Enabling Cooperative Awareness for UAVs: ETSI CAM Protocol Extension

Sandaruwan Jayaweera, Konstantin Mikhaylov and Matti Hämäläinen
Centre for Wireless Communications, University of Oulu, Finland
E-mail: {sandaruwan.jayaweera, konstantin.mikhaylov, matti.hamalainen}@oulu.fi

***Abstract*—The use cases involving single or multiple Unmanned Aerial Vehicles (UAVs) controlled by a pilot or operating autonomously are becoming more and more common these days. To support UAVs' safe and efficient operations, the enablement of cooperative awareness (CA) is crucial. In this paper, we approach this challenge by proposing a modification of the Cooperative Awareness Message (CAM) protocol developed by the European Telecommunications Standards Institute (ETSI) for enabling CA for Intelligent Transportation Systems (ITSs) to support UAVs. First, we identify the information required to provide UAV CA. Then, we introduce a messaging architecture with data fields specifically designed to support 3D mobility. We follow the rules of the existing CAM specification so that the proposed messaging structure can be added with minimum modifications to the existing CAM structure. Finally, we assess the proposed modified CAM operating performance on top of the physical (PHY) and medium access control (MAC) layers specified by the IEEE 802.11p radio access technology, which is widely used for vehicular communications. Our results show that air-to-air communications can be effectively used and provide coverage up to 150 m distance with 64-QAM and 1200 m with BPSK modulations. Furthermore, analysis of the MAC layer suggests that the technology can offer a packet reception probability above 0.9 for 10000 UAVs in the same area transmitting at 1 Hz frequency and 800 devices at 10 Hz transmission frequency.**

***Index Terms*—swarm, drones, wireless communications, safety, Intelligent Transportation Systems, 3D mobility, scalability.**

I. Introduction

The recent improvements for information and communications technologies (ICT) have brought machine autonomy much closer than before. In particular, as a result of the growing number of applications of Unmanned Aerial Vehicles (UAV), the autonomy of individual UAVs and multi-UAV networks (e.g., swarms) has become a key research field during the last years. To enable efficient and reliable autonomous operation and collaboration, the UAVs require awareness about each other and their infrastructure. Although some previous studies implied the availability of the awareness information in UAV networks, no specific mechanism to enable it was proposed to the best of our knowledge. In this paper, we address this gap.

Cooperative awareness (CA) is crucial for many novel multi-UAV solutions suggested in the literature. Zhu et al. in [1] highlight the importance of sharing situational information for swarm cooperative decision-making and control. Lin et al. in [2], introduce an algorithm that can achieve cluster situational awareness while keeping cooperative formation, avoiding collisions and providing control over the UAVs by considering all the UAV members of the network as a whole. A proactive topology-aware inter-UAV routing optimization scheme, which bases on position data sharing, is proposed by Hong et al. in [3]. Finally, Ruan et al. in [4] introduce a clustering-based cooperative relative localization scheme for a UAV swarm. However, most of these studies focus on the cooperative control algorithms and the consensus control theory and leave aside the mechanism and protocol for awareness data exchange and data structuring and composition.

On the practical side, the communications between UAVs and Ground Control Stations (GCSs) today often occurs through communications protocols, such as MAVLink, UranusLink, and UAVCAN [5][6]. Unfortunately, neither of these fits well for exchanging awareness data either. Meanwhile, recently the European Telecommunications Standards Institute (ETSI) has introduced the series of Intelligent Transport Systems (ITS) standards defining the architecture in [7] and formats for CA Message in [8] and Decentralized Environmental Notification in [9]. Motivated by this work, in this study, we investigate the feasibility of reworking these standards to enable awareness for the UAVs. Specifically, the key contributions of this paper are:

- we identify the data fields and structures to support 3D mobility based awareness for UAVs;
- we specify the modified messaging protocol based on CAM for UAVs awareness;
- we deliver the first analytical results revealing the potential performance of the proposed protocol running on top of the IEEE 802.11p radio access technology.

The rest of this paper can be summarized as follows. Section II elaborates on the architecture, CAM and DENM structures proposed by ETSI. Section III identifies the data fields required to enable UAV awareness. We suggest and detail the design of the modified version of CAM for UAVs in Section IV. Section V is devoted to analyzing the performance of the proposed messaging structure. Finally, Section VI concludes the paper and summarizes the lessons learned and possible future directions.

II. Background

To support the vehicular safety and traffic efficiency in ITS, ETSI has specified communications architecture [7] shown in Fig. 1. The Access layer here corresponds to the Open Systems Interconnection (OSI) layers 1 (physical

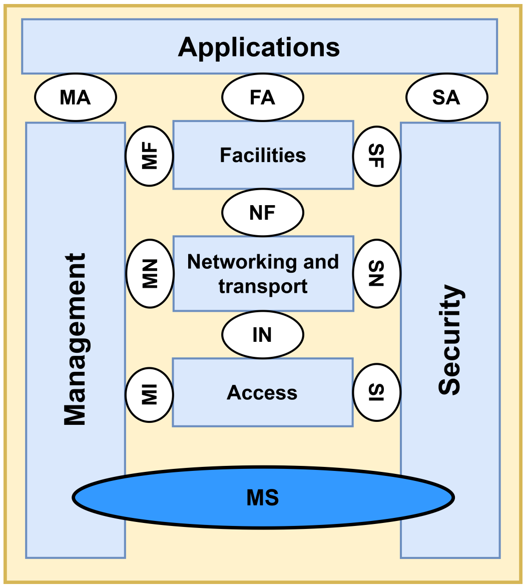

Fig. 1. ITS station reference architecture. Initials denote interfaces between the corresponding layers (e.g., MN - management and network).

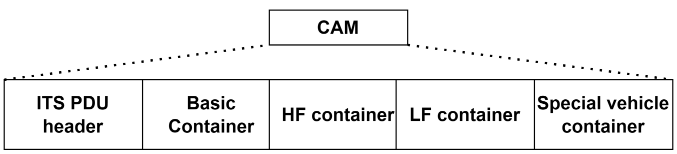

Fig. 2. General structure of conventional CAM.

layer) and 2 (medium access control layer), Network and Transport - layers 3 and 4, correspondingly, and Facilities - layers 5, 6, and 7. To enable CA, the two Facility-level services and respective protocols were defined - CAM and DENM [10], [7].

The CAMs are periodically broadcasted at a given frequency, satisfying both the requirements of target safety applications and transport layer [7]. These messages are used by an ITS station (i.e., a vehicle or a roadside unit) to notify its presence, position, dynamics, and other attributes to other nearby stations [8]. Meanwhile, the DENMs are typically generated asynchronously and triggered by an event [9]. If needed, they can traverse multiple hops to reach the destination. In the following sections, we briefly discuss CAM and DENM, with the primary focus on CAM, which is more relevant in the context of our proposed CA solution for drones.

A. DENM

Decentralized Environmental Notification (DEN) basic service, which resides in the Facilities layer of the ITS communications architecture, is responsible for the construction, management and processing of the DENM [9]. Safety applications usually use these messages to convey information about road hazards or abnormal traffic conditions. The generated DENMs are delivered to the network and transport layer, which takes care of disseminating them in a geographic area through direct vehicle-to-vehicle or vehicle-to-infrastructure communications [9]. The received DENM are forwarded to the relevant applications. The practical applications and use cases based on DENM are collision warning, obstacle avoidance and restricted zone warning services.

B. CAM

Cooperative Awareness basic service, which also resides in the Facilities layer of the ITS communications architecture, is responsible for the construction, management and processing of CAM [8]. The CAM structure is composed of the five main elements, as illustrated in Fig. 2:

- ITS packet data unit (PDU) header;
- the basic container;
- high frequency (HF) container;
- low frequency (LF) container;
- special vehicle container.

The ITS PDU header is a common header for the different facility-level protocols, containing the version, message identifier (ID) and the originating station ID information. The format of the ITS PDU header is defined in [11]. The value of 2 in message ID signalizes that the message belongs to CAM protocol [11]. The roles of the three containers are as follows. The basic container carries the information about the type of the ITS station generating this CAM and its geographic position. The HF container incorporates fast-changing parameters, such as the vehicle's speed or orientation. Similarly, the LF container includes static and slow-changing information about the vehicle (e.g., the status of exterior lights or a path history). Finally, the special vehicle container can be used to deliver additional information about the role of the vehicle. It can denote, e.g., public transport, road work or emergency vehicles. A CAM packet should start with the ITS PDU header and include the basic and HF containers. The use of LF and special vehicle containers is optional.

Notably, the CAM specification is quite flexible and enables extending the protocol to support future ITS applications [8]. Such extensions are possible on different levels. First of all, there is a possibility for defining new containers, which can replace, e.g., the LF container. Second, some of the data fields have values or value ranges that are currently reserved. In what follows, when adapting the CAM for UAVs, we will use both of these approaches.

III. UAV awareness and CAM

We have started our work by analyzing the requirements of the UAV applications and use cases to determine the data which need to be exchanged to support CA for UAVs. Namely, we have identified the following categories of data:

- information about the station (e.g., its type and dimensions);
- current position and orientation in 3D space;
- current movement characteristics (speed, acceleration, etc.);

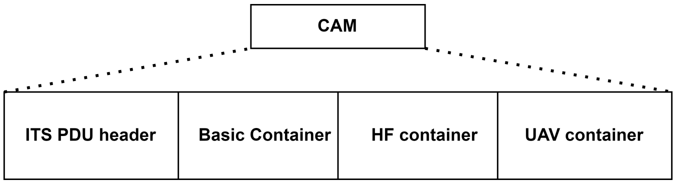

Fig. 3. General structure of suggested CAM for UAVs.

- future trajectory (optional)
- previously visited locations (optional);

Note that some of these data elements might be optional; this depends on the UAV and its mission type. For example, a drone autonomously flying along a prespecified route likely knows its trajectory, while the drone piloted by a human operator may not have this data. Similarly, not every drone may be equipped with a localization/navigation system (e.g., GPS) and possess position information.

The reasoning for selecting these data fields is the following. The information about the station provides other actors insight into the capabilities of this station and its dimensions and are relevant for identification, collision avoidance or establishing a collaboration. The data about the position in space, movement characteristics and the future path of a mobile station are also relevant for avoiding collisions. The previously visited locations may provide some insight into the pertinent information the drone may possess (e.g., the maps, non-flight zones, or weather/sensor data).

As discussed in the previous section, the existing CAM structure contains many of these elements, but these are optimized for ground vehicles moving in 2D and along the roads. Specifically, the orientation and movement fields require vertical components to support these aerial transport scenarios. The need to revise the dynamic range or the measurement units may arise for some other fields. To give an illustrative example, the CAM vehicle width field can have a value in the range from 10 cm to 6.1 m, while for some of the fixed-wing UAVs in development, the wingspan exceeds 40 m. Therefore, we suggest modifying CAM structures to better support drones, and deliver all relevant CA information in the next section. Note that some other research works have offered modifications to CAM, which we consider appropriate also for UAVs. Specifically, Renzler et al. in [12] have proposed to create a data structure for possible future path points, based on the existing path history available in the LF container.

IV. Proposed CAM for UAVs

The general structure of the modified CAM for UAVs is illustrated in Fig. 3. Comparing this figure with that of the conventional CAM presented in Fig. 2, one can notice that the structures are almost identical. We intentionally go for the minimum possible modification of the original CAM structure to support interoperability. Specifically, no changes for the ITS PDU header were needed. The basic

Basic container fields			Bit Width	Range	Unit
		Station Type	8	0..255	
Reference position		Lattitude	31	-900000000..900000001	0.1 µdeg north (N)
Reference position		Longitude	32	-1800000000..1800000001	0.1 µdeg east (E)
Reference position	Confidence Ellipse	Semi Axis length (Semi Major Confidence)	12	0..4095	cm
Reference position	Confidence Ellipse	Semi Axis length (Semi Minor Confidence)	12	0..4095	cm
Reference position	Altitude	heading	12	0..3601	0.1 deg E from WGS84 N
Reference position	Altitude	Altitude value	25	-100000..20000000	cm
Reference position	Altitude	Altitude confidence	4	Enumerated (16)	

Fig. 4. Proposed basic container of UAV CAM.

HF container fields			Bit width	Range	Unit
Heading		Heading value	12	0..3601	0.1 deg E from WGS84 N
Heading		Heading confidence	7	1..127	0.1 deg
		Vertical heading	12	0..3601	0.1 deg up from horizontal
Speed		Speed value	14	0..16383	cm s^{-1}
Speed		Speed confidence	7	1..127	cm s^{-1}
Drive direction	Heading	Heading value	12	0..3601	0.1 deg E from WGS84 N
Drive direction	Heading	Heading confidence	7	1..127	0.1 deg
Drive direction		Vertical heading	12	0..3601	0.1 deg up from horizontal
Vehicle length		Vehicle length value	14	0..16384	cm
Vehicle length		Vehicle length confidence indication	3	Enumerated (5)	
		Vehicle length value (width)	14	0..16384	cm
		Vehicle length value (height)	14	0..16384	cm
Longitudinal Acceleration		Longitudinal acceleration value	9	-160..160	0.1 m s^{-2}
Longitudinal Acceleration		Longitudinal acceleration confidence	7	0 .. 102	0.1 m s^{-2}
Curvature		Curvature value	16	-30000..30001	3.33×10^{-5} m^{-1} towards left
Curvature		Curvature confidence	3	Enumerated (8)	
		Curvature calculation mode	2	Enumerated (3)	
Yaw rate		Yaw rate value	16	-32766..32767	0.01 deg s^{-1} towards left
Yaw rate		Yaw rate confidence	4	Enumerated (8)	
Lateral Acceleration		Lateral acceleration value	9	-160..160	0.1 m s^{-2}
Lateral Acceleration		Lateral acceleration confidence	7	0 .. 102	0.1 m s^{-2}
Vertical Acceleration		Vertical acceleration value	9	-160..160	0.1 m s^{-2}
Vertical Acceleration		Vertical acceleration confidence	7	0 .. 102	0.1 m s^{-2}

Fig. 5. Proposed HF container of UAV CAM.

and HF containers are retained with few modifications, and a new optional UAV container replacing the LF container is introduced.

The data structures of the proposed basic, HF and UAV containers are illustrated in Figs. 4, 5 and 6, respectively. In these pictures, we use a special notation to highlight the level of modification of the different data fields and structures compared to conventional CAM. Namely, in aqua, we mark the data fields, which have not been modified at all; in yellow, we show the fields for which we have re-defined the range of values; we highlight with orange the data fields and structures, which are based on

UAV container fields				Bit width	Range	Unit
			SafetyAreaRadius	14	0...16384	m
PathHistory			PathHistory locations length	6	0...40	
	Pathpoint 1	Delta Reference Position	DeltaLattitude	18	-131071..131072	0.1 µdeg N
			DeltaLongitude	18	-131071..131072	0.1 µdeg E
			DeltaAltitude	21	-1048576..1048576	cm up
			PathDeltaTime	16	1..65535	10 ms
	....			...	...	....
	Pathpoint x	Delta Reference Position	DeltaLattitude	18	-131071..131072	0.1 µdeg N
			DeltaLongitude	18	-131071..131072	0.1 µdeg E
			DeltaAltitude	21	-1048576..1048576	cm up
			PathDeltaTime	16	1..65535	10 ms
Future Locations			Future locations length	6	0...40	
	Pathpoint 1	Delta Reference Position	DeltaLattitude	18	-131071..131072	0.1 µdeg N
			DeltaLongitude	18	-131071..131072	0.1 µdeg E
			DeltaAltitude	21	-1048576..1048576	cm up
			PathDeltaTime	16	1..65535	10 ms
	....			...	...	....
	Pathpoint x	Delta Reference Position	DeltaLattitude	18	-131071..131072	0.1 µdeg N
			DeltaLongitude	18	-131071..131072	0.1 µdeg E
			DeltaAltitude	21	-1048576..1048576	cm up
			PathDeltaTime	16	1..65535	10 ms

Fig. 6. Proposed UAV container of UAV CAM.

the already existing CAM data structures but structured differently or are re-named; in red we display the new data fields and structures, which currently do not exist in CAM. Additionally, we show each field's size and the range of its values whenever feasible.

The modified basic container, depicted in Fig. 4, carries the information about the UAV's identity and location. Even though the current CAM specification includes the field for the altitude, the range of its values is limited to (-1, 8) km above the ground level. We expect that the future UAVs might operate at heights exceeding 8 km, and thus we suggest increasing the bit width to 25 bits, thus enabling us to accommodate the altitudes of up to 200 km. Also, there is a need to modify the ITS station type parameter to include UAVs. The current specification already defines 16 station type values [11]; therefore, any of the currently-unused values between 16 and 255 can be used to denote a UAV.

In Fig. 5, the suggested HF container for UAVs is illustrated. We modified the HF container to include information about UAV's movement and orientation in the 3D space. Specifically, we have introduced (i) a field for the vertical heading, (ii) we re-define the drive direction structure, and (iii) modified the parameters describing the dimensions of a UAV.

- The existing structure already has a heading parameter for the 2D domain. After this 2D heading, a vertical heading parameter is introduced in our proposed structure. Note that to minimize overhead and simplify the design, we consider that the heading confidence parameter, already present in the heading structure, is valid also for vertical heading.
- The drive direction field in conventional CAM is optimized to represent the movement of vehicles and thus provides only two options - back and forward. This is not sufficient for UAVs, especially multi-rotor UAVs capable of moving in any direction. Therefore, we re-defined the structure of drive direction structure to repeat that of the heading structure. This is worth noting the difference between the two: the heading structure denotes the drone's chassis orientation (and serves as the reference for determining the dimensions of the drone), while the drive direction - is the direction in which the drone currently moves.
- We also modified the range of the vehicle length parameter (to allow representing current and prospective drone platforms [13][14]) and used that as the basic data element to denote the length, width and height of a drone. Note that if a drone carries a load, the dimensions should be given accounting for the load.

We also introduce the new container for UAVs, which is depicted in Fig. 6 and replaces the LF container of the existing CAM specification. Note that likewise the LF container, the UAV container is optional and should be transmitted at a much higher period than the basic and HF containers. The UAV container carries (i) the information about the desired safety area around the UAV, (ii) the optional path history of the UAV, and (iii) the optional future path points of the UAV. The safety area is defined as a sphere around the reference position of the UAV, which is carried in the basic container. The safety area radius parameter signalizes the radius of the safety area. This parameter is derived from the protected zone radius parameter in the original CAM specification and is modified to accommodate a 0 - 16.384 km radius. This range is more than enough to accommodate the separation requirement for aircraft [15]. The path history structure is derived from the path history structure in the existing LF container [11]. The delta altitude parameter of a pathpoint is modified to support much higher altitude values. The path history can include up to 40 path points. This path history structure is reused in the future locations structure. The presence of both path history and future locations structures is optional and depends on the type of the drone and its mission.

As one can see, the number of modifications for CAMs required to make them usable by UAVs are relatively tiny. Similarly, the size of the resulting containers is relatively moderate: 136 bits for the basic container, 217 bits for the modified HF container, and from 26 to 5866 bits for the UAV container.

V. Performance insight

In the previous section we have suggested the modification of CAM for the UAVs. To obtain some insight into the feasibility and potential performance of the system based on the proposed modified CAM, in what follows, we obtain the analytic results assessing the maximum communications range and scalability. For these analyses, we imply using IEEE 802.11p radio access technology (which is often utilized in the physical and medium access control layers for vehicle-to-any communications).

A. Communications distance

Obviously, the air-to-air propagation differs from the ground-to-ground one, for which the performance of IEEE 802.11p has been extensively analysed. To account for this difference, we have used the air-to-air radio channel model from the literature - probabilistic two-ray (PTR) path loss model expressed as (1) which has been derived in [16] as

$$PL_{PTR}[dB] = 20log_{10}(4\pi\frac{d}{\lambda}|1 + \Gamma_b exp(i\Delta\psi_b)\alpha \\ \Gamma_g exp(i\Delta\psi_g)(1-\alpha)p_g|^{-1}). \quad (1)$$

In (1) PL_{PTR} is the path loss, d is the link distance, λ is the wavelength and Γ_b and Γ_g are the reflection coefficients from the buildings and the ground, respectively. The phase difference between the reflection from buildings or ground and LOS are represented by ψ_b and ψ_g, respectively. The probability of ground reflection is given by p_g. Furthermore, α is the ratio of the land area covered by buildings to the total land area. The wavelength λ is calculated implying the frequency 5.9 GHz since the safety band for transportation-related communications spans from 5.850 to 5.925 GHz. The $p_g \approx 0.65$ is obtained from [16] for the mean elevation angle of 45°. $\Gamma_b = -0.51$ and $\Gamma_g = -0.45$ are calculated for relative permittivities (ϵ_r) 4.44 and 3 for building and ground, respectively, using $\Gamma_{b/g} = \frac{sin(\theta)-\sqrt{\epsilon_r+cos^2(\theta)}}{sin(\theta)+\sqrt{\epsilon_r+cos^2(\theta)}}$. ψ_b and ψ_g are calculated using $\psi_{b/g} = \frac{2\pi}{\lambda}(d-d_{REF,b/g})$, where $d_{REF,b} = \sqrt{d^2+4(h-h_b)}$ and $d_{REF,g} = \sqrt{d^2+4h^2}$. $h = 150$ m and $h = 120$ m denote the altitude of the UAVs and $h_b = 100$ m is the mean height of the buildings. We further assume that almost all UAVs reside in the same height plane (e.g., at particular flight level). Note, that according to [17], the new European Union rules limit most of the drones from flying above 120 m.

The power of the received radio signal is given by $P_{rx} = P_{tx} - PL_{PTR} + G_{tx} + G_{rx}$. We take the transmit power (P_{tx}) = 23 dBm, transmitter gain (G_{tx}) = 3 dB and (G_{rx}) = 3 dB. To estimate the feasible communication ranges we compare P_{rx} with the receiver sensitivities obtained in [18] for the different ITS-G5 modulations via simulations. The results are presented in Fig. 7. It appears that, although there is a significant effect of fading, the heights of the UAVs have rather limited effect on the maximum communications distance. Also, this can be seen that using IEEE 802.11p in 5.9 GHz band, the UAVs can support up-to 150 m communications distance with 64-QAM (27 Mbps) modulation and over 1200 m with BPSK (3 Mbps) modulation.

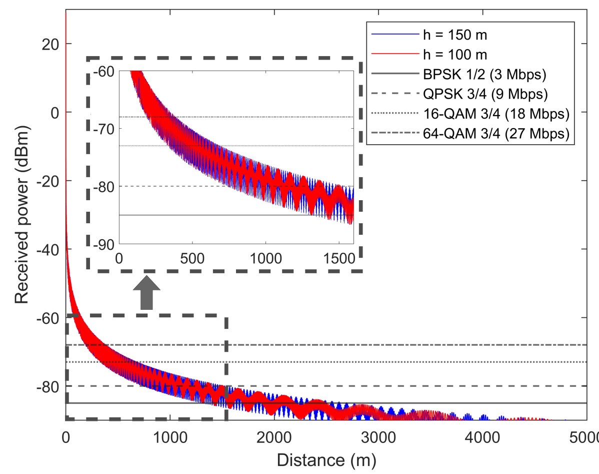

Fig. 7. Received power of radio signal against distance, $\alpha = 0.3$, $p_g \approx 0.65$ [16], and the sensitivity levels for the different IEEE 802.11p modulation-coding schemes.

B. Scalability

The distributed coordination function (DCF) employed by IEEE 802.11p for media access is a variant of carrier-sense multiple access with collision avoidance (CSMA/CA). To estimate the number of drones capable of simultaneously operating in the same 3D space, we use the model proposed by Shah et al. in [19]. The probability of packet reception (P_s) is given by

$$P_s = \frac{NP_t(1-P_t)^{N-1}}{P_b}, \quad (2)$$

where, N is the number of UAVs which might interfere with a transmission, P_t is the probability of transmission during a slot time and P_b is the probability of channel being busy. P_b can be obtained using $P_b = 1-(1-P_t)^N$. Here, we assume a slot time equal to double the on-air duration of a CAM packet (i.e., the collision window or the window of vulnerability) and packet transmission frequency equal to 1 Hz and 10 Hz. These packet transmission frequencies are according to the CAM generation frequency limits defined by ETSI as specified in [8]. We observe $P_t = 0.00002$ and 0.0002 for transmission frequency 1 Hz and 10 Hz, respectively. The P_s is calculated assuming the smallest possible CAM packet, containing just the basic and HF container, since it is the most commonly used packet type. Because of the modifications illustrated in Fig. 5, the packet size is different between the proposed and regular CAM protocols. This results in a slightly higher P_t for regular CAM. The P_s for N from 1 to 10000 is illustrated in Fig.8.

The presented results reveal that for the transmission frequency of 1 Hz, P_s stays above 0.9 even for 10000 UAVs. At the transmission frequency of 10 Hz, the success probability is above 0.9 for about 800 drones. Furthermore, the proposed CAM has a smaller but relatively close P_s to the regular CAM. Note that the provided results illustrate

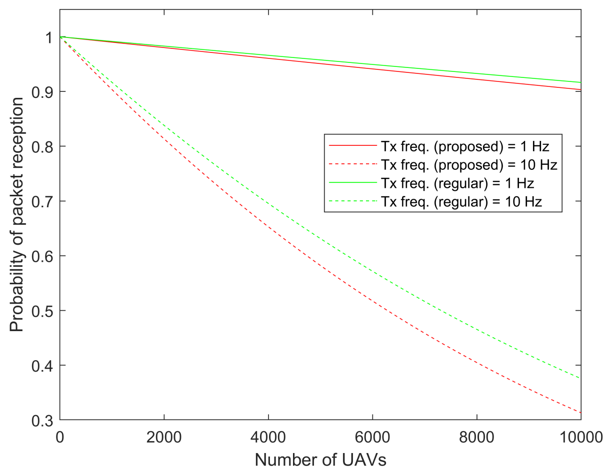

Fig. 8. Probability of successful packet reception against the number of UAVs (N) the proposed UAV CAM and regular CAM protocol under different packet transmission frequencies (TX freq.).

the worst-case scenario when each collision of packets is destructive regardless of the distance between the UAVs.

VI. Conclusion and Future Work

The UAVs are starting to play a more important role these days. This paper has suggested an extension for the existing CAM standard in [8] tailor-made to support UAV cooperative awareness. Specifically, we revisited the CAM structure and introduced the minimum set of data fields and structures to support the 3D mobility scenarios of UAVs. Departing from this, we have used analytical models to obtain some insight into the communications ranges and scalability of the suggested UAV-CAM modification operating over 802.11p physical and medium access control layers. Our results suggest that, the minimum communications range is 150 m for 64-QAM and 1200 m for BPSK. We have also observed that under implication of each collision being destructive, the packet delivery rate exceeds 0.9 in the 800 and 10000 UAVs network, for packet transmission frequencies of 10 and 1 Hz, respectively. Even though these results have been obtained using somewhat simplified models, we consider them rather promising.

As the next step in our research, we plan to detail our models to obtain more accurate results and introduce modifications to the DENM structure to facilitate event-triggered UAV applications. Since DENM are event-triggered, they can be used for such use cases as emergency docking, refuelling, landing and collaborative operations. Also, they can be used to convey information about obstacles and no-fly zones.

VII. Acknowledgements

This work is partially funded by Academy of Finland via projects RoboMesh (grant 336060), MRAT-SafeDrone (grant 341111) and 6G Flagship (grant 346208).

References

[1] H. Zhu, J. Li, Y. Gao, and G. Cheng, "Consensus analysis of UAV swarm cooperative situation awareness," in *Int. Conf. Virtual Reality Intell. Syst. (ICVRIS)*, 2020, pp. 415–418.

[2] Q. Lin, X. Wang, and Y. Wang, "Cooperative formation and obstacle avoidance algorithm for multi-UAV system in 3D environment," in *37th Chin. Control Conf. (CCC)*, 2018, pp. 6943–6948.

[3] L. Hong, H. Guo, J. Liu, and Y. Zhang, "Toward swarm coordination: Topology-aware inter-UAV routing optimization," *IEEE Trans. Veh. Technol.*, vol. 69, no. 9, pp. 10 177–10 187, 2020.

[4] L. Ruan, G. Li, W. Dai, S. Tian, G. Fan, J. Wang, and X. Dai, "Cooperative relative localization for UAV swarm in GNSS-denied environment: A coalition formation game approach," *IEEE Internet Things J.*, pp. 1–1, 2021.

[5] A. Allouch, O. Cheikhrouhou, A. Koubaa, M. Khalgui, and T. Abbes, "MAVSec: Securing the MAVLink protocol for Ardupilot/PX4 unmanned aerial systems," 2019.

[6] N. A. Khan, S. N. Brohi, and N. Jhanjhi, "UAV's applications, architecture, security issues and attack scenarios: A survey," in *Intell. Comput. Innov. Data Sci.*, S.-L. Peng, L. H. Son, G. Suseendran, and D. Balaganesh, Eds. Singapore: Springer Singapore, 2020, pp. 753–760.

[7] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Communications Architecture," *ETSI EN 302 665 V1.1.1*, 2010. [Online]. Available: http://www.etsi.org

[8] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service," *ETSI EN 302 637-2 V1.4.1*, 2019. [Online]. Available: http://www.etsi.org

[9] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service," *ETSI EN 302 637-3 V1.3.1*, 2019. [Online]. Available: http://www.etsi.org

[10] J. Santa, F. Pereñíguez, A. Moragón, and A. F. Skarmeta, "Experimental evaluation of CAM and DENM messaging services in vehicular communications," *Transp. Res. Part C: Emerg. Technol.*, vol. 46, p. 98–120, 2014.

[11] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Users and applications requirements; Part 2: Applications and facilities layer common data dictionary," *ETSI TS 102 894-2 V1.3.1*, 2018. [Online]. Available: http://www.etsi.org

[12] T. Renzler, M. Stolz, and D. Watzenig, "Looking into the path future: Extending CAMs for cooperative event handling," in *IEEE 92nd Veh. Technol. Conf. (VTC2020-Fall)*, 2020, pp. 1–5.

[13] R. M.D, M. B. Kempar, R. U, J. H. J, and N. C. G, "Real time parameter estimation for MAV using low cost hardware," in *Int. Conf. Elect. Electron. Commun. Comput. Optim. Techn. (ICEECCOT)*, 2018, pp. 1418–1423.

[14] Space Exploration Technologies Corp., "SpaceX - Starship," 2022, Accessed on: Jan 25, 2022. [Online]. Available: https://www.spacex.com/vehicles/starship/

[15] G. A. Gilbert, "Air traffic control: The uncrowded sky." USA: Washington DC: Smithsonian Institution Press, 1973, pp. 36–37.

[16] Z. Cui, K. Guan, C. Briso, D. He, B. Ai, and Z. Zhong, "Probabilistic two-ray model for air-to-air channel in built-up areas," 2019.

[17] "European Commission adopts rules on operating drones," 2019, Accessed on: Feb 18, 2022. [Online]. Available: https://transport.ec.europa.eu/news/european-commission-adopts-rules-operating-drones-2019-06-11_en

[18] A. K. Gulia, "A simulation study on the performance comparison of the V2X communication systems: ITS- G5 and C-V2X," Master's thesis, KTH Roy. Inst. Technol., 2020.

[19] A. F. M. Shahen Shah, H. Ilhan, and U. Tureli, "Modeling and performance analysis of the IEEE 802.11P MAC for VANETs," in *42nd Int. Conf. Telecommun. Signal Process. (TSP)*, 2019, pp. 393–396.