Geofences in the Sky: Herding Drones with Blockchains and 5G

Tamraparni Dasu
AT&T Labs-Research
tamr@research.att.com

Yaron Kanza
AT&T Labs-Research
kanza@research.att.com

Divesh Srivastava
AT&T Labs-Research
divesh@research.att.com

ABSTRACT

Unmanned aerial vehicles (UAVs), typically also referred to as drones, are gaining popularity and becoming ubiquitous. As the number of drones in the sky rapidly grows, managing the expected high-volume air traffic is becoming a critical challenge. It is essential to prevent collisions, and to protect the public from nuisances like noise or invasion of privacy, and shield from hazards like falling debris. UAV traffic management should comply with regulation, spatiotemporal constraints and limitations of drones. Spatiotemporal constraints could be no-flight zones or areas where drone flight times are restricted. Drone limitations could refer to their speed, flight range, telecommunication capabilities, etc. Furthermore, managing air traffic for UAVs is very different from managing the traffic of self-driving ground vehicles. First, there are no clearly-marked roads in the sky. Second, some UAVs cannot hover and must have a cleared flight path. Third, air traffic should be managed in a 3-dimensional space. In this paper we present a vision of air-traffic control based on geofencing. We discuss three operation modes: centralized, decentralized and a hybrid of the two other modes. We present some of the challenges involved in drone traffic control and illustrate how geofencing could be a useful tool for that, while leveraging the emerging 5G networking technology.

CCS CONCEPTS

•**Information systems** →*Mobile information processing systems;*

KEYWORDS

Geofencing, Drone, UAV, traffic control, IoT, 5G networks, blockchain

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1 INTRODUCTION

Drones are increasingly used by companies, governments and organizations, and are expected to revolutionize many areas, including commerce, law enforcement, construction, agriculture, rescue missions, disaster relief, and more. Drones are unmanned aerial vehicles (UAVs) of various sizes and configurations, which are either completely autonomous or partially controlled by a remote human operator. The reduction in their costs and the improvement in the technology are leading to a rapid adoption of drones in a variety of applications. There is a recent growing interest in using drones for myriad tasks, including *(1)* applications of information gathering, and *(2)* applications of cargo transport and delivery.

Information gathering. Drones are being used in a variety of information gathering missions. This includes surveillance and monitoring of areas, aerial photography, terrain mapping (e.g., of inaccessible areas), search for survivors in the aftermath of a natural disaster, aerial scientific surveys, etc. They also assist in structural safety inspection of buildings, bridges, power lines, cell towers, gas pipelines and wind turbines [10]. Drones can gather information without risking aircrew and while flying in places that may be too narrow for a large manned aircraft.

Cargo transport and delivery. Drones can be used for express shipments, e.g., for speedy delivery of letters, small packages, fast food, prescription drugs, etc. [11]. They can deliver aid to survivors in the aftermath of a natural disaster or to people in isolated places.

In addition, many people fly drones for personal uses, as a hobby or to shoot videos of their environment [3, 17], and new uses emerge, e.g., window cleaning for skyscrapers.

The number of drones in the sky grows rapidly. More than 770,000 drone registrations have already been filed in the USA, and the Federal Aviation Administration (FAA) estimates that by 2020 there will be more than 3 million drones in the USA.[1] Managing the traffic in a crowded sky is an important but difficult challenge, especially in urban areas. First, there is a need to prevent collisions—with trees, buildings, bird flocks, airplanes and other drones—including in cases of harsh weather, e.g., rain, strong wind or poor visibility. Second, there is a need to protect people on the ground not only from falling drones and falling cargo but also from noise pollution and privacy intrusion.

Air traffic is heavily regulated. Airplane pilots are required to have a license. They must comply with strict rules and restrictions regarding safety zones, flight trajectories and landing and takeoff times. For drones, the regulation is still evolving. Currently, drone operators must abide by the *line of sight* rule, requiring them to keep the drone within eyeshot at all times, but this could change in the future as drones become more autonomous.

In some of the applications described above, drones must fly in proximity to buildings, people, and other drones. Furthermore, there is a need to take into consideration the following constraints.

(1) Spatiotemporal constraints. Geospatial restrictions may include no-flight zones, e.g., above schools, prisons, federal buildings, power plants, etc. Examples of temporal constraints are limiting flights over residential areas to daytime or avoiding flight

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[1] https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/FY2018-38_FAA_Aerospace_Forecast.pdf

near bird migration routes during migration season. In some places drones may only be allowed to fly above a particular altitude to prevent noise pollution or an invasion of privacy.

(2) Drone limitations. Features of drones should be taken into account in traffic control, e.g., the speed limit and flight range of different drones or the lack of ability of fixed-wing drones to hover. Drones have a limited payload capacity and may only be able to carry a small number of lightweight sensors, e.g., some drones use a single camera and have a limited view or no view of the areas above and behind them. This may circumscribe the ability of a drone to merge into existing traffic from certain directions. In some areas, in particular near skyscrapers, drones may not be able to use GPS. They may still be able to navigate in such an environment [14, 15], but their location may not be as accurate as when using a GPS.

(3) The mission. The task carried out by each drone should be taken into account. Some drones may need to transfer items from one place to another, safely and quickly, e.g., transfer organs for transplant between hospitals. Some missions are in a predefined location, e.g., surveillance, or filming a video of a rock concert. In some cases, the flight trajectory could only be determined in real time, e.g., tracking a car that was involved in illegal activity.

Air traffic management is different from ground traffic management because there are no clearly marked roads in the sky, not all drones can hover (i.e., no simple way to cope with a "traffic jam") and spatiotemporal constraints should be taken into account. The challenge is to provide *(1)* flexibility—the ability of drones to complete their missions, including ad hoc missions and missions where the flight trajectory may change during the mission, *(2)* fairness—access to the airspace should not be denied from individuals and small businesses, and *(3)* safety—of people and drones.

Air-traffic management of crowded skies should take into account the different types of constraints described above, but should also scale and be able to adapt to a rapid increase in the number of drones and traffic volume. It should include *admission control* to guarantee that the number of drones in the airspace or in a part of it does not exceed the maximum capacity in that space.

In this paper, we present a vision of air-traffic management based on *geofencing*, that is by creating virtual boundaries and a partition of the space to help coordinate the flights of a multitude of aerial vehicles. We discuss three modes of operation—centralized, decentralized and a hybrid of these two modes. Our contributions are *(1)* envisioning air traffic management based on geofencing, *(2)* suggesting the use of 5G networks for geofencing in urban areas, and *(3)* presenting a novel decentralized approach to traffic control.

2 GEOFENCING

In *geofencing*, virtual perimeters are set to define the limits of a geographical space [19, 21]. Often, geofencing is used to define an area on a 2-dimensional map, e.g., to provide notifications when a cellular device enters or leaves the defined area [16]. However, in the case of air traffic, there is a need to define constraints in a 3-dimensional space, as illustrated in Fig. 1. To specify a trajectory of a UAV, with sufficient buffer to prevent collisions (e.g., see Fig. 2), the constraint is an area that evolves as a function of time.

Different shapes can specify a geofence, e.g., the perimeter of a cuboid (3-dimensional rectangular box) can define a geofence in a compact way. When using cuboids, it is possible to tessellate the space without gaps, and each cuboid can be defined using merely two points—the two corners of a space diagonal. But when managing cuboid-based geofences, it can be computationally expensive to detect when an aircraft crosses the geofence or is close to it. It is simpler to define a geofence by relating to a distance (e.g., Euclidean, Haversine) from a given point, line or curve. A *spherical geofence* is the perimeter of a sphere. It is specified using a center point c and radius r, and it contains all the points at distance r from c. When the distance of an aircraft from c changes from greater than r to smaller than r (or vice versa), the geofence is *crossed*. When the center point is on the surface of the earth, the geofence has a shape of a dome. A *cylindrical geofence* is defined as the perimeter of a cylinder. An example of a cylindrical geofence is depicted in Fig. 1. Suppose that the center of this cylinder is in coordinates c, its height is h and its radius is r, and let L be the line perpendicular to earth at c. Then, an aircraft below altitude h crosses the geofence if its distance from L becomes less than r.

Flying objects, like drones, should keep a safe distance from buildings, trees, and other drones. They should also avoid crossing a geofence. The safety distance could be represented by a buffer around their flight trajectory. The trajectory for a moving object can be defined in the usual way, that is, as a continuous function $\tau : T \rightarrow S$ that maps times in the time interval $T = [t_1, t_2]$ to the flight space S. For each time t in the time interval T, a buffer of size r can be defined as the sphere whose center is $\tau(t)$ and its radius is r. In Fig. 2, the green line is the trajectory and the gray area is the buffer. Note that the problem of managing moving objects has received a lot of attention in the literature [8, 9, 20, 22], but without relating to drones or creating and using geofences.

There are two types of geofences, those that define the boundaries of a flight space allocated to a particular aircraft and those that aim to prevent aerial vehicles from entering a certain space. To enforce a geofence for an aircraft, the aircraft should know its location and fly accordingly, without breaching the allocated space, similar to self-driving cars staying in their lane. To know their exact location, drones may use GPS, rely on other navigation methods [14] or use network access points [12, 18], especially inside buildings and in urban areas where GPS reception could be limited. A geofence for an area could be implemented by a beacon that transmits the accurate location to nearby drones or by network access points (a cellular antenna or WiFi access point) with a known location and a bounded transmission range. In Section 4 we explain how 5G networks could support positioning and provide much more accurate location estimation than existing networks.

Future research should study effective ways of modeling, specifying and enforcing different types of geofences. There is a need to present new methods of planning flight trajectories in the presence of geofences and effectively allocating space, including the buffer (avoiding allocating unnecessary space).

3 DRONE TRAFFIC MANAGEMENT

Managing air traffic for drones is essentially the problem of allocating a flight space for the time of the flight to each drone, according to the constraints defined by the geofences and the buffers around the flight trajectories. *(1)* Each drone must fly only within the

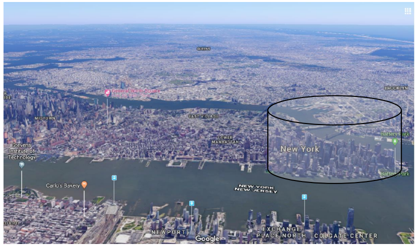

Figure 1: The perimeter of the black cylinder defines a geofence for the financial district of Manhattan, NYC.

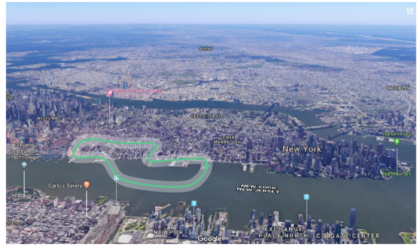

Figure 2: The green line is a planned flight trajectory. The gray buffer defines the flight zone for the aircraft.

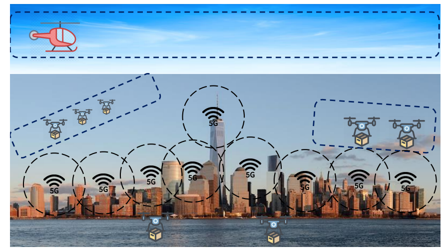

Figure 3: Drones fly in their allocated space. Positioning and geofences are supported by 5G antennas and GPS.

airspace allocated to it, at the time when the space is allocated to it. *(2)* Allocated spaces at overlapping times should not intersect with one another. *(3)* Allocated spaces should prevent drones from crossing geofences into restricted areas. (Enforcing these restrictions should be by the authorities, similar to law enforcement for ground vehicles.) We discuss now three modes of traffic management.

Centralized traffic management. In the centralized mode, space allocation for all the drones is done by a central entity, e.g., in the USA by the FAA or by organizations that were authorized by the FAA. This is similar to the way air traffic is managed today for airplanes. Each drone must get an authorization and allocated flight space for the time of the flight. It may submit for approval a flight trajectory, a space of flight (e.g., as a cuboid), or source, destination and intermediary points. The central traffic control server will return a flight trajectory, with a buffer, or the space in which the drone could fly at the allocated time, limited by geofences that should not be crossed. Changes and handling emergencies could be computed in real-time by preserving free *corridors*, to safely reach a landing spot. The managed space could be partitioned to support parallel space allocation (e.g., allocating flight space in New York should not affect the allocation in Chicago).

Decentralized traffic management. It may be desirable not to give all the control to a single entity, especially regarding flight at a low altitude in urban areas. Also, it could be cumbersome to ask FAA approval for each flight of a small drone. (Recall that for ground traffic there is no central control.) However, it is necessary to coordinate flights, e.g., a fixed-wing aircraft must have a clear flight trajectory because it cannot hover.

One approach to coordinate the flight-space allocation in a decentralized way is by using a *blockchain*. Blockchain is a decentralized, tamper-proof and transparent ledger, managed by peers, connected by a peer-to-peer network. The peers create blocks of transactions and add them to the chain in a way that guarantees consensus regarding the valid transactions and their order. It was initially developed to prevent the "double spending" problem in cryptocurrencies [13], but recently, there has been a growing interest in using blockchains for a variety of applications, including managing IoT devices [4] and geospatial applications [6]. A blockchain can be used for reaching consensus in a decentralized environment. Each drone would try to add to the blockchain a request for the space required for its mission at the time of the flight. Flight trajectories and their buffers would be added to the blockchain only if there is no conflict with a previously allocated space or with a restricted flight zone (similar to the prevention of double spending in a cryptocurrency). The blockchain would guarantee that a space would not be allocated to two different uncoordinated drones at the same time. Each drone will be required to fly only within the space allocated to it.

Note that some existing blockchains have a very low transaction rate, e.g., about 3 transactions per second (TPS) in Bitcoin (https://blockchain.info/). However, new blockchain technologies (permissionless where everyone can create blocks and permissioned where block creators are predefined) with a much higher transaction rate are being developed, e.g., Algorand with hundreds of TPS [7] and Hyperledger [2] with a rate of approximately 3500 TPS and a latency of less than a second. Even if drones would need to add a new request (transaction) every minute, Hyperledger could support flight-space allocation of more than 200,000 drones concurrently.

In the decentralized approach there is no control by a single entity over the allocation of flight space. This will help prevent a bias where large companies or influential organizations gain control over the allocation of the space and severely limit the flight of drones owned by small businesses or individuals. To prevent a *denial-of-airspace* attack, where an attacker takes over the entire flight space, the following two approaches can be used. First, drone operators may pay the municipality for using airspace—with cryptocurrency through the blockchain. This will make it costly to allocate for a flight more space than necessary. The cost of airspace allocation could vary according to the demand, and may take the flight distance into account so that individuals who use drones as a hobby would pay less than companies who use drones for their business. Second, regulation may restrict space allocation per each registered drone, and the transparency and immutability of the blockchain could support its enforcement. That is, a company that would try to block its competitors by allocating more space than needed would have its actions recorded on a transparent and tamper-proof ledger (the blockchain), so it would be easy for a regulator or the authorities to intervene in such cases.

Hybrid traffic management. The hybrid mode combines the centralized and the decentralized modes. Part of the airspace will be controlled by a central authority like FAA. Other parts of the airspace will be available to the public and will be managed through a blockchain. The borders between the centrally-controlled airspace and the airspace with decentralized management could be defined using geofences in an adaptable way that could change based on demand. This illustrates the flexibility of geofences. The centrally-controlled airspace may also be used in cases of emergency and for evacuation routes. Efficiently computing and managing a dynamic partition of the airspace into the two parts of the hybrid mode is an open challenge.

4 USING 5G NETWORKS FOR POSITIONING

To implement geofencing effectively, especially in urban areas (where both the number of drones and number of people who might be affected could be large), there is a need to provide a reliable mechanism to create geofences and to support positioning at a sufficient accuracy, including when GPS reception is bad, e.g., due to high buildings or atmospheric conditions. We envision the use of the emerging 5G networking technology for that.

5G networking technology is the next generation of cellular networks. It is designed to provide much higher speed—larger bandwidth and smaller latency—higher reliability and the ability to serve a larger number of users, in comparison to 4G [1]. To do that, the radio spectrum is partitioned into bands, with different frequencies—from low to extremely high. While 4G networks use frequencies below 6 GHz, 5G will use extremely high frequencies in the 30 GHz to 300 GHz range (millimeter waves). The high frequency supports a much higher bandwidth. Also, due to the short wave length, the antennas are smaller and antennas can be combined to provide MIMO (Multiple Input Multiple Output, using 64-256 antennas) to support many devices concurrently.

In 5G, antennas could be used for much more accurate positioning than 4G, because of the following two reasons. First, the large number of antennas may cause interference. To solve this, antennas will be directional (*beamforming*), that is, cover a small sector rather than transmitting to all directions. Second, high frequency transmissions are easily scattered. They are absorbed by humidity and rain or blocked by buildings. There will be a need to locate many antennas in line of sight with the device, as *small cells*, and in general to deploy many more antennas at a much higher density than antennas of 4G. While this incurs a high cost for telecommunication companies, it supports much more accurate positioning based on cellular reception. The 5G antennas could add to IP packets they transmit the information about their location, bearing and range, e.g., as suggested in [5]. Based on that the aircraft could estimate its own location. See illustration in Fig. 3.

As explained above, 5G will use a range of frequencies, where the low frequencies will allow connectivity when the device is far from the antenna. Overall, the larger bandwidth, better coverage and smaller latency could be used by drones to reliably connect with one another or with the air traffic management system. Computing an optimal positioning of 5G antennas, to support reliable networking using as few antennas as possible, while taking obstructions like buildings and trees into account, is an open problem.

5 DISCUSSION

We discussed the problem of air traffic control for a sky crowded with drones. Given the variety of current or potential uses of drones and the rapid growth in the number of drones, there is an acute need to manage drone traffic. The solution we envision is based on a partition of the sky using geofences. The system could allocate flight space for drones and support admission control. In some cases several drones may be able to share the same space and work in coordination. However, in general, a partition is required to prevent drones from interfering with one another and to reduce the risk of collisions. With the ability to create a partition of the sky, the required space for each flight mission can be allocated either by a central entity or by the use of blockchain in a decentralized fashion. A hybrid mode that combines the centralized and the decentralized modes can be selected. We presented the emerging 5G networking technology and its potential to facilitate positioning in a GPS-denied environment while providing drones with the ability to connect with one another or with the traffic control system.

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