V2V UAS Communications and Use Cases for Advanced Air Mobility

Kamesh Namuduri*, Gürkan Gür†, Stefano Savazzi‡, Saba Al-Rubaye§, Ashwin Ashok¶, Sven G. Bilén‖, Ivan Petrunin§, Marco Hernandez**††, Shane Nicoll‡‡, Batool Dalloul‡‡
*Electrical Engineering, University of North Texas, USA
†Zurich University of Applied Sciences (ZHAW), Switzerland
‡Institute of Electronics, Information Engineering and Telecommunications, CNR, Italy
§School of Aerospace, Transport and Manufacturing at Cranfield University, UK
¶Department of Computer Science, Georgia State University (GSU), USA
‖Engineering Design and Innovation, The Pennsylvania State University (Penn State), USA
**NICT, YRP-AIA, Japan
††CWC Oulu University, Finland
‡‡Unmanned Experts, USA

Abstract*—Advanced Air Mobility (AAM) is emerging as a transformative application in smart mobility with the latest advances in hardware, software, policy development, and regulations. Unmanned Aircraft Systems (UAS) are supposed to become the backbone of emerging AAM services and applications as connected and software-intensive platforms. However, Vehicle-to-Vehicle (V2V) communications in the AAM still deserve further effort in terms of safety, communication protocols, data exchange requirements, concrete use cases and their subsequent standardization. To this end, this paper presents several use cases for UAS communications and relevant message exchange protocols currently investigated in IEEE P1920.2 Standardization Work Group. The use case constellation entails five fundamental use cases for V2V UAS communications in the AAM domain. This paper begins with an overview of these use cases for potential scenarios. Then, it further delves into two critical ones and describes the relevant data exchange and protocol flows for UAS communications. We believe that this contribution will facilitate the discussion of AAM use cases and crucial aspects of V2V communications involved in these scenarios.

I. Introduction

The IEEE P1920.2 Standard for Vehicle to Vehicle Communications for Unmanned Aircraft Systems [1] outlines a protocol for vehicle-to-vehicle communications between unmanned aircraft systems (UAS). While this standard does not focus on particular communication technologies, it aims to build upon existing standards while incorporating new functionalities at the system level. The IEEE 1920.2 Work Group (WG) is tasked with developing scenarios and requirements as part of their work. The group's plan is to develop use case scenarios first, followed by the standard itself. Working group members are also focusing on the concepts of Advanced Air Mobility (AAM) [2]–[5].

Establishing an air-to-air network for UAS vehicles is a highly coveted goal, yet the inherent challenges in creating and sustaining such a collaborative network within the airspace are formidable. Moreover, these systems are instrumental for various verticals and applications, including AAM, Smart-X (Smart Cities, Smart Agriculture, Smart Transportation, Smart Industry, ...), tactical missions, and post-disaster relief and emergency communications in integrated settings such as integrated space, aerial and terrestrial networks (SATINs) [6]. Therefore, a pragmatic approach involves augmenting the UAS network with robust infrastructure, leveraging technologies like satellite or cellular networking, as depicted in Fig. 1. Nevertheless, the development of vehicle-to-vehicle communication protocols is essential for airborne networks as they will function autonomously relying on communications and networking while basically becoming a segment of this integrated network infrastructure.

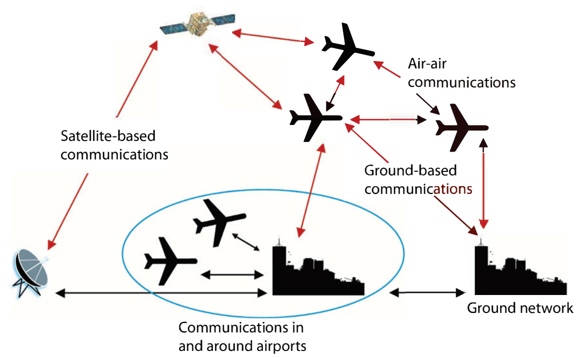

Fig. 1. An illustration of UAS network supported through satellite, cellular, and dedicated radio networking infrastructure.

In this work, we briefly present the five important use cases (UCs) for UAS communications and then focus on two of them, detailing relevant message exchange protocols currently being designed and developed in IEEE 1920.2 WG. These two use cases, namely, collision avoidance and merging, spacing and sequencing of traffic are selected since they are 1) major use cases with wide applicability, 2) critical for UAS networking and operations, and 3) rather illustrative for the protocol and message design in our efforts. In the following

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TABLE I
OVERVIEW OF USE CASES (THE HIGHLIGHTED ONES ARE DETAILED IN SECTION III.)

Use case	Summary
Collision Avoidance (Section III-B)	In this use case, two or more UASs are approaching a region at the same time and they need to avoid a potential collision.
Merging and Spacing/ Sequencing of Traffic (Section III-C)	This use case refers to traffic in structured airspaces, i.e., air corridors. An air corridor is a highway system in the airspace. Air corridors are reserved airspaces at altitudes ranging from 150 meters to 1 kilometer Above Ground Level (AGL).
Airborne separation	This scenario refers to the requirement to keep a safe distance between any two UASs during flight. Depending on whether UASs are operating in structured or unstructured airspace, different scenarios may occur.
Airborne Rerouting	In this use case, a UAS may need to be rerouted if airspace hazards render the planned or existing route unfeasible. If the UAS is Beyond the Radio Line-of-Sight (BRLSO), the rerouting information may be relayed by one or more UASs. These circumstances further highlight the necessity of a UAS network or multi-hop communications for the sharing and dissemination of real-time mission-critical information.
Collaborative Sensing of Weather Conditions	The use case explores the adoption of the UAS-to-UAS communication link for the mutual exchange of weather information. Sudden changes in meteorological conditions during a flight, such as weather or wind speed, might require a UAS to reroute its planned flight path as in the previous scenario or even land. In such situations, the weather information and the message(s) indicating immediate landing need to be delivered to the UAS.

section, we start our work by laying down the assumptions facilitating our use case and protocol development. Then, we provide an overview of AAM use cases. We delineate our two key use cases in Section III-B and III-C, respectively. In Section IV, we describe different message types and protocol flows. Finally, we conclude with some further discussion and potential future advances.

II. Assumptions on the UAS Characteristics

For use case definitions and protocol design, there have to be some assumptions about the envisaged systems in the first place. In this section, we concisely describe these assumptions made in the ongoing standardization work. Please note that they are applicable to all scenarios discussed in this paper.

- UASs can be large and small. In our context, we assume that the vehicles are medium to large and capable of carrying a passenger (e.g., flying car, air ambulance, and air taxi).
- While we are not prescribing technologies, we assume that UASs can carry radio equipment such as SDRs and sense the surrounding environment.
- UASs possess some computing power, such as a dedicated CPU or tensor processing unit (for onboard sensor processing, in addition to maneuvering). Please note that the integration of advanced hardware could be an enabler to many advanced use cases while leading to cost, power, and weight implications.
- UASs may be flying in specific designated routes and altitudes (e.g., air corridors [7]–[9] or sky lanes) as well as on-demand routes.

III. AAM Use Cases

A. Overview

Table I outlines potential use cases considered by the work group. These scenarios are based on the suggestions that came from a meeting organized by the Radio Technical Commission for Aeronautics (RTCA) [10] in September 2022. Fig. 2 illustrates a common framework for all five use case

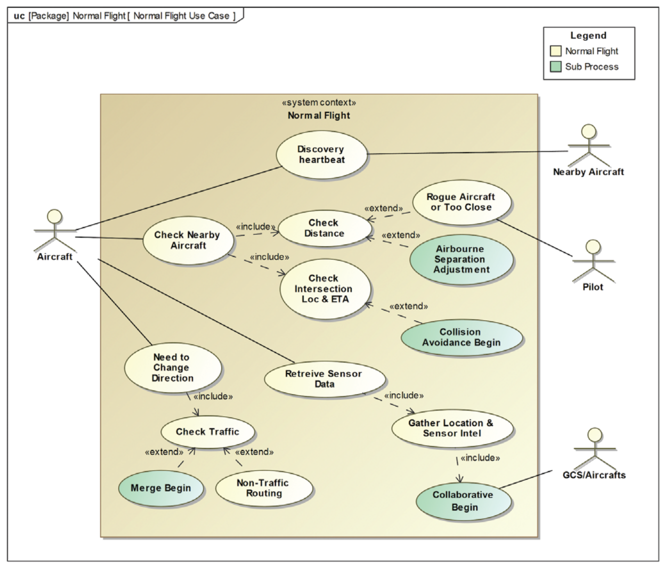

Fig. 2. Use Case Diagram: A Common Framework

scenarios that support the airspace operations in the AAM ecosystem. In particular, these five use cases illustrate the need for communications between UAS vehicles [11]. Note that these use cases are not collectively exhaustive, and subject to change. Moreover, the scope could be extended to any use case scenarios by the work group that is not related to AAM services. In the following two sections, we elaborate on the two use cases, namely Collision Avoidance and Merging and Spacing/Sequencing of Traffic, currently developed in the workgroup. In the first three use cases (including the two selected ones) in Table I, peer-to-peer communication is used whereas in the last two use cases, multi-hop communication is used.

B. UC1: Collision Avoidance

Collision avoidance refers to the capability and relevant actions of UASs for avoiding collisions during flight by traversing collision-free trajectories. There can be many variations to this scenario. For example, the vehicles can be cooperative or non-cooperative. The airspace can be structured or unstructured. Structured airspaces are defined and reserved for certain types of vehicles and are typically applicable to urban areas. Unstructured airspaces are typical for rural regions. In that regard, collision avoidance algorithms and UAS-to-UAS communication between vehicles are crucial for AAM. In this section, we focus on the scenario where UASs are avoiding collision at an intersection.

1) Assumptions - Preconditions: In this scenario, involved UASs are assumed to satisfy some conditions:

- Both vehicles are broadcasting their IDs and kinematic information (e.g., location, velocity) in a format readable by both parties.
- The vehicles are cooperative, i.e., they can decide on the right of way in a mutually agreed way based on priority.
- Both vehicles have the necessary means to decelerate and give the right of way to the other.

2) Scenario Description: Two vehicles are approaching an intersection. Their expected arrival times at the intersection are very close. To avoid a collision, one vehicle (with higher priority) requests for right-of-way. Apparently, there may be many solutions for collision avoidance. We consider the simplest solution in which the low-priority vehicle slows down to arrive at the intersection after the first vehicle exits the intersection.

3) Negotiation: Figure 3 provides a high-level illustration of a collision avoidance scenario being resolved by two UASs.

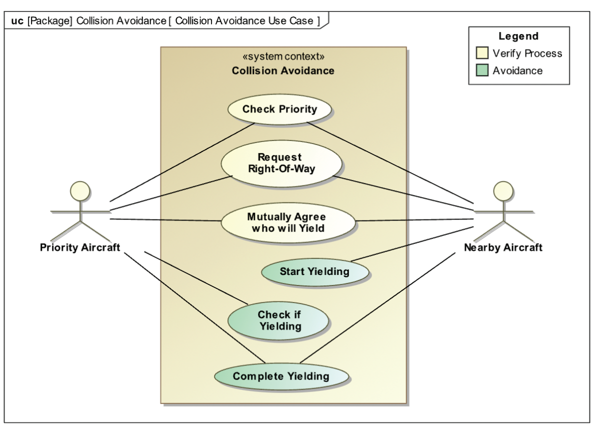

Fig. 3. Use Case Diagram: Collision Avoidance

In Figure 4, we provide a streamlined data exchange for collision avoidance for the envisaged scenario. In this case, UAS_1 has a higher priority than UAS_2. Please note that priority resolution, cooperation, exceptional cases, or error handling are not depicted in this diagram.

C. UC2: Merging, Spacing and Sequencing of Traffic

Considering the complexity of the operational environment for uncrewed air traffic, in particular urban environments with

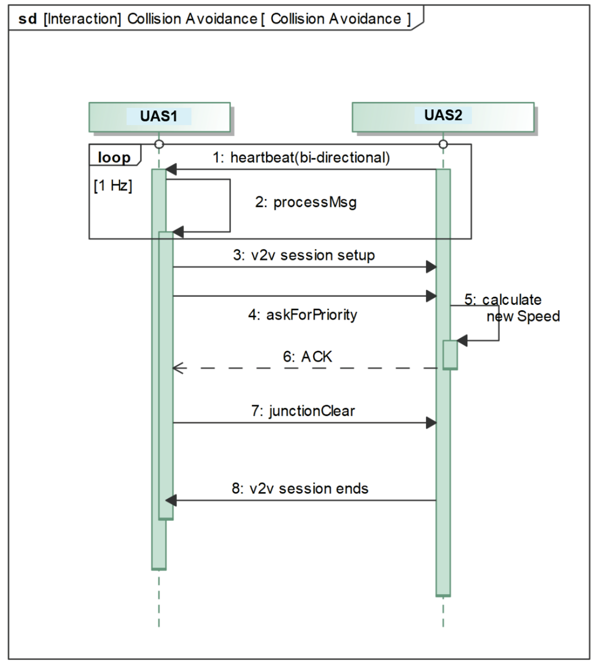

Fig. 4. Message exchange between UASs for collision avoidance.

their dense population and presence of static and dynamic obstacles, safe and efficient regulation and accommodation of high-density UAS traffic is of significant importance. To accommodate the high-density traffic in such constrained environments, a multi-layer system of air corridors or sky lanes is proposed and explored by several researchers and stakeholders of UAS operations. Within this architecture, it is known that a large proportion of conflicts are caused by merging flights. Therefore, efficient management of merging, spacing, and sequencing of traffic requires the integration of the corresponding messaging system within a UAS protocol. This section outlines the scenarios of traffic merging and sequencing with the corresponding assumptions and requirements supporting the protocol's definitions.

We first present the see case related terminology and definitions:

ETA Estimated time of arrival.

Designated Crossing Time (DCT) Designated crossing time that takes into account the UAS speed and bump radius.

Delta Envelope The minimum and maximum speeds as well as the maximum acceleration that a UAS can attain (dependent on its takeoff weight, engine capability, current battery level, etc.).

Gap Radius The required gap for the UAS to merge. It is calculated onboard using the UAS delta envelope, the merged lane's traffic conditions, and current UAS speed.[1]

Through traffic / UAS Traffic / UAS that is in the through lane.

Traffic Radius The radius around the intersection within

[1] It is assumed at the completion of a merge, a UAS will have a compliant, fully functional Bump Radius.

which the merging UAS checks for traffic and requests gap formation.

Action Radius The radius around the intersection within which the through UASs may ignore any gap formation requests from the merging UAS; however, for the UASs outside this radius, they should act to form a gap.

Bump Radius The radius around the merging UAS aiming to maintain the minimum separation distance from it to the UAS ahead in the direction of the traffic. The Bump Radius is different for a different UAS and depends on its delta envelope.[2]

Traffic The traffic is represented here by a sequence of UAS following each other back to back, i.e. with a distance that is less than the required gap radius and which occupies spatially the area greater or equal to the traffic radius.

Yielding and merging UAS The UASs that form the gap by slowing down and request gap, respectively.

1) Assumptions - Preconditions:

- The merging lane is over or under the through lane. So, the merging UAS would ascend or descend to merge using an entrance ramp.
- The entrance ramp and merging lane go to infinity. So, the UAS does not have a time limit to merge. It merges when it is safe to do so, starting from an entry point.
- There are multiple entry points to the merging lane. An entry point is a position where the UAS initiates the merge and not when it gets onto the lane completely. The first one is the waypoint that is included in the UAS mission plan. It is assumed that the mission is changed in case there is no immediate gap.
- All UASs should at all times maintain a minimum separation distance from other UAS ahead of it through the concept of bump radius as shown in Fig. 5.
- Reference to the UAS includes the UAS itself and its Bump Radius.
- The status of the UAS (e.g., *Merging*, *FormingGap*) and the gap radius are updated as a part of the heartbeat process.

2) Scenario Description: The AAM scenario considered for the protocol definition is based on a three-layered air corridor system with the lanes at the top layer presenting the northbound and southbound routes, the bottom layer lanes representing the eastbound and westbound routes, and the middle layer assigned to the UAS turning . The turns within the middle layer are conducted using so-called ramps, mimicking the highway arrangement on the ground. Turning traffic is expected to reduce speed; therefore, arranging the turning traffic in a separate layer reduces conflict probability and minimizes potential disruptions between the top and bottom through flows.

Merging process: A UAS attempting to merge searches for a gap around its first entry point based on its ETA to that location. The process of searching for a gap starts by checking

[2]This radius can be utilized in a last resort scenario in case all other communication fails and another vehicle comes into this radius, then a UAS can slow, or stop to maintain, or regain a safe bump radius.

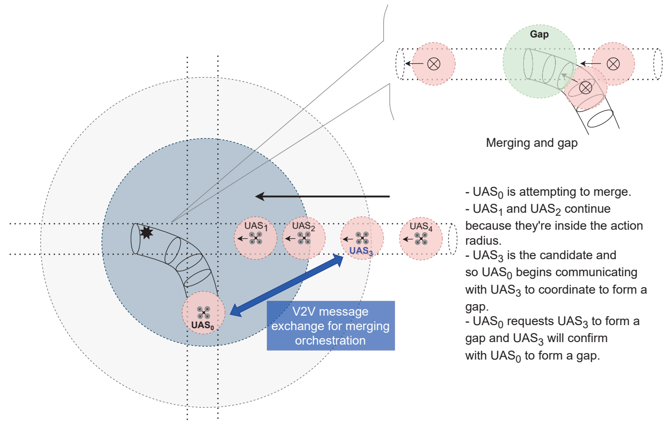

Fig. 5. Merging process.

for a DCT overlap of a conflicting UAS at the desired/needed entry point and checking for spacing of nearby UAS's that would influence the gap. The size of a gap is equal to the gap radius. Once a gap is detected, the merging UAS, depending on its delta envelope, determines if it is possible for it to use the gap to merge. The UAS might not find a gap when the traffic in the merging lane is separated by the minimum distance only, or the gap might not be suitable due to the delta envelop limitations of the merging UAS. As the merging UAS approaches the intersection and in case traffic has been detected, it searches for the best candidate able to slow down or hold to form a gap and is influenced by UAS priority and delta envelope. The first candidate would be the first UAS outside, but closest to, the action radius. The distance between the action radius and the traffic radius exists to facilitate that process (see Fig. 5).

3) Negotiation: The negotiation process is based on the communication between the merging UAS and those in the through lane. The merging UAS sends a gap formation request to the candidates, which are expected to be outside of the action radius but within the traffic radius. The candidates who received the request will confirm the attempt to form a gap and will work on forming it before a soft time limit. A new limit can be set in case the yielding UAS fails to form a gap before the given time. That limit and any changes to it are communicated to the merging UAS that would, in return, attempt to remain near the yielding UAS. Once the latter forms a gap, it sends a confirmation to the merging UAS that would adjust its speed accordingly to reach that gap and merge successfully.

IV. Message Exchange Protocols and Formats

This section provides an integrated view of the three message types and transmission protocols used to exchange messages between UASs in the foregoing scenarios: *Broadcast*, *Direct*, and *Relay*. In this context, the protocol used to send a message dictates how the message propagates through the network as well as the type of content allowed in the message payload. Therefore, each protocol has a unique set of messages

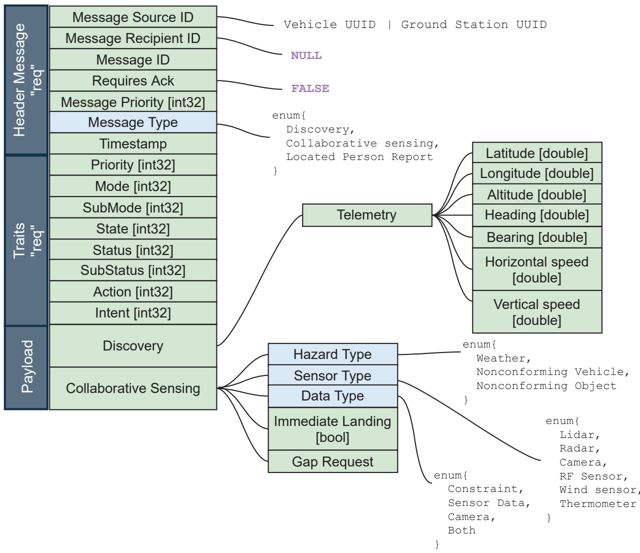

Fig. 6. Broadcast Message

associated with it. For example, the discovery message is associated with the broadcast protocol, so it is known as a broadcast message. Conversely, the re-routing message uses the direct protocol, so it is known as a direct message. Relay messages are special in that they can encapsulate both broadcast and direct messages. All messages follow the same general message format, which includes the message header, traits, and payload.

A. Broadcast Protocol and Broadcast Messages

A broadcast message is a message that is sent to all neighboring UASs within range of the source UAS. Two message types can be broadcast from the scenarios described: *discovery* and *collaborative sensing*. A discovery message, also referred to as a heartbeat, is a message that is periodically broadcast by a vehicle and contains general information about the UAS, such as its UUID and telemetry data. Figure 6 shows the information elements contained within the discovery message. On the other hand, the collaborative sensing message is used to provide sensor or constraint data to surrounding vehicles (as was outlined in Table I).

The broadcast message format follows a general structure where the main fields are:

1) *Message Header* - Contains all the relevant fields for sending a message, including the message source ID, message recipient ID, message ID, acknowledgment flag, message priority, message type, and timestamp.
2) *Traits* - Contains general information on the current state of the UAS.
3) *Payload* - Encapsulates scenario-specific information including, but not limited to, discovery message, collaborative sensing message, etc.

The message header and traits fields provide data on the message being sent and information on the current state of the sender UAS. It is important to note that the recipient ID field is stated as `null` as shown in Figure 6, and there is no need for acknowledgments because these messages are broadcasted. The payload of the broadcast message is determined by what message is being broadcast. For instance, if the message is a discovery message, then the payload contains telemetry of the UAS. It should be noted that there is still room for development with regard to new types of broadcast messages, as those detailed here are a result of the specific scenarios discussed. Therefore, an extensible message format is proposed.

B. Direct Protocol and Direct Messages

A direct message is used to communicate directly between two vehicles as well as a Ground Control Station (GCS) in various scenarios. Similar to the broadcast message, direct messages have the ability to support a number of different informational exchanges while maintaining a standardized format, irrespective of the information being transmitted (with the only notable exception being the message payload). The underlying rationale is to be able to apply this message format to all current and future scenarios for information exchanges. The proposed generalized direct message format achieves this by including common fields with broadcast messages.

Types of Direct Messages: The format of the information contained within the payload will vary depending on the type of direct message being sent. For example, if the contents of two distinct direct messages were analyzed, one for re-routing and the other for a constraint area, then the format of message header and message type fields in both messages would be the same (albeit different values). However, the format of the information contained within the payload would differ between these message types due to the fact that each of their respective scenarios requires scenario-specific information with varying fields. A depiction of the generalized direct message format is shown in Fig. 7.

C. Relay Protocol and Relay Messages

If a message cannot be directly transmitted from source to destination, the relay protocol can be used to relay the message through a series of nearby UASs using a multi-hop connection. The source and destination of a relay message can be either a UAS or GCS, meaning that both have the capability to send and receive relay messages. A relay message is created by packaging a "base message" inside the relay message's payload, thus acting like a wrapper encapsulating the base message inside. Both the relay message and base message use the same generalized message format in accordance with the other message types. It should be noted that the base message can be any message type (excluding relay); however, only two types of relay messages are shown within the scope of this paper. Specifically, in two of the aforementioned scenarios – Airborne Re-routing and Collaborative Sensing – the relay message is used to send updated flight plans and constraint areas, respectively.

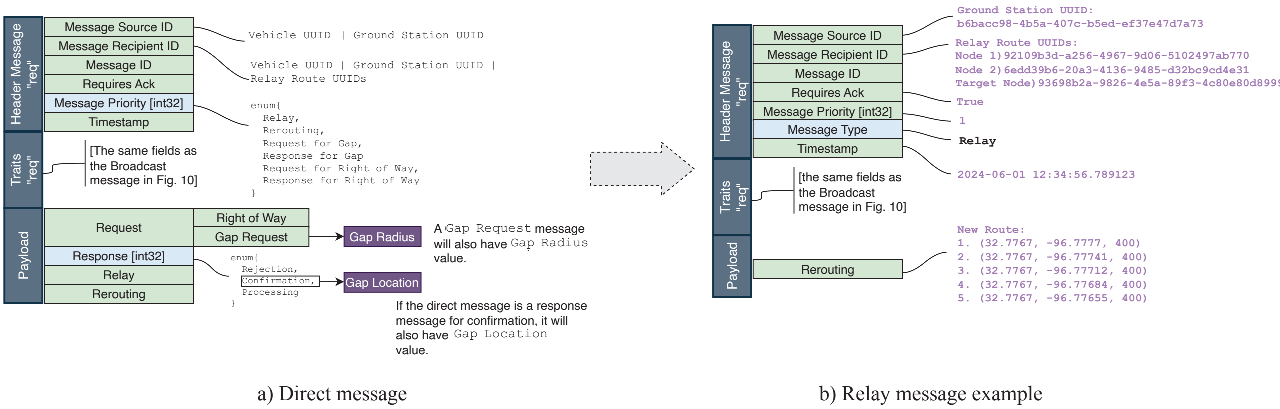

Fig. 7. Direct Message and a Relay message example showing how it is derived from a Direct Message.

a) Constructing a Relay Message: The header, message type indicator, and payload of the base message can be constructed normally and do not require any additional information. As for the fields of the relay message, the message header is to be constructed as normal with one important proviso – the recipient ID field must contain a list of vehicle IDs ordered in correspondence with the path of UASs or "relay nodes" to be taken through the UAS mesh network (excluding the original sender vehicle ID). Including this list offers a way for the UAS receiving the relay message to know which UAS to relay it to next.

b) Processing a Relay Message: Once a relay node processes the relay message, the payload can be extracted and repackaged into a new relay message in accordance with the previous explanation. At this point, the relay node must remove its own vehicle ID from the received list of recipient IDs (the first entry in the list) and use the newly formed list as the recipient ID list included in the message header of the new relay message. The first entry in the newly formed recipient ID list should then be the vehicle ID of the next relay node along the path. This process repeats until it reaches the intended destination, at which point it may extract the base message and process it accordingly.

V. Conclusion

In this paper, we described two use cases for V2V UAS communications from the AAM perspective. This work stems from the recent activities of IEEE P1920.2 WG, which aims to define the V2V protocol for exchanging information between the UASs for the purpose of command, control, and navigation or for any application-specific purpose. Although we have presented some key scenarios, our coverage is apparently not exhaustive. The ongoing discussion in our community, which is served by this work, will be beneficial to converge to a representative set and further identify UAS communications requirements. It is also evident that cooperation and collaboration with other relevant standardization work groups are instrumental due to the multifaceted nature of AAM and UAS communications. For future outcomes, more work on the message formats and more detailed protocol flows while extending the use cases are crucial.

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