, the use of Unmanned Aerial Vehicles (UAVs) is being considered more and more for Smart Cities [7], especially for civil commercial use cases. Such use cases include UAVs flying various types of different missions, for example, infrastructure inspection [8], delivery of medical supplies [9], or parcel delivery [10]. Particularly parcel delivery has seen an early push towards the use of UAVs in urban areas. Companies like DHL[1] and FedEx[2] have developed prototypes for parcel delivery services. The focus has often been on what was termed *last mile* deliveries in urban areas [11]. This last mile is often covered by delivery trucks, which strongly negative impact inner-city traffic [12]. Therefore, the use of UAVs is still being researched [13] and is also being discussed in an industrial context. Thus, we expect future smart cities to have a large number of UAVs in the air.

*This is an extended version of our WONS 2022 paper [1], which focused on the use case of cooperative awareness. We extend its coverage with in-depth information and also investigate a second, novel use case: channel access coordination.

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[1] https://www.dhl.com/discover/en-global/business/business-ethics/parcelcopter-drone-technology
[2] https://newsroom.fedex.com/newsroom/global/elroyair

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Both air (mission planning, coordination) and road traffic (e.g., cooperative awareness, platooning) will be largely autonomously controlled and thus essentially dependent on reliable communication [3, 14]. Communication between road and air vehicles is usually based on Device-to-Device (D2D) communication using wireless technology such as IEEE 802.11p or approaches from the 3GPP. However, especially in urban scenarios, buildings and other obstacles impact radio propagation [15, 16]. These influences often mean that communication no longer works reliably. This leads to a substantial safety risk for many applications in the field of cooperative driving.

There are several approaches to address the problem of unreliable communication, such as the simultaneous use of several communication technologies [17], adaptive protocols [18], or the installation of additional infrastructure such as Roadside Units (RSUs). Considering, however, that both aforementioned trends coincide – that is, *(i)* many UAVs are likely to be in the air performing monitoring tasks or will be used for last-mile parcel delivery services 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 (without changing the primary mission of a UAV) for Internet of Things (IoT) data – specifically as relays or as a component for coordinated channel access to support communicating road vehicles.

In more detail, we show that UAVs can be beneficial for cooperative driving while the primary mission and characteristics of UAVs remain unchanged. We consider two scenarios: an artificial urban intersection and a realistic one using an intersection in Luxembourg.

We further evaluate two different use cases for an opportunistic airborne virtual network infrastructure for urban wireless networks:

First, we show that randomly passing UAVs lead to an increased awareness of other road users (within a defined Region of Interest (ROI)) on the same order of magnitude compared to the case where UAVs are deployed specifically to support 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.

Second, we show that randomly passing UAVs can opportunistically coordinate the wireless channel access for vehicles on the ground such that two vehicles do not transmit simultaneously and cause packet collisions. For this, we consider platoons driving in an urban area and show that our approach substantially reduces packet collisions and thus increases safety on roads.

We illustrate both use cases in Figure 1. The UAV in the center of the intersection may retransmit cooperative awareness broadcasts (use case 1) or coordinate wireless channel access between vehicles (use case 2).

The presented results can be achieved without deploying additional infrastructure like RSUs or introducing multi-hop approaches between vehicles on the ground. Moreover, since we also do not change the primary mission of a UAV, the presented improvements are achieved without additional costs nor an additional (mission planning) effort.

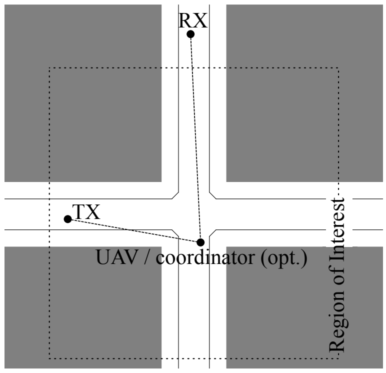


Figure 1: Sample use case for the artificial scenario: receivers of cooperative awareness broadcasts are interested in the presence of transmitters within a 90 m region of interest around an intersection. UAVs can opportunistically help aggregate and relay cooperative awareness broadcasts (Sections 3 and 4) or help coordinate channel access (Section 5).

We build this study on our previous work [19], where we analyzed only a single (typical) parameter configuration for UAVs using the awareness use case in the artificial scenario. In contrast, in this paper we explore different parameter spaces for UAVs in full detail using two scenarios and investigate different optimized configurations. Furthermore, we extend our prior research by introducing and assessing the channel access use case.

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.
- We show that an opportunistic coordination of transmission times of multiple platoons by UAVs can lead to a reduction of approx. 86 % regarding the packet collisions at urban intersections.

2. Related Work

Related work proposes a wide range of work in which UAVs are used as part of wireless networks [20]. Many publications focus on a dedicated use of UAVs to support a particular mission or on the prediction of flight trajectories or positions to best fulfill a mission. This is done to enable ground nodes, especially vehicles, to use UAVs as a repeater or as a flying data storage [21, 22, 23]. However, there is only little to no related work proposing an opportunistic utilization of UAVs.

Hadiwardoyo et al. [24] developed a positioning technique for UAVs to establish a Line-of-Sight (LOS) wireless link between vehicles on the ground and UAVs in the air. The authors also consider irregularities on the ground, such as bumps or elevations in the landscape. Using simulations, they show that their approach can provide and maintain an LOS link between vehicles and a UAV. However, the approach uses UAVs explicitly for this purpose and does not utilize existing UAVs. In contrast, we base our approach on opportunistic relaying that does not require additional deployment costs or changes to the primary UAV mission.

Further work by Hadiwardoyo et al. [25] 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.

Liu et al. [26] use a dynamic hierarchical game model to address the problem of UAV selection, time allocation, and multi-channel access. Using simulations, the authors show that the presented approach performs better than comparable solutions in terms of the achieved data rate. The cornerstone of this work is a strong adaptation of the UAV towards the requirement of the communication partners.

Weisen et al. [27] propose a UAV-assisted framework to connect UAVs with vehicular networks on the road. The framework supports 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 using the proposed framework decreases average delay while increasing throughput. However, the work requires a dedicated deployment of UAVs and does not use existing UAVs in the air.

Liu et al. [7] present different opportunistic transmission models and corresponding application scenarios for UAVs. Besides that, the authors show that the average data rate of a network can be increased for delay-tolerant users, but also the amount of collected data gathered by a large number of UAVs is increased. The purpose of the presented work is to collect data from sensors during a mission and deliver it to a central entity. Our work, in contrast, focuses on local exchange of information between vehicles using a sporadic UAV. However, the work shows clear research directions for future work regarding the use of UAVs for opportunistic relaying.

Related work regarding the interaction between UAVs and platoons is still limited.

Liu et al. [28] present a scenario where a UAV assists a moving platoon with computation capacity as a kind of a mobile edge cloud. The evaluation of this work is strongly related to the UAV's energy aspects and to the offloading of computational efforts to the UAV. The work assumes UAVs that are explicitly deployed for this use case where our work uses opportunistic UAVs to improve the reliability of communication in scenarios with multiple platoons.

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. Many approaches show a clear positive impact regarding 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 straightforward settings or, indeed, not at all. This is especially true of the combination of platoons and UAVs, which to our knowledge, has not yet been a subject of any research.

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 first analyze four different UAV properties on cooperative awareness in two different urban scenarios and assume no more than a purely random, immutable flight route for UAVs. Second, we investigate whether and to what extent UAVs can contribute to low-collision communication in situations with multiple platoons in an urban environment.

3. Opportunistic Relaying

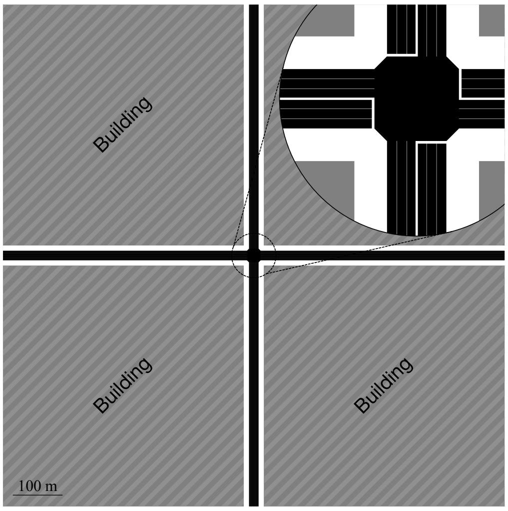
In preliminary work [19], we investigated the effects of exploiting randomly passing UAVs at an urban intersection to improve awareness of vehicles on the ground. We showed that such a system can increase the number of perceived vehicles by about 5 percentage points (% points). However, we considered only a 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 strongly impact 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 [7] that follow 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.

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:



(a) artificial scenario

(b) Luxembourg scenario

Figure 2: Our evaluation includes two scenarios. The first scenario is an artificial, symmetric four legged intersection of roads with 3 plus 3 lanes, surrounded by fully opaque buildings. The second scenario is a real world scenario: the intersection of Boulevard Grande-Duchesse Charlotte and Avenue Monterey in the center of Luxembourg.

- 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 fly in a straight line that passes by the center of the intersection at a normally distributed distance. We vary its standard deviation.

We employ computer simulations based on the popular open-source vehicular network simulator Veins [29], coupling the OMNeT++ INET Framework for modeling wireless networking with SUMO [30] for modeling road traffic.

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 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)	$52\,\text{s} = 2 \times (15\,\text{s} + 2 \cdot 3\,\text{s} + 5\,\text{s})$
Cycle time (LuST)	$96\,\text{s} = 2 \times (30\,\text{s} + 2 \cdot 4\,\text{s} + 10\,\text{s})$

Table 1: Common parameters of the simulation scenarios.

We are using two different scenarios to evaluate the impact of opportunistic UAV relaying. 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 toward the intersection. Thus, transmissions from vehicles partly already reach UAVs and vice versa.

The first scenario is an artificial intersection with four legs (500 m each) that is surrounded by buildings, sketched in Figure 2a. It is the same scenario we used in our preliminary work [19]. 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 (radio signals are unable to penetrate walls, resulting in complete signal loss) . Vehicles are not blocking radio transmissions. Vehicles are spawning at a rate of 0.25 veh/s at the end of each leg 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). A static traffic light program controls the intersection.

The second scenario is a section of the city of Luxembourg, extracted from the SUMO LuST scenario [31]. 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 2b. The configuration of radio shadowing, traffic volume, and turn directions are identical to the first scenario.

Table 1 summarizes the most important parameters regarding road networks in the simulation study. The parameterization

Parameter	Value
Technology	IEEE 802.11p
Carrier Frequency	5.89 GHz
Bit rate	6 Mbit/s [32]
Transmit power	20 mW [3]
Beacon interval (vehicles)	0.1 s
Beacon interval (UAVs)	0.5 s
Path loss (Friis model)	$\alpha = 2$
Shadowing	fully opaque buildings

Table 2: Wireless network simulation parameters.

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

Table 3: Common parameters for UAV simulation (unless otherwise specified for experiments).

relies on data obtained from related work (e.g., duration of traffic light phases), on default parameters obtained by the used simulators (e.g., σ), or those specified by legal regulations (e.g., speed limits).

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 2 summarizes the most important parameters for wireless communication in our simulation study. The parameterization relies on data obtained from related work and those specified by legal regulations.

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 a ROI of 90 m around the center of the intersection (i.e., those which might be relevant for realizing an intersection collision avoidance application). Figure 1 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.

Table 3 summarizes the most important parameters used for UAVs in the simulation study. Though our findings are not expected to be sensitive to the choice of these parameters, we list them for documentation purposes.

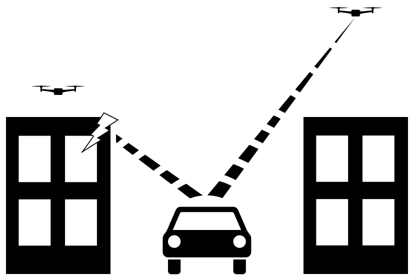


Figure 3: Illustration of shadowing effects by buildings: A higher flight altitude decreases shadowing, but, at the same time, also decreases received signal strength of transmissions.

4. Impact of Primary Mission on Opportunistic Relaying

Our preliminary work [19] investigated the influence regarding the awareness of the vehicles on the ground for a single parameter combination (using a single value for flight altitude, speed, and flight route from the literature). However, different properties of the primary mission 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.

4.1. UAV altitude

In urban areas, radio shadowing by buildings is often a problem for both road traffic [16] and UAVs [33]. Figure 3 illustrates the effects of the flight altitude on the LOS to vehicles on the ground. If the altitude of a UAV is too low, buildings strongly influence 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-LOS conditions: Considering only the path loss, it becomes apparent that the received power decreases with the square of the distance. Thus, it is not possible to let a UAV fly at an arbitrarily high altitude in an effort to reach as many vehicles as possible in an urban area [34]. We, therefore, study the effect of the UAV 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 different heights) for the artificial 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 reduction 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

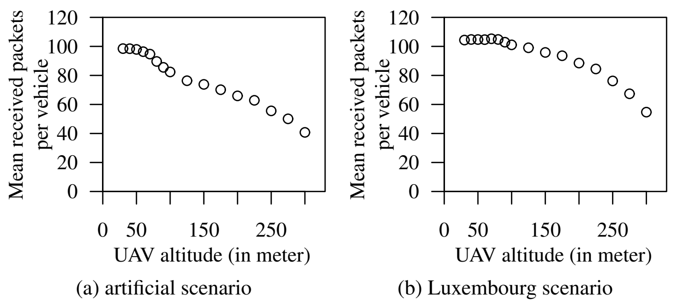


Figure 4: Number of packets received by vehicles from a UAV that is statically hovering above the center of the intersection, depending on hover height. As the altitude increases, the number of packets received decreases. The reason for this is the path loss, which increases quadratically with distance.

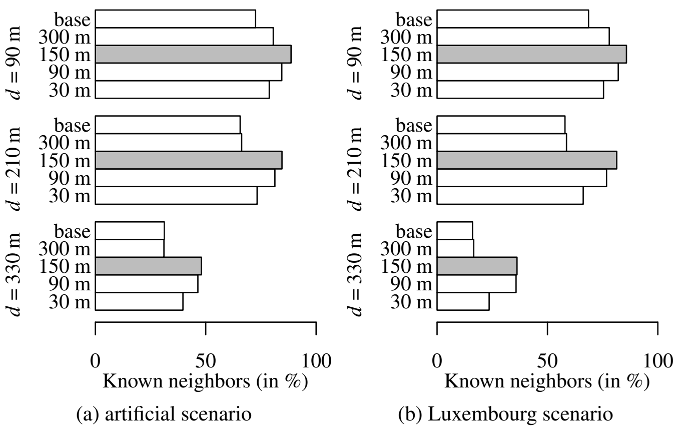


Figure 5: Relative proportion of vehicles known to the ego vehicle, depending on UAV altitude and plotted for different distances d of the ego vehicle to the center of the intersection. The proportion of known neighbors shows an optimum at a flight altitude of about 150 m to 175 m (data not shown). The 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.

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. 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 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 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 quantitative effects are 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 to rises. 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. However, even the scenario with the highest altitude (300 m) achieves better results (approx. 9 % points) than the scenario without any UAV.

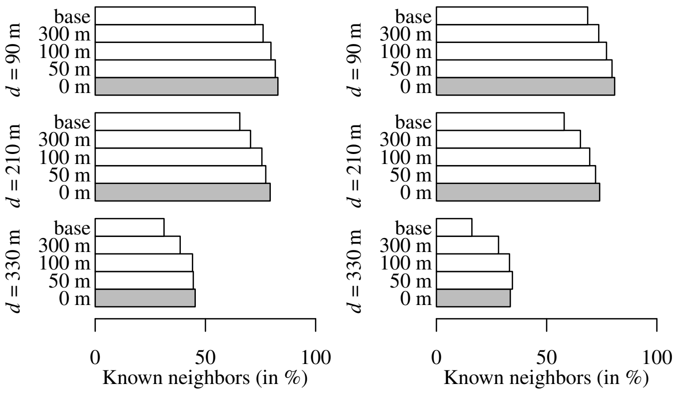
Based on our data, it cannot be concluded that a UAV should fly as high as possible to get a better LOS on the roads. Rather, the optimum is a medium flight altitude.

4.2. *UAV flight route*

The flight route of a UAV impacts 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.

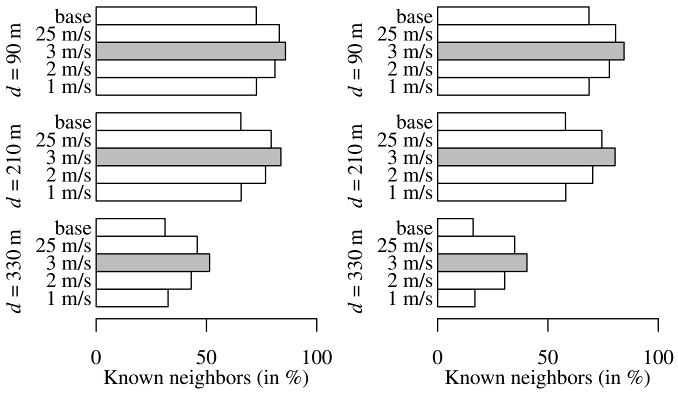
For this and the following experiments, we thus let UAVs fly over the scenario at a normally distributed random distance from the center of the intersection. We perform a parameter study regarding the standard deviation of the distance towards the center of the intersection, starting at 0 m distance 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 an 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 far from the center of the intersection. Since UAVs are not necessarily directly above the intersection area but perhaps only fly over one leg of the intersection, such a trajectory can only detect a fraction of the vehicles on the ground. Consequently, the relative number of perceived



(a) artificial scenario (b) Luxembourg scenario

Figure 6: Like Figure 5, but showing the impact of 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.



(a) artificial scenario (b) Luxembourg scenario

Figure 7: Like Figure 5, but showing the impact of 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).

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 shapes 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 an LOS connection to the legs 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 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. Complex algorithms and protocols might not necessarily be required to achieve this. We come back to this hypothesis later in this study.

4.3. 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 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 3). If a spawn interval is used for UAVs and UAVs are configured to move with a very low speed, this will lead to an extreme increase in 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 due to the channel load), but this is not a realistic scenario. Therefore, the number of UAVs is kept constant (10 UAVs) for this parameter study.

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

Our data shows that the lowest speed (1 m/s) has the smallest effect on the chosen metric. Simulations show that there is only a negligible effect on the used metric at this speed, 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 an 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 can 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 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 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 flyover time 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 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.

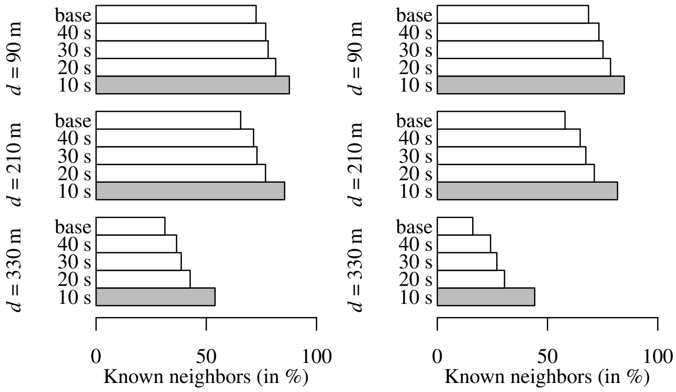
In the end, the data for the artificial and the realistic scenario shows that the speed has no substantial influence on the awareness, provided it has reached a certain minimum. At high speeds (35 m/s, data not shown), the difference to the optimal case in our experiments is only approx. 3 % points lower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

4.4. *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



(a) artificial scenario (b) Luxembourg scenario

Figure 8: Like Figure 5, but showing the impact of 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 can occur.

well. This is the case for both scenarios. Accordingly, as the frequency of the flyovers is 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.

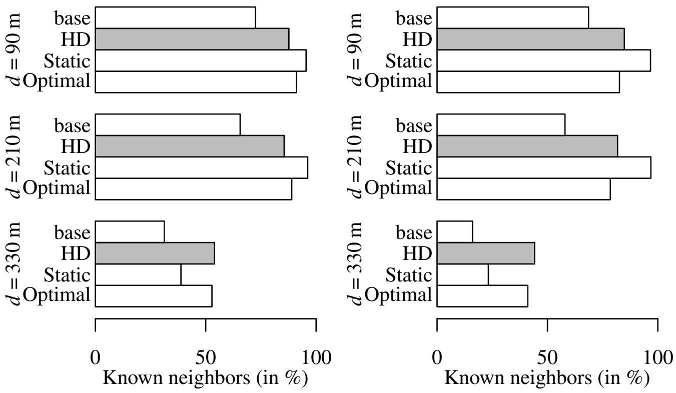
From the viewpoint of our metric, it would be desirable if as many UAVs as possible are active in the scenario, as long as the wireless channel is not too heavily loaded. In our case, the average channel busy ratio in the center of the intersection is approx. 17 % on average. Accordingly, there is still 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).

4.5. *Optimal Primary Mission vs. Increased Density*

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).

Then, 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



(a) artificial scenario

(b) Luxembourg scenario

Figure 9: Like Figure 5, but comparing different scenarios. Purely opportunistic relaying (labeled as HD) yields comparable performance to deploying UAVs for optimal missions (albeit at moderately higher UAV density), particularly for higher distances d.

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 also 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.

5. Opportunistic Channel Access Control for Urban Vehicular Networks

We now turn to another use case of UAVs as opportunistic airborne virtual network infrastructure: supporting channel access control.

Platooning is an application considered particularly safety-critical and for which communication is essential [3]. To improve the system's reactivity, vehicles in a platoon must share real-time data about their current vehicle dynamics. Without reliable communication, this data is missing as input for the CACC, which drives the vehicle based on this input data. This situation can lead to severe consequences regarding the safety and stability of a platoon [35].

Related work proposes different strategies to improve the reliability of communication. Traditional approaches often rely on *static beaconing*, where vehicles transmit platooning beacons with a fixed frequency of usually 10 Hz [36]. Such approaches have a severe drawback since they operate based on a fixed and static timing: If two vehicles transmit simultaneously, all transmissions from these two vehicles will collide, and safe driving is no longer possible.

A common approach to improve communication within a platoon is the *slotted beaconing* protocol [37]. The idea of this protocol is that all vehicles in the platoon synchronize to the leader's transmission time of a platooning beacon. Based on the reception time of the leader's platooning beacon, a platoon member calculates its transmit time depending on its relative position within the platoon, the leader's transmission time, and the desired interval between two beacons sent by the same member (usually 10 Hz [36]). This dedicated slot for each vehicle prevents two vehicles within the same platoon from transmitting simultaneously. However, an inter-platoon synchronization mechanism is not provided: If several platoons are in the same collision domain, this protocol does not prevent collisions if vehicles from different platoons transmit simultaneously.

Since using purely-opportunistic UAV relays for the use case of cooperative awareness applications in vehicular networks has proven to be very promising (cf. Sections 3 and 4), we now investigate potential uses of such opportunistic airborne virtual network infrastructure also for the use case of supporting channel access.

Since UAVs in the air can detect the periodic platooning beacons of leader vehicles on the ground, they can use this information to predict future packet collisions due to the periodic and foreseeable transmission behavior of *slotted beaconing*. With this, UAVs can coordinate the transmission times of vehicles in different platoons so that the number of packet collisions is reduced. We note that, while this study assumes that communication within a platoon is realized by the *slotted beaconing* protocol, our approach applies to any other protocol where future transmission times can be predicted.

We focus on platooning in urban areas because of the more complex communication requirements due to buildings and other characteristics [15], but also because of the likely use of a high number of UAVs in future smart cities [7].

5.1. Inter-Platoon channel access coordination with UAVs

The leading vehicle uses static beaconing with a frequency of 10 Hz. The transmission time t_i of a vehicle in the platoon is based on the vehicle's position i, reception time t_0 of the platooning beacon from the leader, the total number of vehicles $|v|$ in the platoon, and the interval of platooning beacons T (here: 100 ms corresponding to 10 Hz). Based on this information, the slotted beaconing protocol calculates the transmission time of a vehicle as

$$t_i = t_0 + i\,T\,|v|^{-1}. \tag{1}$$

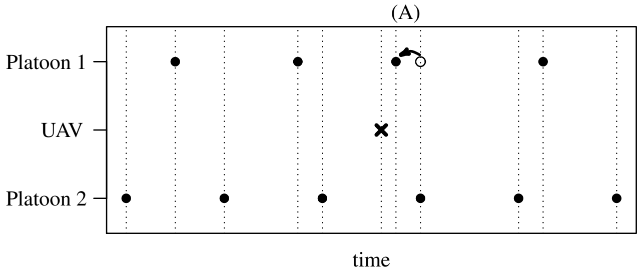


Figure 10: Transmission times of vehicles in two platoons (black dots) and of a UAV overhearing beacons from both (black X). Even though the leading vehicles transmit at different times, the third vehicle of platoon 1 and the fourth vehicle of platoon 2 calculate identical transmission times. This would lead to a packet collision. Since the UAV detects this, it can advise the third vehicle in platoon 1 to slightly shorten its inter-beacon interval, marked as *(A)*. This successfully avoids the packet collision.

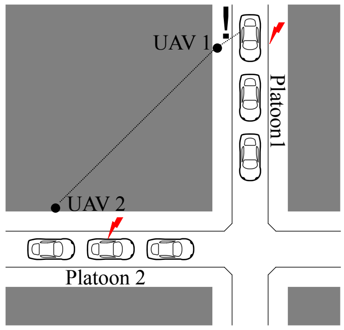


Figure 11: Illustration of target use case. Here, two platoons are driving on two different legs of the intersection. One UAV happens to cover one platoon each. Due to the shared knowledge, the UAVs can detect a future collision in channel access and can advise individual platoon members of the need to selectively shorten a beacon interval.

Parameter	Value
Platooning simulation model	Plexe 3.1
CACC implementation	PATH controller [38]
CACC desired gap d_d	5 m
CACC bandwidth ω_n	1 Hz
CACC damping ratio ξ	2
CACC weighting factor C_1	0.5
platooning beacon packet size	200 Byte

Table 4: Common parameters to simulate platooning.

The slotted beaconing protocol ensures collision-free communication within a platoon but not between multiple platoons. In multi-platoon scenarios, it can therefore happen that two vehicles calculate identical transmission times.

To prevent this situation, we propose an *inter-platoon synchronization* mechanism using randomly passing UAVs as opportunistic infrastructure. For this, neighboring UAVs use the received beacons from platoon vehicles to generate a local overview of predicted platooning beacon times. This overview is based on the received platooning beacons of leading vehicles since the corresponding calculation of slots for the remaining platoon vehicles can then be performed and stored by the UAVs without needing to receive further transmissions from these vehicles.

When a leader's platooning beacon is received by a UAV (or after a timeout of 0.1 s), a UAV checks if at least two vehicles will transmit a platooning beacon at the same time (and thus might cause a collision). If this is the case, an earlier transmission time for one of the two vehicles where no other transmission is yet taking place is identified. We only allow earlier times so that the maximum interval of 100 ms (10 Hz) between two transmissions remains unchanged [36]. The UAV then transmits the new desired transmission time to the corresponding vehicle wirelessly, which can adapt its transmission time.

We leave extended mechanisms (e.g., those that reschedule leader beacons as well) and permanent changes in scheduling as future work and concentrate only on the broader use case of changing individual transmissions. We do, however, enable neighboring UAVs to share information regarding future transmissions with each other. The message containing the new transmission time for a vehicle, however, is only sent by the UAV with the smallest Euclidean distance to this vehicle.

Figure 10 illustrates our scheme using the example of two platoons with 6 and 4 vehicles, respectively. Here, due to the calculations in Equation (1), the third and fourth vehicle of platoon 1 and 2, respectively, are both scheduled to transmit a beacon at the same time. Since the vehicles are transmitting platooning beacons with a fixed frequency of 10 Hz, this scheduling will result in packet collisions for the respective vehicles. This is detected by a UAV in range which sends an adjustment packet to the offending vehicle, causing it to slightly shorten its beacon interval at the time marked *(A)*.

Figure 11 further illustrates this behavior. Here, the third vehicle from platoon 1 and the second vehicle from platoon 2 would transmit a platooning beacon at the same time. UAV 1 and UAV 2 are situated above the surrounding buildings in the air, maintaining an LOS connection to each other. By exchanging locally acquired information, they can construct a comprehensive scenario wide view of the intersection and its vehicles on the ground, thus enabling them to detect potential wireless collisions. Next, one of the two UAVs is randomly selected. This UAV transmits a request (to change the transmission time of the next platooning beacon) to the third vehicle in the platoon. Upon reception, this vehicle changes its own transmission time, thus avoiding a collision in the next transmission slot. This way, a collision can be avoided when both platoons reach the center of the intersection (the same collision domain).

5.2. Experimental Setup

We investigate the effect of our approach using computer simulations. As for our previous study, we base this on OMNeT++, Veins, and Sumo and all parameters for the road traffic simulation, wireless communication, and UAVs are the same as in Section 3.

To simulate platooning, we additionally employ the Plexe [39] simulation module library for Veins. We configure vehicles to use the PATH [38] CACC as it is one of the most used CACCs in the literature [4]. Table 4 summarizes the parameters used for Plexe. To generate road traffic, we create complete platoons at the outer end of the scenario. Platoons have a size that is

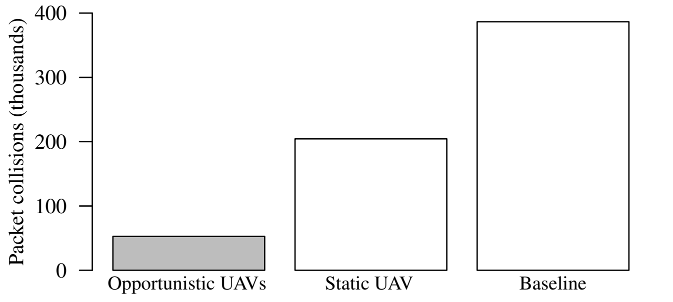


Figure 12: Mean number packet collisions for all platoons. The *Opportunistic UAVs* scenario far outperforms the *Static UAV* and the baseline scenario.

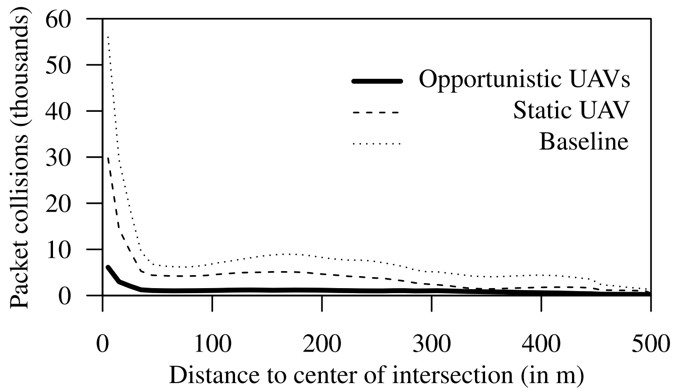


Figure 13: Packet collisions for all platoons. The *Opportunistic UAVs* approach keeps the number of collisions low in the center and on the legs of the intersection.

uniformly distributed between 3 and 10 vehicles. We spawn new platoons with a random route every 10 s to 15 s. We focus only on the artificial scenario since the differences to the Luxembourg scenario are negligible. We perform 15 independent runs for statistical confidence and collect data for 500 s after the transient phase at the beginning of each simulation.

To quantify the effect of our approach, we record the total number of collisions during the simulation and compare three different UAV scenarios:

1. **Opportunistic UAVs:** UAVs are spawned with an inter-arrival rate of 10 s, the rate which proved to be the most beneficial for the cooperative awareness use case.
2. **Static UAV:** A single static UAV is hovering above the center of the intersection. The UAV in this scenario has a perfect view into all legs of the intersection and thus also mimics the case of ideally pre-deployed static infrastructure per intersection.
3. **Baseline:** No UAVs are available. We use this scenario as a reference for the other two scenarios.

5.3. Performance Study

Figure 12 shows the mean number of packet collisions over all simulation runs for all three scenarios. We do not show confidence intervals since they are negligibly small.

Our data shows that the *Opportunistic UAVs* approach achieves the greatest effect. Compared to the baseline scenario, the total number of packet collisions is reduced by almost 86 %. In comparison, the idealized *Static UAV* approach results in only a reduction of approx. 47 % compared to the baseline scenario.

Several reasons may exist for the reduced performance of the *Static UAV* approach. First, in the *Opportunistic UAVs* scenario, multiple UAVs can collect, aggregate, and share data as opposed to only a single UAV. Second, at the center of the intersection, the static UAV is completely surrounded by buildings and thus more likely to be impacted by hidden terminal problems, leading to further packet loss [15]. Lastly, compared to multiple mobile UAVs, the single static UAV is likely to be further away from both the platoon members it must receive data from and those it might need to transmit data to. All of this gives *Opportunistic UAVs* an edge over *Static UAV* deployment.

Figure 13 shows the packet collisions as a function of the distance toward the center of the intersection. The classic hidden terminal problem is visible in the results from the *Static UAV* and the baseline scenario, which also lead to more collisions on the legs of the intersection. On the other hand, the *Opportunistic UAVs* approach maintains a low level of packet collisions and thus enables safe platooning in an urban environment.

Our data thus clearly shows that opportunistic use of UAVs for supporting channel access can improve communication for platoons and reduce the number of collisions when multiple platoons drive in the same collision domain. Again, this benefit is achieved without affecting the primary mission of UAVs. Thus, the demonstrated added value is reached without additional cost, without a dedicated deployment of UAVs, and without the need to install additional infrastructure such as RSUs.

6. Conclusion

In this work, we studied the impact of opportunistic airborne virtual network infrastructure on urban wireless networks. For this, we used Unmanned Aerial Vehicles (UAVs) flying random, arbitrary missions and analyzed two different use cases:

First, we examined the effects of UAVs being used as relays for cooperative awareness applications in vehicular networks.

Second, we investigated how UAVs can opportunistically coordinate channel access for urban vehicular networks to reduce packet collisions.

To gauge the benefit of the first use case, 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 optimal missions.

For the second use case, opportunistic channel access control, we considered urban platooning as an example application that requires particularly reliable communication for stable operation. We compared our approach to a baseline scenario where no UAVs are used and to a scenario using a static, single UAV. We were particularly interested in how opportunistic coordination by UAVs compares to that by a static, optimally positioned UAV.

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 for opportunistic relaying. On the other hand, suboptimal altitudes of opportunistic relays 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. Moreover, the impact of suboptimally-positioned relays on system performance can be recovered simply by moderately increasing the number of UAVs flying arbitrary missions.

We further showed that UAVs can indeed be used to opportunistically coordinate channel access and substantially reduce the number of packet collisions in urban vehicular networks: In our scenarios, we reduced the number of collisions by approx. 86 % compared to a scenario where no UAV is available, thus resulting in increased road safety. Moreover, while a single, statically positioned UAV – a model for local infrastructure such as a Roadside Unit (RSU) – can have positive effects locally, the opportunistic UAV approach performs substantially better.

Finally, we stress that, in all studies, we did not require that UAVs alter either trajectory nor speed to opportunistically serve as virtual network infrastructure. Thus, other than is the case with dedicated deployments of UAVs or when installing additional infrastructure for V2X, the demonstrated added value manifests at no additional cost except that spent for transmitting network packets.

In addition to the contributions of the present study, several opportunities exist for future research to expand upon our findings and advance the knowledge base in this domain.

First, our opportunistic channel access coordination approach can be extended to achieve a permanent change in scheduling or a mechanism that reschedules the leader beacon.

Second, field tests of either proposed methodology in a dense urban area would be of great interest, particularly in light of complex building shapes and additional signal reflections within urban environments.

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