UAS Reference Scenarios for MANET Development

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After autonomous flight for Unmanned Aerial Vehicles (UAVs) has been accomplished, research was stipulated to look into application related challenges in connection with Unmanned Aerial Systems (UAS). As one possible scenario, swarms of collaborating UAVs can be envisioned and allow for more complex missions and scenarios.

One essential building block in simultaneously operating several UAVs is the UAS internal and external communication. Ground control station operators need to communicate guidance, navigation, and control (GNC) data, external beneficiaries of the UAS operation need to be provided with obtained sensor data and intelligence. All this requires sophisticated wireless communication networks and Mobile Ad-hoc Networks (MANETs) step into the picture.

However, evaluating the performance of different MANETs in a UAS environment is non-trivial: relevant metrics and evaluation procedures have to be established for a simulation based performance prediction during the design phase of a MANET. Unfortunately, published results on MANET performance are not necessarily comparable across different papers, due to differences in the underlying assumptions. Some findings might not even be applicable to a UAS environment.

This paper proposes a set of reference scenarios in order to allow for comparable and applicable results in MANET simulations. The presented scenarios mimic realistic UAS missions, both, on the operational side of the participating network nodes, as well as on the network traffic side. The reference scenarios capture the essence of current UAVs and UAS missions in a civil, research, or military context, hence providing the means to simulate different MANET protocols in a UAS setting.

I. Introduction

Currently, there is ongoing research in the field of Mobile Ad-hoc Networks (MANETs) for several different scenarios. A large interest is in applications for vehicular traffic scenarios, mobile phone systems, sensor networks, future combat systems, and low-cost networking (1, 2, 3, 4, 5).

Research has focused on topology-related challenges such as routing mechanisms or addressing systems,[6] as well as security issues like traceability of radio communication or encryption (7, 8). In addition, there are very specific research interests such as the effects of directional antennas for MANETs[9] or optimized transmission techniques for minimal power consumption[10] or range optimization.[11]

Most of these research topics aim either at a general approach to wireless networks in a broad setting (and so operate on a more abstract level) or focus on an extremely specific issue that bundles software and hardware challenges into one tailored problem.

Unmanned aerial vehicles (UAVs), and unmanned aerial systems (UAS) in general, need wireless systems to communicate. Current UAS are very flexible and allow for a wide spectrum of mission profiles by means of utilizing different UAVs, according to the requirements at hand. Each mission poses special needs and requirements on the internal and external UAS communication, and special mission scenarios, calling for UAV swarms, increase the complexity and require specialized communication solutions.

The research community has proposed many different MANET protocols and the results of performance tests and comparisons have been published. Though there is interest in the specifics of MANET application

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and implementation , most research is motivated from the communications and networking side - which causes most of the current challenges.

This work presents some new aspects for the development of ad-hoc wireless networks for UAVs and UAS. Focussing on MANETs in the context of diverse UAS environments, this paper presents a set of reference scenarios, providing common basis for MANET development and simulation in an UAS environment.

In order to create a repeatable test setup, which is utilized for comparison and performance evaluation, it is important to describe not only the performance metrics, but also the execution of the test. However, the selection of performance metrics for MANETs is independent of the test execution and not part of the scope of this work [a].

A. Outline of this paper

In Sec. II, the network related specifics of UAVs are introduced and their influence on general MANET development. This covers the specific motion patterns (Sec. B), common networking hardware (Sec. D, and general types of network traffic (Sec. C). In Sec. III, the second major part, the actual proposed scenarios are covered. The actual network load is stated in Sec. A and in Sec. C to Sec. E the reference scenarios are stated.

II. The Actors: UAVs - And Why This Makes a Difference for MANETs

Unmanned Aerial Vehicles compose the majority of the nodes in the discussed network scenarios. This results in several different aspects that are seldom covered in MANET research. Several different peculiarities of a UAS environment effect the utilization (and hence also the simulation) of a MANET in such an environment.

A. Diversity Amongst the Nodes

At this point, UAVs rarely operate in swarms of dozens of vehicles of the same type. UAVs are still considered a unique asset, providing special capabilities to their users. Based on this fact, a pictured UAS MANET will consist of several, physically different UAVs. This is true for the main areas of UAV applications:

Research Environments will normally gradually develop UAVs and hence end up with several different and differently equipped vehicles (if dedicated UAV swarm research is omitted). These will then either be operated in a single-vehicle-only fashion or in a heterogeneous network.

Military Environments tend to utilize UAVs also in a single-vehicle-only fashion (for example a squadron utilizing a MAV for local reconnaissance) or in a larger, more network centric oriented fashion (this would be given, for example, by a HALE UAV observing the global development, coordinating with several MALE UAVs as well as the local ground units and UGVs). The latter also comprises a heterogeneous network.

Civil Applications are mainly limited to SAR or border patrol applications. Examples of these applications show that UAVs in these scenarios are mainly used in a single-vehicle-only fashion[b].

The differences in the environments result in the requirement to introduce a diversity in the nodes when it comes to performance as well as capabilities. Current research mainly focuses on homogeneous networks.

In this work, diversity is introduced by two types of vehicle roles, a supportive and an active one. Details on these roles and how they are utilized can be found in the description of the reference missions in Sec. III. In general the role of the supportive UAVs could be understood as a carrier, an observing mothership, or, if the scenario would be made larger, as a refueling tanker.

Since the GTUAVRF depicts a target implementation environment, Fig. 1 pictures two UAVs operated by the GTUAVRF. The GTMax could be assumed to operate as a supportive UAV, the AFI Hornet Micro as an active UAV.

[a] This decoupling is based on modern network simulators, like `ns2`[12] or Qualnet,[13] to be configurable to record any relevant network parameter during the execution of the simulation.

[b] The US Department of Border Patrol plans to utilize a single Predator UAV at the US/Canadian border, for example (from "Unmanned Systems", December 2007). Missions involving UGVs at Ground Zero were also conducted in a single-vehicle-only fashion, even though the gathered information in both cases is shared afterwards.

(a) The 2lbs AFI Hornet Micro utilizes a MaxStream Wireless Serial Link and an Analog Video Transmitter

(b) The 160lbs GTMax Research UAV utilizes 802.11b/g, FreeWave Wireless Serial Links, and an Analog Video Transmitter

Figure 1. The Georgia Tech UAV Research Facility (GTUAVRF) operates several vehicles, fixed wing and helicopters, which are all able to perform the reference scenarios. Two rotary vehicles have been exemplarily picked to illustrate the diversity amongst UAVsand their networking features and capabilities.

B. Realistic Motion Patterns

The necessity to replicate a realistic scenario has been realized in the field of MANET research a long time ago. Hence, different motion patterns have been developed to account for different behaviors of different networks.

Random Motion obviously is a first implementation. It is easy to create and confronts MANET networks with all kinds of network topology related problems due to motion. This motion pattern is used, for example, to replicate the movement of people in a mall, on a huge plaza, or during other big venue events, like concerts. Parameters are boundaries for velocity of the nodes, pause or halt times, behavior when reaching the boundaries of the simulated area, or areas of congestion (e.g. the food court).

Random Waypoint Models evolved from random motion models and mimic more natural motion consisting from stretches of linear motion, turns, and stops. This was done in order to avoid a Brown's motion-like behavior. In general these models generate a higher amount of directed motion, i.e. nodes do not tend to vibrate more or less stationary in a certain area.

Manhattan Scenarios try to mimic mainly vehicular motion, that is a random motion bound to certain passages (streets). These scenarios work well for vehicular ad-hoc networks (VANET) and replicate the problem of a more coordinated motion.

A common denominator among all these motion patterns is, that they all make sense for a *single node* and that the motion of each node is more or less independent of the motion of other nodes. In a UAS, unfortunately, this separation principle tends not to be true. In the mentioned examples, the whole heterogeneous network is utilized as a single entity in order to accomplish a certain task. This assumes the military example to be of a certain maximum size. Once the network grows too large, obviously several independent tasks can be performed by independent subgroups of a network. This leads to the fact that, in order to create a reference (mid size) UAS scenario, the whole scenario has to be coordinated and planned. The motion patterns of every single UAV has to happen in consistence with the motion of the others and the general task of the mission.

When it comes to representative motion patterns, one feature that has a high impact is whether a UAV has the ability to hover or not. In order to maintain a broad base for possible real missions, the reference mission try to not be restrictive when it comes to that. If there are limitations, the mission will spell that out.

C. Representative Network Traffic

The goal of a truly tailored protocol for an UAS environment also calls for a realistic representation of the expected network traffic. This requirement results in two different factors.

First, the amount of data, the volume of traffic, has to be realistic. The digital communication in a UAS MANET consists of several different parts: protocol related traffic, UAV control related traffic, and mission related traffic.

Protocol Traffic means packets that have to be sent in order to maintain the network functionality. This includes messages exchanged during a node's instantiation as well as messages related to routing, like a possible receive acknowledgement or other low-level network functions.

UAV Control Traffic represents the traffic from control station units to the UAVs in order to set a flight plan, trigger a certain action at the UAV or perform any other kind of control over the nodes. Another part also contains the information the network is providing to its operators in order to establish a general overview about the network status. This contains, for example, all kinds of health status or navigation related information, such as position, velocity, or current fuel consumption of a node. The information in this section in general provides situation awareness for the user.

Mission Related Traffic can be considered the payload of network traffic. This section covers sensor data streams or single critical sensor measurements. The mission related traffic either comprises the reason for the execution of the mission (SAR or reconnaissance missions) or is necessary for mission critical decisions (for example target confirmation procedures).

Some sensors provide analog data streams, however, e.g. analog video cameras. Since relaying this data in analog form is normally avoided due to signal quality concerns, UAVs carrying analog sensors normally operate within a single-hop distance from either the final destination of that data stream (most probably a control station operator) or an appropriate A/D converter. In both cases the analog transmission part in this work is considered negligible, either due to the fact that it is completely separated from the rest of the communication or due to the fact that it could be substituted by a digital data stream, originating at the node which is carrying the A/D converter.

Second, besides a representative traffic volume, also the direction of the traffic is of importance. In recent MANET research there are mainly two types of traffic distributions present. One is a random distribution of traffic source and destination, combined with a small traffic volume per transmission. The other main representation gives a limited number of connections which transfer packets over a prolonged period of time, hence creating a higher traffic volume per transmission and a more sparse distribution of traffic routes.

Even though both models provide certain focus areas for MANETs (the first on route detection and latency, the second on route maintenance and throughput), none of them is suitable for mimicking realistic UAS network traffic. This is mainly due to the fact that main parts of the traffic volume in a UAS network are very directed. Traffic normally is directed towards the users of the network, which is mainly equivalent with the control station node(s) here. This is due to the nature of the UAS network, whose primary task most often is to gather intelligence, i.e. sensor data, and provide it to the human operator (at the control station or behind any other gateway node). This results in challenges due to congestion and contention in the area close to the control station, where area means the nodes in a one or two hop neighborhood of the applicable network topology.

Hence, comparable to the motion part, the network traffic part has to be tailored and created as a whole, adapted and matched to the actual mission and motion situation.

D. Representative Communication Hardware

Along with representative traffic comes the use and simulation of representative communication hardware. In order to stay representative, several different communication devices have to be considered. Unfortunately, especially in a military environment, proprietary or highly specialized communication links and Rx/Tx power specifications outside the legal civil limits are common. The availability of SatCom, for example, is realistic for a military HALE UAV, however, satellite communication poses extra challenges[c] and hence is ignored for

[c]Due to the high latency and the imbalance of up- and downlink bandwidth, special ad-hoc protocols have been developed and simulated for satellite based communication (see for example the satellite section in[12]).

this work. Following a similar reasoning, the list of representative communication units is limited to COTS devices.

III. The Scene: Reference Scenarios

Based on special considerations for UAVs, a scenario has to be created. A scenario describes the combination of a UAS mission and the corresponding network activities. The mission part covers the operational side of the scenario. This would be the motion trajectory and motion patterns, bounds on velocities, and the (simulated) utilized hardware. The network activities describe the actual (simulated) the network traffic. These two parts play into all the fields found to be relevant. The creation of the scenarios was driven by the idea to replicate all of the essential aspects for MANET development in at least one of the scenarios and at the same time create missions that contain all (or at least very many) aspects of realistic UAS missions.

A. Network Traffic in the Missions

As outlined in Sec. C, there are certain parts of the network traffic which are more or less independent of the mission at hand, and these are mainly the protocol and control traffic. The protocol traffic obviously does not need to be artificially created in a scenario, as it is introduced into the scenario directly by the MANET protocol. Hence, only the control traffic needs to be specified beforehand.

In order to obtain representative data, all scenarios copy the control traffic situation of the GTUAVRF. In this work, it is assumed that all mission planning has been done offline and necessary flight plans, trajectories, waypoints, etc., have been transferred a priori. Hence, in all scenarios, no traffic is generated at the control station and uploaded to the vehicles. On the downlink side every mobile node generates two messages during the whole mission execution time. One is a 68bytes message, sent at 10Hz, containing an essential set of data for situational awareness. The second message is a 184bytes message, sent at 1Hz, providing extended status information of the vehicle. As an initial requirement, both messages have to be at least sent to the control station in order to meet the requirement that a control station operator would want access to all the status and health information in order to obtain and maintain situation awareness. In order to mimic the mission data, each (simulated) sensor has been assigned a corresponding traffic volume. The occurrence of this traffic is scheduled according to the reference missions stated below.

Summing this section up, the total network load comprises of the following parts:

- Message 1: 68bytes at 10Hz, originating at a UAV.
- Message 2: 184bytes at 1Hz, origination at a UAV.
- Medium Bandwidth Data Stream: 300kbit/s
- High Bandwidth Data Stream: 1Mbit/s
- Single Event Sensor Data: 2MB

The data for the data streams and the single event sensor data was chosen to mimic medium and high quality digital video streams as well and a digital still picture, respectively. These data rates were considerably chosen to be at these high levels. Utilizing appropriate compression algorithms and depending on the quality requirements, the necessary bandwidth for an acceptable video stream could be much lower, but higher rates were chosen in order to stress the network. It is not guaranteed at this point that any particular MANET can actually handle this network load.

B. General Motion Parameters in the Missions

All simulated missions make a couple of simplifying assumptions in order to keep the scenario generation less complex and to keep the focus on the MANET development, not on multi vehicle mission planning.

- All UAVs operate either at a fixed non-zero velocity or hover.
- All UAVs operate at the same altitude above ground, resulting in a 2D motion.
- No vehicle dynamics are modeled or simulated.

C. Scenario 1: Non-Intrusive Surveillance

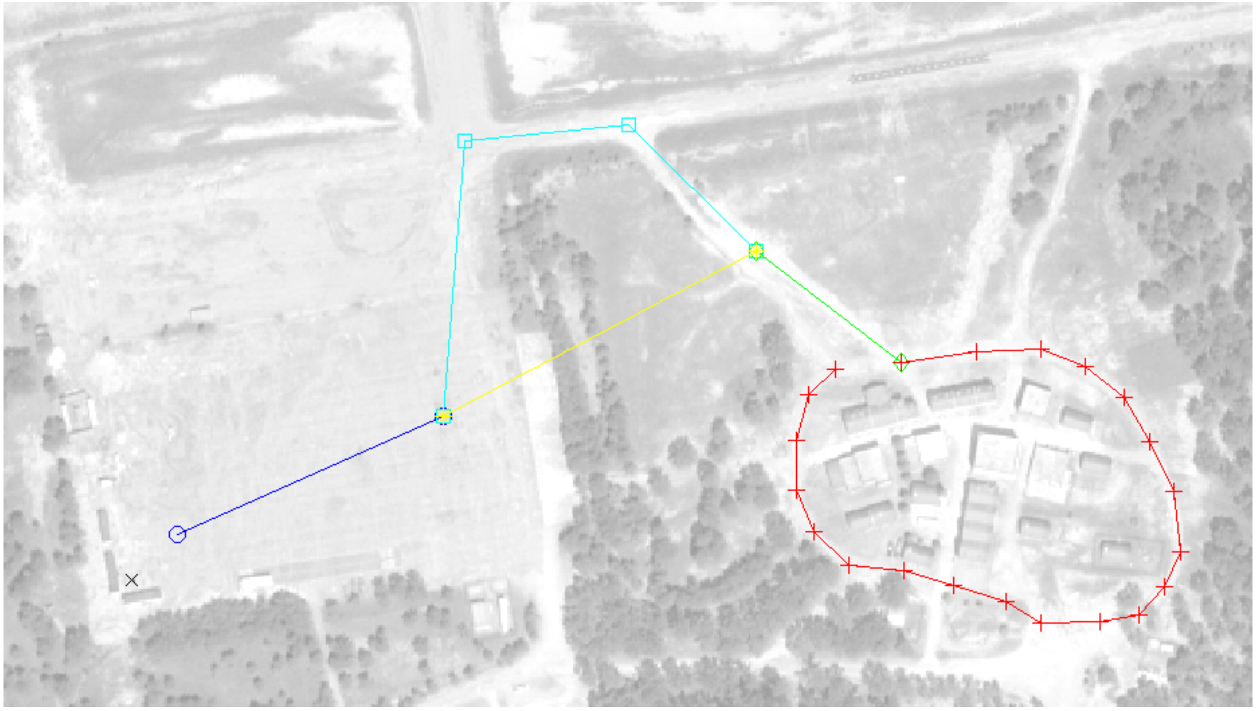

Figure 2. A non-intrusive surveillance mission. The network is tasked to provide surveillance information on an area of interest for some time.

This mission represents the most basic of the proposed reference missions. It intends to mimic a classic beyond line of sight (LoS) operation for either a civil or military environment. The task is to obtain surveillance information of an area of interest and relay that back to the control station. Fig. 2 illustrates the flight plan for that mission. The control station is located in the lower left area of the picture, and the area of interest is given in the right area of the picture.

The mission utilizes eight UAVs in total. Two UAVs play a supportive role while the rest act in an active role. During the beginning of the mission, the UAV swarm approaches the area of interest in formation flight, represented by the blue and cyan colored path in Fig. 2. One UAV in the supportive role stays at the end of the blue path, one stays at the end of the cyan. From there the UAVs in the active role dispatch one after the other towards the area of interest, indicated by the green path. Once at the area of interest, the UAVs perform their continuous surveillance task. In this mission, this is given by flying a surveillance loop around the area of interest, indicated by the red path. After the active UAVs have gone through that loop several times, they return to the loiter position of the supportive UAV at the end of the cyan path and return to the control station from there (following the yellow path), again in formation flight. On their way back they pick up the second supportive UAV.

The loiter positions for the supportive UAVs are recreated as a static point in the simulation scenario, mimicking a UAV with hover capabilities, for example a helicopter. A small circle loiter pattern for a fixed wing UAV without hovering capabilities would also be possible but was not implemented in order to keep the mission generation less complex. The continuous surveillance loop was chosen over static holding points for helicopters for two reasons: in order to allow for fixed wing aircraft to perform the mission as well and to try to be more realistic. A continuous motion in this broader surveillance task provides a more complete overview due to a larger area under surveillance. This is comparable to a civil SAR mission in which, for example, an initial assessment has to be obtained after a chemical spill, earthquake, or wildfire, and the rescue teams need to compile this assessment on a larger area.

The mission traffic situation is given by a single medium quality video stream during the formation flight, originating at the supportive UAV. Whenever an active UAV dispatches from the supportive UAV, this vehicle also transmits medium quality video. During the encircling of the area of interest, several still pictures are taken and transmitted back.

D. Scenario 2: Expanding Search

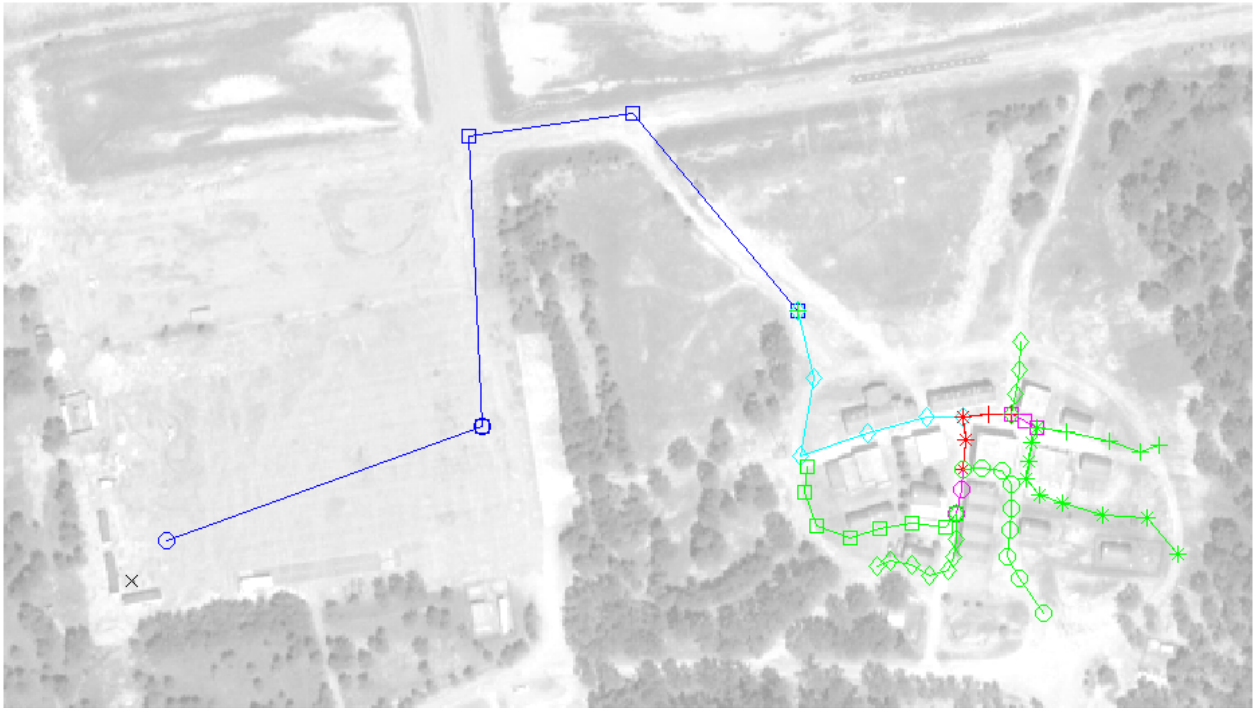

Figure 3. An expanding search mission. The network is tasked to perform an extensive search over an area of interest.

The expanding search mission pictured in Fig. 3 provides a natural extension of the non-intrusive surveillance mission. After an initial assessment has been obtained and further actions have been decided on, the need for a more detailed search arises. In this mission, the task is to map an area of interest in detail and return the gathered surveillance information.

The mission utilizes eight UAVs in total. Again, two UAVs play a supportive role, and the rest act in an active role. The start of the mission is identical to the non-intrusive mission at the control station in the lower left area of the picture. All eight UAVs take off from there and approach the area of interest in formation flight (leaving one supportive UAV at the first square marker). At about the same detach position as in the prior mission (the end of the blue formation flight path), the active UAVs leave the supportive UAV behind and approach and enter the area of interest along the cyan path. Inside the area of interest, the active UAVs split up at the first intersection encountered (the red paths). By repeating this action the active UAVs branch out into the whole area of interest. Once single UAVs are isolated, they keep on going till they reach the boundaries of the area of interest and then return to the loitering supportive UAV at the detach point (green routes). Once all supportive UAVs are back at the detach point, the whole group returns to the control station in formation, picking up the second supportive UAV on the way.

Beside the loitering positions of the supportive UAVs, no other requirement for hover capability is present. However, as stated before, these hover points could also be circular loiter paths.

The mission traffic situation of this mission is the same as in mission one. During formation flight the supportive UAV transmit a medium bandwidth video. After dispatch, all active UAVs engage their medium quality data stream. During the sweep of the area of interest several still pictures are taken and downloaded to the control station.

E. Scenario 3: Coordinated Approach

The coordinated approach mission could be seen as yet another extension of the previous missions. After an initial overview has been gained (mission one) and the more detailed surveillance gathered in mission 2 has been post processed, a specific point of interest has been located and requires extensive surveillance. The

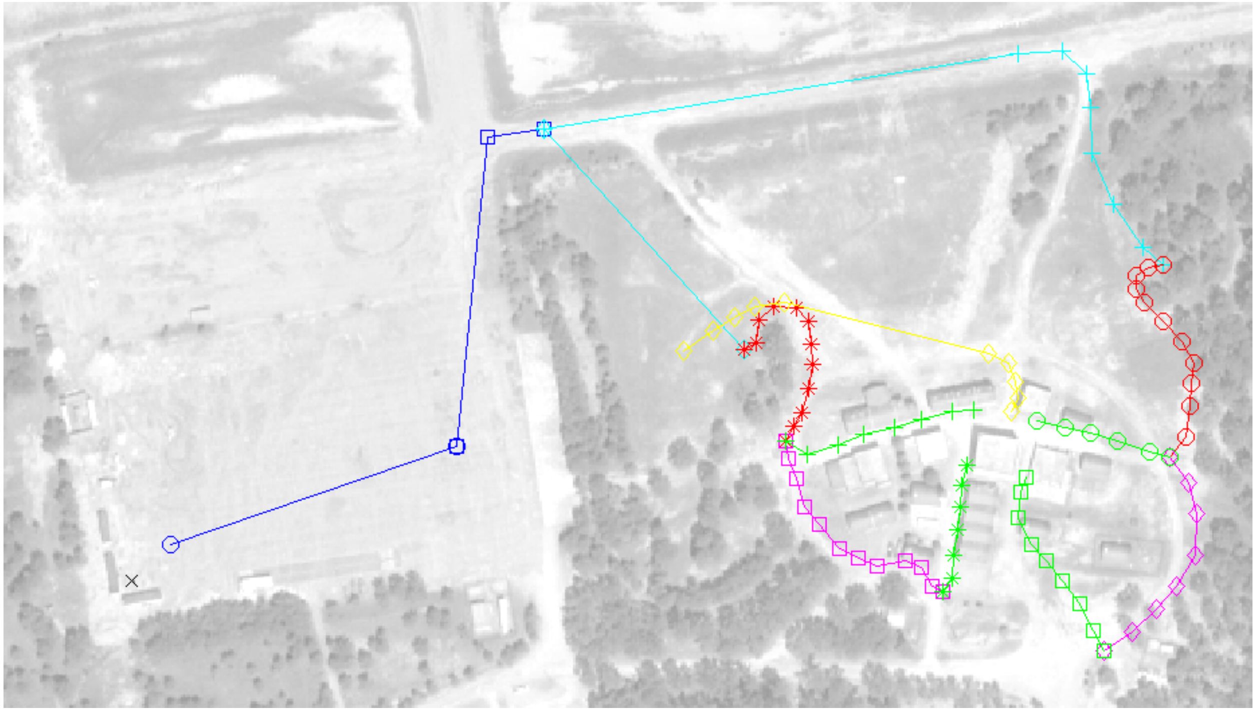

Figure 4. An coordinated approach mission.The network is tasked to approach a point of interest in a coordinated fashion and provide surveillance information.

task of the network is to reenter the area of interest, proceed to the point of interest and provide extended surveillance data to the control station. Fig. 4 showcases the flight trajectories for this mission.

The mission utilizes six UAVs, two in a supportive role and four in active ones, and tries to mimic a more military tailored setup. This is reflected by a more covert approach pattern and holding points at strategic locations. The group takes off at the control station, pictured in the lower left area of the picture, and approaches along the blue path towards the area of interest. The formation of the six vehicles is broken into two groups halfway to the area of interest, indicated by the cyan paths. Each group contains one supportive UAV and two active UAVs and proceeds to the end of the cyan path, the loiter location for the supportive UAV of the respective group. From the loiter points, the active UAVs are dispatched along the red and magenta lines to the starting points of the green paths, taking an observing position at the perimeter of the area of interest. After a short pause, reflecting waiting on an external event, all four active UAVs engage towards the point of interest in the center of the area of interest. This part, along the green trajectories, is coordinated such that all four vehicles reach the point of interest at the same time. Once there the active UAVs perform a short hold, mimicking, for example, aerial support for a ground assault, and then evade the area of interest in formation along the yellow path. This motion is coordinated with the still loitering supportive UAVs such that all six vehicles reach a formation at the left end of the yellow line. The rest of the return to the control station is done in formation.

This scenario is tailored towards a helicopter swarm of UAVs. However, the loitering of the supportive UAVs could be a small circle, suitable for a fixed wing. Also, comparable to the non-intrusive surveillance mission, the hover at the point of interest could be altered into a surveillance pattern, flying around the point of interest.

This mission has a slightly different mission traffic situation, tailored towards the high interest in a single point of interest. During the formation phases only the supporting UAVs send out a medium quality video stream. When dispatched from the supportive UAVs, the active UAVs enable their medium quality video stream. While at the holding position at the perimeter of the area of interest, the supporting UAVs disable their video feeds and the active UAVs enable the high quality video feed. When the active UAVs are leaving the point of interest the video feed quality is dropped back to medium. The supportive UAVs enable their medium quality feed and proceed to the formation forming point, at which the active UAVs as well as one of the supportive UAVs terminate their video feeds.

IV. Conclusions

The presented scenarios cover specific aspects necessary to create a MANET simulation, mimicking a UAS. This covers the involved nodes and their networking capabilities (Sec. II), the motion behavior during a realistic mission (Sec. B), and the network traffic during these missions (Sec. C).

The presented scenarios can be utilized in various network simulators and hence allow for for a performance comparison of different MANET protocols in a UAS environment.

Note

The source code related to the presented scenarios is available upon request from the authors or via their respective website.[14]

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