On the Impact of Wireless Communication on Cooperative UAV Collision Avoidance

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***Abstract*—Aerial base stations mounted on Unmanned Aerial Vehicles (UAVs) enable rapidly deployable coverage. However, coordinating multiple UAVs in a shared airspace requires reliable communication, e.g., using UAV-to-UAV communication for collision avoidance. Although IEEE 802.11p and 5G NR-Vehicle-to-Everything (V2X) sidelink are well-established in vehicular networks, their suitability for UAV use cases remains largely unexplored. In this work, we combine a force-field collision avoidance algorithm with a geometric imminent-collision fail-safe and extend it to cover static obstacles and wind disturbances. We evaluate the algorithm using IEEE 802.11p and 5G NR-V2X sidelink (Mode 1). Through computer simulations, we demonstrate that in an open area no UAV collisions occur with either technology. Although the packet delivery ratio (PDR) for IEEE 802.11p decreases for a larger number of UAVs, the performance of our collision avoidance algorithm remains unchanged. On the other hand, 5G device-to-device (D2D) shows lower resource utilization which provides resources for future applications. In contrast, in an urban scenario, a few UAV collisions occur due to communication failures. They are caused by hidden terminal interference for IEEE 802.11p or blockage of the direct link between a UAV and the Next-Generation Node B (gNB). Further, collisions with obstacles occur at a speed of 10 m/s for both technologies. These collisions are primarily caused by limited braking and turning capabilities of UAVs. Our evaluations demonstrate that both technologies support cooperative collision avoidance, while safety is primarily limited by communication availability and UAV maneuverability.**

***Index Terms*—Unmanned aerial vehicle (UAV), collision avoidance, vehicle-to-everything (V2X), IEEE 802.11p, 5G NR-V2X**

I. Introduction and Related Work

Unmanned Aerial Vehicles (UAVs) are increasingly considered as mobile components of future communication networks. Equipped as aerial base stations or relays, they can provide on-demand coverage, extend existing networks, and provide rapidly deployable coverage in emergency situations and areas with temporarily high traffic demand [1]. Deployments comprising multiple aerial base stations can further increase the covered area and serve spatially distributed users [2]. The operation of such aerial wireless communication networks requires the UAVs to be deployed and to reposition themselves safely within the shared airspace. In this setup, wireless communication serves two purposes: providing connectivity to ground users and enabling cooperative collision avoidance among the UAVs.

Direct UAV-to-UAV communication allows low-latency exchange of mobility information required for autonomous collision avoidance [1]. Moreover, this information must be delivered reliably and in time to detect conflicts and initiate avoidance maneuvers.

In general, collision avoidance has a long history in the context of vehicular communication, where vehicles exchange mobility information for coordination with IEEE 802.11p and Cellular Vehicle-to-Everything (V2X) being established communication technologies in that domain [3]. However, to the best of our knowledge, these technologies have not been studied in depth for cooperative aerial systems yet. In the following, we review related work on coordination mechanisms and communication protocols that enable cooperative collision avoidance in aerial systems.

Today, conventional aviation typically employs Traffic Alert and Collision Avoidance System II (TCAS II) and Automatic Dependent Surveillance–Broadcast (ADS-B), both of which rely on information exchange. TCAS II detects collision threats and can coordinate complementary vertical resolution advisories between aircraft. Since these advisories are designed for pilot execution, the system requires adaptation for autonomous small UAVs. ADS-B broadcasts aircraft state information but may suffer from message collisions in dense airspaces [4].

Schalk and Becker [5] propose DroneCAST as a decentralized device-to-device (D2D) communication and surveillance system for urban airspace. They derive communication requirements for collision avoidance and review IEEE 802.11p, IEEE 802.11bd, LTE C-V2X, and NR C-V2X as potential PHY foundations based on existing studies. In a follow-up study, Becker and Schalk [6] implement a dedicated DroneCAST physical layer and evaluate it using simulations of urban D2D channels. Their results show that dual-carrier modulation reduces the packet error rate, but nearly doubles the message duration. Based on link-level analysis, they derive a candidate OFDM parameter set for DroneCAST. DroneCAST and our work share the objective of enabling cooperative UAV collision avoidance through reliable D2D exchange. DroneCAST evaluates a dedicated physical layer at link level. In contrast, we integrate IEEE 802.11p and 5G NR-V2X sidelink using Mode 1 resource allocation (5G D2D) and evaluate their performance on our UAV collision avoidance algorithm.

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IEEE International Conference on Computing, Networking and Communications (ICNC 2027), CNC Workshop

Further, Casas and Mitschele-Thiel [7] present a self-organized collision avoidance algorithm in which UAVs exchange flight information and form virtual roundabouts. They analyze how packet loss affects UAV collision avoidance but do not evaluate specific V2X technologies. Our algorithm extends their risk-based force-field by replacing the virtual roundabout with an imminent-collision fail-safe, and extends the force-field to static obstacles.

As a feasibility study, we quantitatively compare IEEE 802.11p and 5G D2D in terms of packet delivery ratio (PDR), channel utilization, collision safety, and flight efficiency.

Our main contributions can be summarized as follows:

- We combine the force-field cooperative UAV collision avoidance of Casas and Mitschele-Thiel [7] with an imminent-collision fail-safe based on the geometric prediction method of Park et al. [8] and extend the resulting algorithm to account for static obstacles and wind-induced deviations.
- We develop a UAV simulation framework with a mobility model applying flight measurements from [7]. The framework includes stochastic wind disturbances and a unified Line-of-Sight (LOS)/Non-Line-of-Sight (NLOS) propagation abstraction for both communication technologies.
- We evaluate IEEE 802.11p and 5G D2D for cooperative collision avoidance of UAVs in urban and open-area scenarios, giving an outlook on operational limits with respect to UAV density and speed.

II. Our Collision Avoidance Algorithm

The collision avoidance algorithm runs distributed on each UAV. Each UAV periodically broadcasts its current position and three-dimensional velocity vector, together with the corresponding generation timestamp. We assume that the clocks of all UAVs are synchronized, e.g., by using GPS.

Further, we extend the force-field algorithm of Casas and Mitschele-Thiel [7] by considering static obstacles and wind disturbances and combine it with the geometric collision prediction of Park et al. [8]. The force-field component adjusts the trajectory by combining attraction toward the next waypoint with repulsion from neighboring UAVs or static obstacles. The geometric component then predicts whether the adjusted trajectories still lead to a collision. If so, the UAV reduces its speed and, if necessary, changes altitude.

A. Force-Field Guidance

The force-field component is based on the risk model of [7]. The next waypoint acts as an attractive force, while neighboring UAVs generate repulsive forces. We extend the approach by also considering static obstacles as repulsive forces. The sum of these forces determines the new horizontal flight direction.

A neighboring UAV or obstacle generates a repulsive force within the reaction distance (d_{reaction}). We extend the reaction distance of [7] by a speed-dependent safety distance and a tolerance for wind disturbances:

$$d_{\text{reaction}} = d_{\text{safety}} + d_{\text{msg}} + d_{\text{brake}} + d_{\text{GPS}} + d_{\text{tol}}. \tag{1}$$

Unlike the fixed safety distance proposed in [7], we calculate the safety distance (d_{safety}) from the current speed v:

$$d_{\text{safety}} = \begin{cases} 1\,\text{m} + d_{\text{UAV}}, & \text{if } v < \dfrac{1\,\text{m} + d_{\text{UAV}}}{1\,\text{s}}, \\ v \cdot 1\,\text{s}, & \text{otherwise.} \end{cases} \tag{2}$$

Here, d_{UAV} denotes the UAV diameter. For simplicity, we require a minimum distance of $1\,\text{m}$ between the surfaces of two UAVs. The remaining speed-dependent components are:

$$d_{\text{msg}} = 2v\Delta t_{\text{b}}, \qquad d_{\text{brake}} = 2\frac{v^2}{2a}, \qquad d_{\text{tol}} = v \cdot 1\,\text{s}, \tag{3}$$

where Δt_{b} denotes the beacon interval and a denotes the magnitude of acceleration and deceleration. The definitions of d_{msg} and d_{brake} follow [7], but we calculate the braking distance assuming constant deceleration. The factors of two in d_{msg} and d_{brake} account for a head-on encounter between two UAVs traveling at the same speed v. We assume a GPS uncertainty (d_{GPS}) of $2\,\text{m}$, as outlined in [7]. We conservatively set the wind tolerance (d_{tol}) to the distance traveled within one second. In contrast to Casas and Mitschele-Thiel [7], we calculate the reaction distance using the current speed instead of the maximum speed. This allows the reaction distance to adapt when the UAV decelerates and avoids unnecessarily large trajectory changes at lower speeds.

Every $0.1\,\text{s}$, each UAV extrapolates the neighbor's current position from the most recent beacon, assuming constant velocity. For a neighbor i within d_{reaction}, the distance d_i to its estimated position determines the collision risk and thus the magnitude of the repulsive force. Consequently, based on [7], the collision risk is defined as

$$f_{\text{risk}}(x_i) = -x_i^2 + 1 \tag{4}$$

with the normalized distance

$$x_i = \frac{d_i - d_{\text{safety}}}{d_{\text{reaction}} - d_{\text{safety}}}. \tag{5}$$

We limit x_i to $[0, 1]$, resulting in a risk of zero at the reaction distance and one at the safety distance.

Each neighbor exerts a repulsive force directed towards the receiving UAV, with magnitude $f_{\text{risk}}(x_i)$. We sum these forces into $\overrightarrow{F_{\text{ext}}}$.

We extend [7] to static obstacles by calculating repulsive forces based on their closest boundary points. We sum these forces into $\overrightarrow{F_{\text{obs}}}$.

Together with the attractive force $\widehat{F_{\text{goal}}}$ towards the next waypoint, the resulting force is

$$\overrightarrow{F_{\text{result}}} = \widehat{F_{\text{goal}}} + \overrightarrow{F_{\text{ext}}} + \overrightarrow{F_{\text{obs}}} \tag{6}$$

The normalized resulting force ($\overrightarrow{F_{\text{result}}}$) determines the direction of a new avoidance waypoint, whose distance increases

with UAV speed. Without repulsive forces, the UAV continues towards its original waypoint.

When multiple UAVs interact, forces may cancel each other out or produce unsafe directions. While [7] use virtual roundabouts to resolve such conflicts, our algorithm activates an imminent-collision fail-safe.

B. Imminent-Collision Fail-Safe

Based on the geometric approach by Park et al. [8], the fail-safe checks whether the trajectories from the force-field guidance lead to insufficient separation. Assuming constant velocities, it predicts the time of closest approach for each neighboring UAV:

$$\tau_i = -\frac{(\mathbf{p}_i - \mathbf{p}) \cdot (\mathbf{v}_i - \mathbf{v})}{(\mathbf{v}_i - \mathbf{v}) \cdot (\mathbf{v}_i - \mathbf{v})} \tag{7}$$

Here, $\mathbf{p}$ and $\mathbf{v}$ denote the ego UAV's position and velocity, and $\mathbf{p}_i$ and $\mathbf{v}_i$ denote those of neighbor i. We skip neighbors with zero relative velocity or $\tau_i < 0$.

Otherwise, the predicted minimum separation is

$$d_{\text{min},i} = \|(\mathbf{p}_i - \mathbf{p}) + \tau_i(\mathbf{v}_i - \mathbf{v})\| \tag{8}$$

We consider a collision imminent if the predicted minimum separation distance $d_{\text{min},i}$ is below d_{safety} and the current distance d_i is below d_{imminent}. The latter is defined as

$$d_{\text{imminent}} = d_{\text{safety}} + d_{\text{brake}} + d_{\text{tol}} \tag{9}$$

The second condition limits the fail-safe to conflicts that require immediate action. If a collision with another UAV is imminent, the ego UAV first decelerates and, if necessary, changes altitude by climbing or descending, as in manned aviation [8]. Deceleration alone may resolve the conflict because a lower speed improves maneuverability. To prevent both UAVs from performing conflicting vertical maneuvers, only the UAV with the larger identifier changes altitude.

The maneuver ends once sufficient horizontal or vertical separation has been re-established. This also allows the UAV to resume its mission when the conflict is resolved through deceleration.

Static obstacles are handled by a separate geometric check. Since the force-field guidance may change the flight direction, the check considers a range of possible trajectories instead of only the current trajectory. If an obstacle conflict is detected, the UAV decelerates. If necessary, the UAV then climbs to avoid the obstacle, potentially passing over the building. Once the obstacle has been cleared, the UAV continues to its waypoint.

III. Evaluation

We conduct a simulation study to evaluate the proposed algorithm using IEEE 802.11p and 5G D2D.

Table I
Mobility parameters

Parameter	Value
Acceleration	$2\,\mathrm{m/s^2}$
Maximum angular velocity	$20\,^\circ/\mathrm{s}$
Desired speed	$\{1, 5, 10\}\,\mathrm{m/s}$
Mobility update interval	$0.1\,\mathrm{s}$
UAV diameter	$0.2\,\mathrm{m}$
Wind-noise variance	$0.16\,\mathrm{m^2/s^2}$

A. Simulation Setup

All simulation runs use the same UAV collision avoidance application and mobility model, while we use the *INET* framework of OMNeT++ [9] and *Simu5G* [10] to model wireless communication.

To provide comparable propagation conditions, we implement a LOS and NLOS abstraction. LOS links use free-space path loss, while buildings are fully opaque to wireless communication in the NLOS case. Both frameworks account for interference and antenna gains, while Simu5G additionally includes Jakes fading. This represents a conservative assumption, as reflections and diffraction may enable reception in real environments.

Moreover, we use a three-dimensional mobility model with bounded acceleration, deceleration, and angular velocity. The mobility parameters follow measurements of a small quadcopter reported by Casas and Mitschele-Thiel [7]. We additionally consider velocities up to $10\,\mathrm{m/s}$ to investigate the limits of collision avoidance under constrained maneuverability. Horizontal wind disturbances are represented by zero-mean white noise.

In Table I, we summarize the mobility parameters used throughout the evaluation. For each configuration, we conduct 50 independent simulation runs. Each run has a maximum duration of $120\,\mathrm{s}$, or $300\,\mathrm{s}$ for the Urban Intersection scenario.

Each UAV broadcasts a $190\,\mathrm{Byte}$ beacon every $100\,\mathrm{ms}$, corresponding to a beacon rate of $10\,\mathrm{Hz}$. This is a commonly used beaconing frequency in vehicular networks [11] for safety critical applications. Longer beacon intervals reduce the frequency of neighbor updates and may delay collision detection. Although our reaction distance accounts for the beacon interval, outdated information can still affect the collision avoidance. In contrast, shorter intervals increase the channel load and may cause more packet collisions which would also lead to outdated information. Thus, the beacon interval represents a trade-off between information timeliness and communication reliability.

Table II summarizes the PHY and MAC parameters used in our simulation models.

B. Evaluation Scenarios

We consider three evaluation scenarios.

a) Controlled Conflicts: The first scenario uses predefined trajectories that lead to collisions if no avoidance maneuver is performed. We verify the behavior of the collision

Table II
COMMUNICATION PARAMETERS

Parameter	IEEE 802.11p	5G D2D
Carrier frequency	5.9 GHz	5.9 GHz
Channel bandwidth	10 MHz	10 MHz
Transmit power	23 dBm	23 dBm
Data rate	6 Mbit/s	–
Detection threshold	−89 dBm	–
Resource blocks	–	52
Numerology	–	0
D2D CQI	–	7

avoidance algorithm under controlled conditions with two and four UAVs. We use this scenario to validate our collision avoidance algorithm and omit a detailed evaluation of the communication performance with this low number of UAVs.

b) Open-Area Random Waypoint: Each UAV repeatedly selects a random destination within the flight area, while the mobility model applies the constraints listed in Table I. We use a $40\,\mathrm{m} \times 40\,\mathrm{m}$ flight area and vary the number of UAVs from 10 to 80. We assess collision safety, flight efficiency, and communication performance at increasing UAV densities.

c) Urban Intersection: The third scenario represents an urban intersection surrounded by buildings. The mobility follows a constrained random scheme in which UAVs travel between opposite sides of the intersection. We investigate UAVs densities from 10 to 80. UAVs spawn sequentially at the four ends of the intersection. Occasionally, a UAV spawns directly in front of another UAV, leaving insufficient time for collision avoidance. Such collisions are excluded from the evaluation as initialization artifacts. We evaluate how restricted flight space and NLOS communication affect collision avoidance and communication performance.

C. Evaluation Metrics

For simplicity and space limitations, we report only the most important results of our simulation study. In general, we cover three evaluation dimensions: collision safety, flight efficiency, and communication performance.

Collision safety is measured by the *collision ratio*, defined as the fraction of simulation runs with at least one physical collision between two UAVs or between one UAV and a building.

Flight efficiency is characterized by the *mean distance traveled per UAV* and the *detour ratio*. The latter relates the additional distance caused by avoidance maneuvers to the total distance traveled.

Communication performance is evaluated using the *packet delivery ratio (PDR)*, i.e., the fraction of all potential beacon receptions that are successfully received, and channel utilization. Since IEEE 802.11p transmissions occupy the entire channel, we measure channel utilization as the fraction of time during which the channel is sensed busy. In contrast, 5G D2D can allocate different resource blocks to simultaneous transmissions, so we measure channel utilization as the fraction of allocated resource blocks. Both metrics reflect resource utilization of their respective MAC.

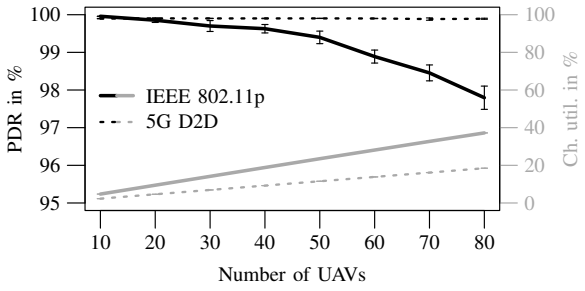


Figure 1. Performance for the *Open-Area Random Waypoint* scenario: PDR (black) and channel utilization (grey) for an increasing number of UAVs.

Communication metrics are omitted from the *Urban Intersection* scenario because the LOS/NLOS abstraction prevents reception whenever a building obstructs the direct path.

D. Results

The results are presented according to the scenarios introduced in Section III-B. In *Controlled Conflicts*, all predefined conflicts involving two and four UAVs are resolved without collisions, confirming the expected behavior under controlled conditions. In the *Open-Area Random Waypoint* scenario, no UAV collisions are observed. The collision ratio remains zero for both IEEE 802.11p and 5G D2D across all evaluated UAV densities and desired speeds.

Figure 1 presents the communication results for a desired speed of $1\,\mathrm{m/s}$. We omit the results at $5\,\mathrm{m/s}$ and $10\,\mathrm{m/s}$ as they are nearly identical and follow similar trends.

Channel utilization increases approximately linearly with the number of UAVs, because each UAV generates beacons at a constant rate. At 80 UAVs, the IEEE 802.11p channel is sensed as busy for 37.2% of the time, while 18.5% of the available 5G D2D resource blocks are allocated. Thus, 5G D2D shows lower resource utilization for the same beacon traffic, based on the different MAC mechanisms of both technologies. Although the IEEE 802.11p PDR decreases non-linearly, its channel utilization remains approximately linear. At the evaluated load, simultaneous transmissions occur too infrequently to noticeably affect this trend.

The increasing IEEE 802.11p channel load is accompanied by a reduction in PDR from 99.96% with 10 UAVs to 97.8% with 80 UAVs. As the number of contending nodes increases, multiple transmitters are more likely to complete their backoff simultaneously. This results in overlapping transmissions (i.e., frame collisions) and unsuccessful frame reception. In contrast, the configured 5G scheduler assigns separate resources to simultaneous D2D transmissions. Its PDR consequently remains close to 99.8% throughout the evaluated density range. The 95% confidence intervals for 5G D2D are negligibly small. The remaining 5G D2D packet losses result from channel-dependent decoding errors based on the received signal-to-noise ratio (SNR) and the fixed CQI.

The communication differences shown in Figure 1 do not translate into different UAV collision ratios. At the applied beacon rate, the measured channel utilization indicates that neither communication technology approaches saturation. Both technologies therefore deliver the large majority of generated beacons. The collision avoidance algorithm estimates neighbor positions between received beacons using the last reported position, velocity vector, and timestamp. The reduction in IEEE 802.11p PDR does not prevent the algorithm from maintaining sufficient separation between the UAVs under the evaluated open-area conditions. The evaluated channel load remains below a level at which packet loss affects the UAV collision ratio. Consequently, the results do not indicate a safety advantage for either technology in this scenario, although the 5G D2D PDR is less affected by increasing UAV density. Even more, the saved channel capacity of 5G D2D allows other and possibly future applications to operate on the same communication link without sacrificing safety applications.

At $1\,\mathrm{m/s}$, the detour ratio increases from approximately 5% to 17% as the UAV density increases, whereas it remains close to 23% at the two higher desired speeds. Increasing UAV density also reduces the mean distance covered per UAV. At $5\,\mathrm{m/s}$ and $10\,\mathrm{m/s}$, it decreases from approximately $240\,\mathrm{m}$ to $113\,\mathrm{m}$. Differences between IEEE 802.11p and 5G D2D remain negligibly small. The flight efficiency is influenced primarily by UAV density and desired speed rather than by the selected communication technology. However, this observation is limited to the evaluated communication conditions. Higher packet loss, leading to outdated neighbor information, may delay avoidance maneuvers and require stronger braking or larger detours.

In the *Urban Intersection* scenario, no collisions occur at a desired speed of $1\,\mathrm{m/s}$. At $5\,\mathrm{m/s}$, one UAV collision occurs with IEEE 802.11p and 60 UAVs. It is mainly caused by hidden terminal interference. All other configurations remain collision-free in our simulation study.

At $10\,\mathrm{m/s}$, both obstacle and UAV collisions occur. There are obstacle collisions in 43 runs with IEEE 802.11p and 47 runs with 5G D2D. We observe two communication-related UAV collisions with IEEE 802.11p and three with 5G D2D. For IEEE 802.11p, hidden terminal interference prevents the reception of beacons. Additionally, one collision is preceded by obstacle shadowing of the direct link. The missing information leaves insufficient time to avoid the collision.

For 5G D2D, obstacles block the connection between a UAV and the Next-Generation Node B (gNB). Consequently, no transmission resources are allocated for the affected UAV. Thus, the collisions could not be avoided due to missing neighbor information.

Obstacle collision frequency does not increase monotonically with UAV density. In other words: There is no observable correlation between channel utilization and degraded communication quality and UAV collisions involving buildings. This variation indicates that the randomly generated encounter geometries strongly affect whether an obstacle collision can be avoided. At $10\,\mathrm{m/s}$, the increased braking distance and turning radius limit maneuverability and prevent some obstacle conflicts from being resolved.

Overall, the urban scenario reveals two distinct limitations: First, missing neighbor information causes UAV collisions, and second, limited maneuverability at higher velocities (e.g., $10\,\mathrm{m/s}$) causes obstacle collisions.

IV. Conclusion

In this paper, we investigated IEEE 802.11p and 5G D2D communication for cooperative UAV collision avoidance. Both technologies support the proposed approach under most investigated conditions. In the open-area scenario, no UAV collisions occur with either technology. Communication performance changes with increasing UAV density, but no safety advantage is observed.

In the urban scenario, obstacle collisions occur at $10\,\mathrm{m/s}$. They are primarily caused by limited braking and turning capabilities. A small number of UAV collisions result from delayed or missing neighbor information. For IEEE 802.11p, this is caused by hidden terminal interference and obstacle blockage. For 5G D2D, obstacle blockage interrupts the gNB connection and prevents transmission. Both technologies can therefore support cooperative UAV collision avoidance. However, safety depends on communication availability and UAV maneuverability. Yet, 5G D2D shows a lower channel utilization leaving communication capacity for future applications, e.g., cooperative maneuvers for UAV swarms.

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