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Maintaining a permanent connectivity between nodes of an air-to-ground communication network

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Abstract—Unmanned Aerial Vehicles (UAVs) can be a solution for deploying temporary networks by serving as Access Points to users on the ground. The aim is to provide multiple communication services (voice, data, video, etc.) over a specific area. The network must be deployed quickly for a relatively short period (emergency situations, sporting events, etc.), in the case of cellular network overload or blackout. A Flying Ad-Hoc Network will be deployed to cover all the potential users.

The objective of this paper is to investigate the impact of drone replacement due to the limitation of battery lifetime. A constraint for this kind of network is service continuity. For this purpose, an adaptation for the routing mechanism is proposed, to overcome the loss of connectivity observed in the simulations.

In the beginning, a state of the art on use cases employing drones is given, followed by a description of our scenario. Thenceforth, the system is described as well as the deployment mechanism and the induced connectivity loss. In the end, we present a way to adapt the routing scheme so that the network remains connected when a node is replaced due to energy level reasons.

Index Terms—ad-hoc networks, UAV, drone, OLSR, handover, routing

I. INTRODUCTION

Technological advances have allowed the development of a new kind of devices, capable of collecting information (sensors for temperature, humidity, pressure) or generating data (images, video), independently. We are referring to unmanned aerial vehicles (UAVs). They are equipped with means of communication and designed for public usage. From here, one observes, in the scientific literature, a significant expansion of research on machine-to-machine (M2M) networks. Communication between drones and either sensors on the ground or another drones.

The aim of our research is to propose a communication network, available to users on the ground. In addition, the drones can collect information from sensors, take photos or stream video for monitoring. Being in the air, a UAV offers the perfect means to provide a particular service to a group of people or devices. All it is possible due to its maneuverability and the capacity to carry supplementary equipment.

In this paper, we will focus on how to replace the UAVs dynamically, applying the physics principle of electrostatic interaction between electric charges to networking. The initial deployment of the network as well as the optimization of the number of drones used is done by applying the same principle, but its description is beyond the scope of the paper. The need of replacement is due to the short battery lifetime of the drones

and our aim is to maintain a continuous connectivity during this handover.

We must note here that the network has some very specific characteristics. Firstly, it is a temporary network, due to the fact that it is deployed only when necessary. Secondly, it must be suitable for heterogeneous traffic. We consider a variety of applications that can send data (IoT sensors, cameras, voice communications, etc.). Moreover, the lifetime is constrained, as the drone battery charge is an important factor and replacements have to be done without service interruption. Lastly, the network should be affordable since it can be built with off-the-shelf equipment (UAVs, antennas, on-board computers). We imagine that it can be used by event organizers, police, civil security, etc.

The paper is organized as follows. Section II introduces the context and the scenario. Section III offers a more detailed picture of the used system. In Section IV we introduce a drone replacement mechanism using the electrostatic interaction. Section V presents the problems encountered by the routing algorithm during handover and describes our solution. At the end, some research tracks for future work and a conclusion are given.

II. CONTEXT

A. Potential use of UAVs

UAVs are now involved in a large number of different applications. Beginning with military reconnaissance missions that take advantage of the cameras installed on board and of the drones mobility. In the civilian sector, drones are used for taking photos of tourist attractions, for example [1], [2]. Another application is data collecting from sensors on the ground. In the agricultural field, we can collect measurements such as temperature, humidity [3]. Other applications can be mentioned, such as the use of drones in the theme parks or sporting events to entertain the public, or take advantage of the flight abilities to perform 3D models of an area [4].

These applications do not encounter difficulties from a communication standpoint. Each drone is equipped with a storage device that saves the information for later upload on a ground station. They can be classified as DTN (Delay Tolerant Networks). The scientific community has broadly studied this kind of networks, [5].

Other applications require a permanent or quasi-permanent connection between the drones or with equipments on the ground. This allows to adapt the fleet's behavior according

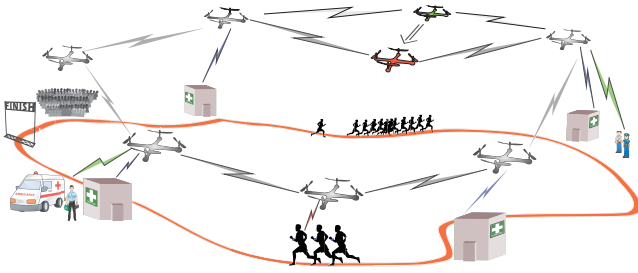


Fig. 1: Studied scenario

to the latest information recorded, the decisions being taken directly by the drones.

For example, a search and rescue operation, where several UAVs are deployed to cover a given perimeter [6]. In this case, we consider a collaborative flying network, FANET (Flying Ad-Hoc NETWORKS). The drones will share data to adapt the search patterns or to stop the searching mission in case that the target was found. In the same spirit, UAVs are used to monitor natural disasters [7].

Other examples of drone uses include border monitoring [8], or assistance for the Fire Department in the case of massive fires [9]. For these purposes, we refer to time constraint networks because the drone must be able to send the data (images, video, sensors measurements) without any delay to a control center.

Thus, we imagine a network consisting of several drones that act as hotspots for teams on the ground (fire-fighters, paramedics, staff). The purpose is to create a local ad-hoc network allowing the exchange of voice calls, capturing images and streaming videos during events or disasters, when the mobile networks are either saturated or inoperable. The next part presents in detail our scenario.

B. Scenario

The aim of our scenario is to deploy a temporary network infrastructure over a particular scene like a public event or a disaster site. This network should be quick to deploy and cheap to implement, with off-the-shelf equipment, so that involved rescue teams (firemen, doctors, public services) or event organizers could afford it.

For a more detailed picture of the context, imagine a marathon in a mountain village, depicted in figure 1. It extends over a fairly large area with several checkpoints where the response teams are located. In this case, there is a specific need for communication means between the teams. In addition, there is a strong demand for monitoring the progress of riders at each checkpoint.

By deploying this network of drones we are able to provide VoIP (Voice over IP) communication service between team members. In addition, UAVs will be able to take pictures to monitor the event. These photos will be sent to the control center on the ground through the network of drones. Sensors positioned on each runner permit, also using the drones, to

identify the position of the racer and each's physical condition in a sporadic traffic flow.

To be able to implement this novel scenario we needed to make some technical choices for our system, presented in the next section.

III. SYSTEM DEFINITION

A. Communication means

This section presents the technical choices made to implement the scenario. For cost reasons, our choices are based on standard, ready-to-buy solutions to facilitate the deployment, but other technical options could be imaginable.

The radio connection between drones as well as the air-to-ground link is based on WiFi and it is assured by directional antennas. Between UAVs, the antennas are oriented vertically in direct line of sight with the peer drones communicating on 5 GHz frequencies. For the WiFi coverage on the ground, another directional antenna is placed on the bottom of the drone offering coverage on the ground. In this case, the frequency used is 2,4 GHz to avoid interferences between on-board antennas.

An experiment performed on two flying drones is presented in the article [10]. The authors study the performances of WiFi communications in aerial conditions using directional antennas. The measured throughput between the machines is acceptable, showing promising results. The paper also states that omni-directional antennas will offer poor performances due to the dissipation of energy in all directions and the different reflection of radio waves in the air.

Another paper, [11], justifies the interest of using directional antennas in this type of scenario. The main idea raised by the study is that omni-directional antennas are subject to high fading, offering a shorter range of coverage, forcing the use of more drones to cover the same area. An example of poor performances caused by the range of omni antennas is presented in [12]. The throughput measurements show that the reachable distance with this kind of antennas is 350 meters. In our scenario we are interested in spacing the drones by at least 1 km and, with omni-directional antennas, this performance can rarely be achieved.

The experimental study presented in [13], proposes to use GSM antennas and the Linux open source BTS (Base Transceiver Station) to cover a given area. The problems facing this solution are the frequencies used to operate this technology. Licensing or the use of free spectrum change from country to country which is and the low throughput of 2G communications are inconvenient for an off-the-shelf data network.

In our scenario we consider using the same network for different throughput demanding applications. For the aerial network to be used worldwide, WiFi will be used as communication standard for its facility to deploy and because no license is needed.

The traffic flowing through our network is presented in more detail in the next part.

B. Traffic characterization

Concerning the application, the generated traffic flows carried on the network can be considered as heterogeneous in terms of constraints. The VoIP communications require a low latency routing algorithm to establish the connection and a low jitter network so it can provide a satisfactory quality of the call [14].

Besides the VoIP calls, a multimedia service will be provided in the form of a live streaming of the events on the ground, offered by the cameras installed on board. This service poses the same kind of constraints as the VoIP calls, with a lesser pressure on the latency [15].

The same cameras will take photos of important events on the ground, or, with the help of dedicated instruments, thermal or night vision photos could be taken. The particularity of the generated traffic stands in the size of the messages. In comparison with the voice or video traffic, where the messages have a relative short size, the image files can induce a fairly high load.

Data containing information from sensors on the ground will also transit the network, [3]. Even though, in general, IoT traffic is often considered as non-urgent, in our case, it provides vital information about the events on the ground and helps to plan the event or the response, in case of a disaster. In the light of traffic carried by the network, a DTN solution cannot be envisaged.

C. Routing in Flying ad-hoc Networks (FANET)

In this part we consider Ad-Hoc wireless networks routing protocols, and more precisely FANET networks. Derived from mobile Ad-Hoc networks, the nodes can move in 3D space, typically designed for UAVs. The same routing algorithms like in MANET networks (Mobile Ad-Hoc Networks) can be used. Several MANET protocols have been adapted to the context of FANET [16].

Routing in MANET networks is quite complex. Indeed, it should adapt to frequent topology changes, and this adds complexity comparing to a network where the topology remains static.

There are two main types of approaches in the Ad-Hoc routing protocols: reactive and proactive routing protocols [17]. Each approach has its advantages and its disadvantages as briefly discussed here.

Reactive protocols establish routes only on demand. An advantage is that they use bandwidth only when needed. However, the establishment of routes can cause delays for the transmitter. This effect can be very disturbing especially in networks where low delay is essential, as is the case in our study.

Proactive protocols will establish all routes and maintain periodically routing tables using a discovery mechanism. The routes are available immediately after the tables were set up. The advantage of this type of protocol is that the node can transmit the packet directly regardless of the route calculation. On one hand, the periodic route update is important especially in a network where the topology changes frequently and

rapidly. On the other hand, the discovery mechanism can cause extra traffic in the network.

For our scenario, we choose a proactive routing protocol, OLSR (Optimized Link State Routing Protocol) [18]. We made this choice as OLSR is well adapted to high density traffic and a large number of nodes, [19], and it was extensively tested in different MANET. Our network represents just a particular MANET for UAVs. Besides, in our context, battery lifetime plays an important role in maintaining the node in flight as long as possible. A reactive protocol would use more power to establish the routes on an on-demand basis compared to maintaining the routing tables with OLSR. Moreover, the VoIP traffic which travels on the network needs as reduced latency as possible. The time needed by a reactive protocol to establish the route will delay the VoIP call. A study [14] on the impact of routing for VoIP traffic in a multi-hop network shows that OLSR is more adapted due to a shorter response time in terms of delay and the resiliency against sequence errors.

D. Network deployment

As for network deployment, the initial placement and the inter-node interaction to maintain and optimize the coverage on the ground as well as between drones is done by implementing an algorithm based on the electrostatic interaction of electric charges based on Coulomb's law. This kind of adaptations have been already used for the movement of robots and the deployment of nodes in Wireless Sensor Networks.

In the literature, [20], [21], [22] this technique is presented as a highly scalable, self-organizing deployment: the decisions being taken on local information. The main idea is that each node can exert a force on its neighbors. Similarly to electric charges, the force can either be repulsive or attractive depending on certain criteria. The main advantage is that they can be tuned to suite up the system's characteristics.

In our case, we choose to consider that too much interference between 2 adjacent nodes will create a repulsive force proportional to interference levels and a low throughput between them will create an attractive force so that the minimum throughput level is satisfied. Likewise, the UAVs are attracted by user hotspots, we presume that the position of hotspots is known, the attractive force being proportional to hotspot's user demand in terms of throughput and services.

In the next section, we will focus on the replacement problem in such a model.

IV. DRONE REPLACEMENT

One technical problem that we tackle in the considered scenario is maintaining a continuous flow of data, VoIP call, live stream, etc., when a drone at the end of battery life, or demanded for a specific task, needs to be replaced. At the best of our knowledge, no work has been done to study this particular issue.

Imagine a simplified scenario such as the one depicted in figure 2. In a network containing four nodes, a VoIP call takes place between two users each connected via a WiFi Access Point installed on UAVs, named S and D . Drones, $R1$, $R2$ and

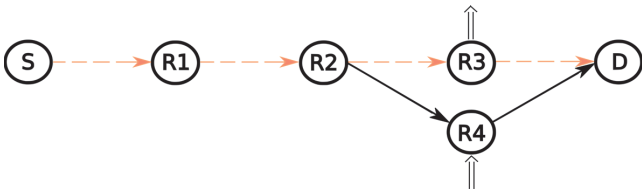


Fig. 2: Paths used to transport data

$R3$, relay the messages from source to destination. During the call, a drone in the middle, $R3$, notify the network that its battery is nearly depleted, and therefore it should be replaced. Another drone, $R4$, will move to this position to replace it. Our interest is to find means of integrating the new drone in the network and reroute the traffic seamlessly. All these maneuvers need to be done while keeping the same quality of service for traffic in the network.

There are different manners in which this replacement could be done. Either the depleted drone is leaving after notifying the network that it should be replaced, or the new drone comes first and it moves into position in the same time as the old one leaves.

In the first case, the deployment algorithm will dynamically adapt the position of the network so that the minimum throughput requirement between $R2$ and D is satisfied. Once the new UAV arrives, $R4$, its repelling effect will force $R2$ and D to move to their original positions and so it could gain $R3$'s initial spot.

In the second case, when $R3$ leaves and $R4$ arrives in the same time, the attractive force between $R2$ and D will cancel out with the repulsive force generated by $R4$, thus the network remains still.

In either case, we noticed a loss in connectivity, observable in figure 3. By observing the duration of the throughput drop we notice that it is approximately 10 seconds, which corresponds to two TC (Topology Control) message intervals. The messages are necessary so that the source is informed about the new route to D . We then imagined that the new UAV would place itself in the proximity of the old one 10 seconds before to allow this message exchange. In figure 3 we notice the same 10 seconds cut in connectivity. In the next section we will study more deeply the causes for this throughput drop and we propose a possible solution that solves the issue.

V. MAINTAINING CONNECTIVITY

A. Problem illustration

At $t = 20$ seconds, a drone, denoted $R4$, as presented in figure 2, begins its movement to replace the node that will soon run out of battery, called $R3$. For another 10 seconds, both UAVs stay next to each other allowing the routing algorithm, OLSR, [23] to integrate the new node in the network. At the time $t = 40s$, the node $R3$ already left the network, being out of the range with its neighbors.

The initial results, depicted in figure 3, showed a loss in throughput at $t = 39$ seconds, right after the departure of the

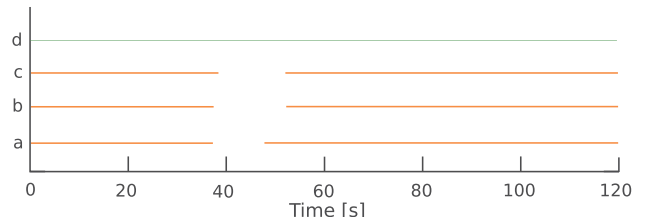


Fig. 3: Connection loss when: a: old drone leaves first; b: new drone arrives first; c: the old drone waits 10 seconds after the new drone arrival; d: our solution

depleted node, $R3$. This signifies that the VoIP calls running through the network will be interrupted. The interpretation is that it is happening because the routing tables are not yet up-to-date.

After inspecting the log files and the routing table on each node we represented in figure 2 the path that the call is taking from the source S to the destination D . In dotted orange, you can observe the path on which the source thinks the packets will go and in plain black, the actual path the packets are using, being influenced $R2$.

In this ns-3 simulation, the node $R2$ decides to route the packets by $R4$, known from `Hello` messages, because of the link $R4 \rightarrow D$ is the last one in its list of links. On the other hand, the routing table of node S does not contain the route $R4 \rightarrow D$, because no TC message was sent, so it thinks that the packets are passing through $R3$, the only available route to D . When $R3$ gets out of range and $R2$ notifies the network that the link is lost, S to stop the transmission since there is no other route to D in its routing table.

The fact that no TC message was sent, is caused by the selection of MPR (Multi-Point Relay) nodes. When $R4$ arrives in position it advertises `Hello` messages to notify its presence. $R2$ calculates then its MPRs. The calculation of a new relay node is mandatory in case $R4$ brings some new routes in the network, thus making it a favorable candidate.

In our case $R3$ and $R4$ have the same number of nodes at a distance $d = 2$, so either one can be chosen as MPR. Due to the implementation of OLSR in ns-3 the first node in the list will be chosen as MPR. As more than one node can reach the same 2-hop nodes, $R3$ will be elected MPR even if $R4$ is a possible candidate.

The fact that $R4$ is no one's MPR signifies that, in respect with the RFC, it should not send TC messages. The consequence of this rule is that the nodes which are not in direct contact with $R4$ will never be aware that another path to D is available.

In the next part we introduce our proposed solution.

B. Proposed solution

To tackle the problem depicted above, we propose a generic control plane charged with the drone replacement management. In this specific scenario, it comes to adapting how OLSR chooses the MPRs. Each OLSR node includes an adjustable attribute called `willingness`. This feature depicts how

inclined a node is to relay messages from other neighbors. Its value varies between 0 and 7. This variable influences the selection of MPRs, the node with the highest willingness, having the same node coverage, will always be chosen as relay. We decided to tie this parameter with the battery level of each drone, thus adapting dynamically the willingness, 7 for an almost full battery and 1 for very low levels of charge.

Therefore the ns-3 scenario was modified to take into account the energy levels and the willingness. The ns-3 implementation of OLSR lacks a simpler way to address the willingness of each node, and the possible values of willingness that are available are 0, 1, 3, 6, 7, leaving us with less room to vary its value.

As expected, after all these adaptations, we tested the scenario and we noticed that R4 has a greater willingness than the other UAVs since it arrives with an almost full battery making it favorite in the selection of MPRs.

In the figure 3(d), we observe that there is no loss in throughput thanks to the election of R4 as MPR once it enters in the network. Now, it will advertise its routes through TC messages, the source being aware that another possible path to the destination exists. When R3 quits the network the source will still have another viable route in the routing table eliminating the risk of communication interruption.

In this section we observed that in our specific scenario OLSR is sensible to node replacement, even if, normally, it possesses some mechanisms to integrate a new node seamlessly. Due to the MPR selection process a connectivity loss between nodes is noticed. To adapt the routing protocol to our circumstances we introduced the battery charge of our drones as a routing parameter by means of the willingness. In the next section we will present some future contributions to our scenario and to the routing mechanisms on which we currently work on.

VI. FUTURE WORK

Our future directions include an in-depth study of the handover process in a more general case of replacement than battery charge. The presented solution works very well in this case, but we think that it will be interesting to see how the network reacts if the replaced UAV is needed elsewhere due to its unique sensors on board and both drones, the one leaving and the replacement, have the same amount of battery charge.

We think the control plane should be defined to bring more coordination among the UAVs. A solution in this scenario could be to modify automatically the willingness based on collaborative and dynamic parameters and generally to define an architecture of this type of communications. This solution should be as generic as possible and it should be based on external factors, depending on the network's use case so that the routing can be adapted as needed without communication losses. Furthermore, even if we focus on OLSR, the solution should be agnostic of routing protocol.

Another interesting subject is network deployment in accordance with user's demands on the ground, position, movement, speed, point of interest. The interesting idea is how to adapt

the network arrangement to cover the demands (voice calls, video steaming, sensor data acquisition) efficiently to conserve battery lifetime and a minimal number of drones.

VII. CONCLUSION

The objective of this paper was to introduce dynamic handover between UAVs due to battery depletion. Firstly, we presented a state of the art of use cases for UAVs and we introduced a new drone network providing multiple types of applications. This network is capable of offering video steaming, thermal imagery, etc., thanks to cameras installed on board, VoIP services for users on the ground and reading sensor data considering its high maneuverability, all via WiFi antennas installed on board. The replacement of drones is done by using an algorithm based on the electrostatic interaction of electric charges.

We brought up the importance of battery life in this kind of networks and the impact that it could have over the routing mechanism and the overall network connectivity. We studied multiple solutions for the dynamic handover and we encountered a routing problem related to OLSR. Maintaining a permanent connection during the handover was done by adapting an OLSR attribute, the willingness, to our needs, in particular, battery charge. At the end we introduced some interesting future research topics in FANET on which we are currently working on.

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