Overview of the Use of Drones for Spectrum Monitoring Applications

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TERMS, CONDITIONS & NOTICES

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Executive Summary

This report summarizes spectrum monitoring technologies and regulations using drones, also known as Unmanned Aerial Systems (UAS) or Vehicles (UAV). Spectrum monitoring is a critical component for the spectrum management process to support functions such as: 1) spectrum assignment and planning, 2) monitoring data concerning the actual use of frequencies and bands including channel occupancy and band congestion, 3) verifying proper technical and operational characteristics of transmitted signals to ensure that technical parameters and standards for radiocommunication systems are adhered to, and 4) detect and identify illegal transmitters. This report focuses on the spectrum compliance activities, i.e., 3) and 4).

Compliance activities by regulators ensures that spectrum is being used as intended. They typically include but are not limited to:1) tower inspection and compliance verification, 2) verification of proper technical and operational characteristics of radiated signals, and 3) detection, identification, and localization of illegal interfering transmitters.

Currently, ground-based sensor systems are mostly used in spectrum monitoring applications. Since ground-based systems have limited antenna heights from the ground, they may experience inferior performance due to the environment such as surrounding urban buildings. In some applications such as tower inspection and microwave link measurements, the desired measurement locations may be inaccessible to ground-based systems. The use of drones for spectrum monitoring has been shown to be a promising technology to counter the limitations and inefficiencies of ground-based systems. Drones have significant benefits for spectrum monitoring including 1) flying to locations inaccessible to ground-based measurements, 2) ascending in altitude providing improved line-of-sight (LOS) to transmitters particularly in mountainous and dense urban environments, 3) making three-dimensional measurements of a transmitter by moving to various heights enabling 3-dimensional antenna pattern measurements, and 4) determining the height of a transmitter.

Drones are aircraft and the operators of drones are pilots. When flying drones, there are rules and regulations that need to be followed. Currently, there are no unified rules for all countries. This report summarizes regulations in Canada, the United States, the European Union, and the United Kingdom. Most countries require special flight authorizations for typical spectrum monitoring scenarios, which takes time to acquire and affects the effectiveness of the use of drones for this application. However, as new technologies such as onboard detect and avoid (DAA) systems are being applied to improve the safety of drones, the aviation authorities are opening the sky for more complex operations. It is possible to work with the national aviation authorities to expedite the process of obtaining special approval or operation waiver for flying drones for spectrum monitoring applications.

There are a few companies offering commercial drone solutions for spectrum monitoring. LSTelecom provides spectrum monitoring services and its subsidiary Colibrex specializes in producing specific-purpose drones for RF measurements. Nokia and Ericsson both have capabilities in their drone operations to measure spectrum but don’t currently provide any services.

We survey the activities by spectrum regulators on the use of drones for spectrum measurement. The International Telecommunication Union Radiocommunication (ITU-R) has published a report on functional components of drone-based monitoring systems. Innovation, Science and Economic Development (ISED) Canada is collaborating to provide air unmanned traffic management (UTM) services to Remotely Piloted Aircraft Systems (RPAS) for Beyond Visual Line of Sight (BVLOS) in rural areas to reduce flight authorization time. The National Frequency Agency (ANFR) in France has been experimenting since 2017 on the use of drones for spectrum measurement activities. The Office of Communications (Ofcom) in the United Kingdom has been experimenting with the use of drones for the last 5 years in rural area to verify coverage and carry out antenna pattern measurements. The Federal Communications Commission (FCC) in the United States does not currently have any drone applications or drone equipment. However, they haven't ruled out use of drones and see the benefits where elevation is required to detect interference.

Academic institutions are making significant contributions on a broad range of research interests benefiting a variety of industries including aerospace and defense, national defense, public safety, conservation, manufacturing, materials, technology, and health. We survey only academic research activities that are focused specifically on the use of drones for spectrum monitoring purposes.

Wide-scale field testing of drone spectrum monitoring techniques is impractical. Simulation is a low-cost solution that requires no special equipment or flying/spectrum usage permits. Requirements for simulating spectrum monitoring using drones include 1) an ability to simulate radio frequency (RF) propagation in a 3D environment and 2) a capability to model transmitters and receivers, including drones, moving in that space. Two types of tools are discussed. The first models the characteristics of point-to-point or point-to-multipoint RF propagation within a static 3D environment. The second type are network simulation tools. Many simulators that support in-depth RF coverage, propagation, and planning (e.g., COVLIB, PathTracer, and Planet) do not support movement of transmitters/receivers during simulation. Most network simulators that support movement have not implemented detailed RF simulation (e.g. NS3 and OMNET++). It is recommended that detailed RF measurements from COVLIB, PathTracer, and Planet can be integrated into OMNET++ using the open source GNU Radio libraries.

We detail considers and observation on the use of drones for spectrum monitoring. We conclude that

- regulation is currently a major limiting factor for drone use in spectrum monitoring. However, situation will improve as regulators are opening more sky as new technologies are being applied to improve the safety of drones.
- multi-rotor drones are best suited for spectrum monitoring, and commercial off the shelf (COTS) equipment available today have the right capabilities to meet the basic requirements for sensor payload on drones for spectrum monitoring.
- Electromagnetic Compatibility (EMC) shielding and Inertial Measurement Unit (IMU) are critical and essential for drone use in spectrum monitoring.

- the capabilities of path pre-configuration and Beyond Visual Lines of Sight (BVLOS) are desirable for drone use. Transportation Canada is currently testing RPAS Traffic Management (RTM) services that may expedite the authorization of BVLOS operations in the future.

We identify and summarize seven use cases where the use of drones can be beneficial: 1) Radio Tower Inspection and Compliance Verification, 2) Cellular Radio Tower Emissions Compliance, 3) Broadcast Station Compliance, and 4) High Power Tower to Tower Interference, 5) Microwave Link Monitoring, 6) Interference Assessment for 5G networks, and 7) Above Ground Interference Detection.

Finally, we conclude that as new technologies such as onboard detect and avoid (DAA) systems are being applied to improve the safety of drones, the aviation authorities are opening the sky for more complex operations. Drones in the future will become less restricted making the use of drones practical for spectrum monitoring.

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Overview of the Use of Drones in Spectrum Monitoring Applications

1 Introduction and Background

Spectrum monitoring is the process of observing the radio frequency spectrum and reporting on its use. It serves as the eyes and ears of the spectrum management process to support various functions such as spectrum assignment and planning [02]. Spectrum monitoring is able to provide valuable data concerning the actual use of frequencies and bands to the spectrum management process (*e.g.*, channel occupancy and band congestion) to: support spectrum assignment and planning functions; help verify proper technical and operational characteristics of transmitted signals to ensure that technical parameters and standards for radiocommunication systems are adhered to; and detect and identify illegal transmitters. Compliance activities by regulators ensures that the spectrum is being used as intended. They typically include but are not limited to [02]

- tower inspection and compliance verification,
- verification of proper technical and operational characteristics of radiated signals,
- detection, identification, and localization of illegal interfering transmitters.

Non-compliance issues can occur due to the complexity of the equipment, interaction with other equipment, a malfunction or deterioration of equipment, misconfiguration of equipment, deliberate misuse or intentional interference. With the emergence of new technologies and the recent phenomenal growth of wireless services, there has been an exponential growth in spectrum usage in the last two decades, leading to a significant increase in the occurrence of interference among the systems. Furthermore, as RF technologies have become increasingly more accessible to the public, intentional interference (typically not malicious) has been observed to exacerbate in recent years [04]. These factors have resulted in increased challenges in efficiently carrying out spectrum compliance activities.

Currently sensors in spectrum monitoring are mostly ground-based, which include fixed, transportable, mobile, manpack and handheld systems. Fixed F systems are installed at permanent monitoring sites with antennas mounted on a tower. They have good line-of-sight (LOS) conditions and wide coverage but at considerable cost. Transportable systems are a simplified version of fixed sensors that can be transported to different locations to carry out temporary spectrum measurement jobs. Mobile systems are systems mounted in vehicles, which carry out spectrum measurements as the vehicles moves along. Mobile systems are flexible but their movement is constrained by streets or accessible pathways. Manpack and handheld systems are small size and lightweight sensors that can be carried by a person. They usually have limited frequency range and low sensitivity and are typically used for last-mile hunting for interference. Ground-based sensors have limitations for certain compliance applications because their antennas have limited height from the ground. For example, ground-based sensors cannot reach to the desired locations to measure signals of microwave links and very-small-aperture terminals (VSATs). In certain geographic areas such as valleys, canyons and urban areas, ground-based sensors may experience measurement difficulties due to blockage and multipath effects caused by buildings and terrain *etc*. For example, it was found that in Korea, ground-based sensors can only monitor 35% of the geographical areas nationwide, and the remaining 65% of the areas is left uncovered [03]. To deal with the inefficiencies of ground-based sensors, there is a growing and increasingly urgent requirement for the development of new flexible deployable monitoring solutions that will allow regulators to carry out spectrum monitoring more effectively and efficiently.

The use of drones for spectrum monitoring has recently attracted interest from regulators and private industries across the world due to their potential advantages and unique features as a complementary technology to current spectrum management practices. Both civilian and military applications have accelerated over the last decade mainly attributed to their steadily decreasing costs and improved technical and safety capabilities and portability. They are also driven by applications and operational requirements which may not be met by other tools or systems.

Drones can be operated with the addition of various payloads and have been used for a variety of civilian and military applications including combat, surveillance, monitoring, disaster relief, agriculture, transportation logistics and security *etc*. Among these applications, monitoring is one of the most popular applications for drones. Generally speaking, all drone monitoring applications are similar and include 1) measurement tools (*i.e.*, sensors), 2) flight-based information acquisition, and 3) analysis based on the collected data. The main differences between different monitoring applications are in the type of drones used, the types of sensors onboard the drones, and how the information is collected during the mission. Drones may also need to be designed and optimized with certain capabilities to adapt to specific applications to enhance the performance and efficiency of the drones. Table 1 shows different industries, by sector, that are currently using monitoring services. They encompass a wide range of industries from aerospace to manufacturing.

Table 1: Industries that Use Drones for Monitoring Service

Private Sectors	**Industries**
Industrials	aerospace & defense services, construction & engineering services, environmental services, manufacturing & facilities' services & transportation services
Communication Services	cell towers & communication facilitators
Energy	exploration of renewable energy
Utilities	generation & distribution of renewable energy
Materials	mining & manufacturing & facilities' services
Information Technology	software, hardware & other related instruments/semiconductors, IT service providers & communications equipment
Healthcare	emergency service providers
Real Estate	real estate services & real estate development
Consumer Staples	manufacturing & facilities' services
Consumer Discretionary	manufacturing & facilities' services

Table 2 outlines the different publicly funded organizations and agencies using drone monitoring services. The definition of a publicly funded organization varies by country but broadly they include law enforcement, regulators, healthcare , education, *etc*.

Table 2: Public Organizations and Agencies that Use Drone for Monitoring Services.

Public Sectors	Organizations & Agencies
Public Safety	law enforcement, military & emergency services
Regulatory Agencies	various
Conservation / Parks & Recreation	various
Transportation	various
Healthcare	distribution of medical supplies; remote medical exams
Education	on-going research & specialized aviation training programs
Public Works Projects	construction & engineering services; inspection & maintenance services & project management services

In spectrum monitoring applications, drones carry RF sensors and/or other types of sensors such as a camera when required. The main advantage of using drones in spectrum monitoring is their ability to elevate far above what a ground-based sensor system can reach. The additional elevation may prove extremely beneficial for countering the inefficiencies of ground-based sensors. Specific benefits of using drones for spectrum monitoring applications can be summarized as follows:

- drones can fly to desired locations, which are usually inaccessible by ground-based sensors, to carry out spectrum measurements. These scenarios include the Fresnel zone measurement of station towers, microwave links, and VSAT ground stations.
- drones can ascend in altitude to provide improved line-of-sight (LOS) conditions to the transmitters. This is important in scenarios such as mountainous areas with complex terrain, and dense urban environments. This benefit is particularly important for interference detection and localization in urban scenarios where severe shadowing and multipath effects make interference localization extremely difficult.
- drones can make three-dimensional measurements of a transmitter by moving to various heights during the measurement. This makes 3-dimensional antenna pattern measurements and interference localization possible. Another use case for 3-dimensional localization is determining both the location of a transmitter and its height. This is important for the resolution of interference in urban scenarios because the regulators may need to know where and on which floor the interference is located. A ground-based sensor can only localize in a 2-dimensional plane.
- drones move fast and over flexible routes, making them efficient in interference detection.

This report provides an overview of activities by various national spectrum regulators, industries, and academics in using drones for spectrum monitoring applications. Note that we may use the terms “spectrum monitoring” and “spectrum measurement” interchangeably. Spectrum monitoring is typically used to refer to long-term continuous measurement and observations of certain sites while spectrum measurement is used to describes the process of measuring RF transmissions of a site at certain specific time instances. The report is organized as follows:

- In Section 0, the rules and regulations for drone flight operations in different countries are described, which include Canada, the US, the UK and the European Union (EU). There are no international standards at this time. Even within a country (e.g., the United States), the laws may be different for each state or province. Note that drone regulations are in a constant state of change. This report only provides an overview as of the time of publication.
- In Section 3, we provide a survey of the use of drone for spectrum monitoring by industries, regulators and academia. The survey is based on both publications in the literature and interviews with managers, engineers, and field operators from regulatory organizations and companies across the world. The companies included are LSTelecom, Colibrex, Nokia, Ericsson and a brief discussion on others. The regulatory organizations include ITU-R (The International Telecommunication Union Radiocommunication), ISED (Innovation, Science and Economic Development Canada), ANFR (The National Frequency Agency) of France, Ofcom (The Office of Communications) in the United Kingdom and FCC (The Federal Communications Commission). Implications of the activities for spectrum monitoring are also discussed.
- Section 4 provides a survey of simulation tools and use cases that could be used for spectrum monitoring simulations. The selection of appropriate tools is one of the key issues with any simulated virtual environment, including its simulation capabilities for drones. Some key propagation and network simulation tools that could be used to evaluate the effect of using drones for spectrum monitoring are discussed, and recommendations of tools are provided for simulating drones acting as a spectrum monitoring and measurement system.
- In Section 5, we discuss the considerations and requirements of drones use in spectrum monitoring applications including drone flight regulations, drone type and weight, sensor payload, EMC (Electromagnetic Compatibility) shielding, path planning, drone navigation and stabilization, and control and data links.
- In Section 0, we summarize and discuss a set of spectrum monitoring use cases that the use of drones can be of benefit to. Finally, in Section 0, conclusions s are provided.

2 Rules and Regulations for Flying Drones

Drones are aircraft and the operators of drones are pilots. When flying drones, there are rules and regulations that need to be followed. Currently, there are no unified rules for all countries. Each country has different specific laws and regulations. In the following, we briefly describe the rules and regulations for drone operations in Canada. The discussions of rules and regulations for the US, the UK and the European Union (EU) are included in Annex B. Note that the EU has recently introduced new regulations for drone operations with the aim to achieve harmonization between EU states and make the regulatory process easier. The new regulations came into effect on January 1, 2021. It is noteworthy that drone regulations by nations are in a constant state of change. What is described in the following text only provides an overview as of the time of publication. Drone manufacturers are working with regulators to enhance airspace compliance by the adding "geofencing" that prevents flights in unapproved airspace.

2.1 Canada

In Canada, flying drones must follow the rules in the Canadian Aviation Regulations (CARs) [05]. Part IX of the regulations contains most of the rules that apply to drones up to 25 kg. What we describe in the following are the new rules that came into force on June 1, 2019 [06].

The new rules apply to all pilots flying drones between 250 g and 25 kg that are operated within the drone pilot's visual-line-of-sight. For drones that weigh over 25 kg or fly outside the rules (above 122 metres or at an advertised event), a Special Flight Operation Certificate (SFOC) is required from Transport Canada. Drones for spectrum monitoring are most likely below the 25 kg weight limit. All drones or Remotely Piloted Aircraft Systems (RPAS) with a maximum takeoff weight of less than 25 kg must be registered, and a drone pilot license is required for flying. Transport Canada has put together a list of drones and operations they are allowed to be used for [06].

Transport Canada categorizes drone flights as basic or advanced operations. The following five conditions are used to determine the type of operation.

- flying in controlled airspace
- flying over bystanders
- flying within 30 metres (100 feet) of bystanders (measured horizontally)
- flying less than 5.6 km (3 nautical miles) from a certified airport or a military aerodrome
- flying less than 1.9 km (1 nautical mile) from a certified heliport

If any one of these conditions is met, the flight is classified as an advanced operation; otherwise, the flight is a basic operation.

- For basic operations, drones need to be registered with Transport Canada before the first flight.
- For advanced operations, extra steps are required. The drones are required to have appropriate safety declarations for the intended operation and to pass a flight review with a flight reviewer. In addition, permission from air traffic control is required if the drones will fly in controlled airspace. The permission can be requested via an RPAS Flight Authorization from NAV CANADA.

While flying, drones must be below 122 metres (400 feet) of altitude and within visual-line-of-sight at all times of either the pilot or a visual observer.

Aside from the specific outline of Basic and Advanced operations, other laws should be respected when flying, including relevant sections of the Criminal Code, Offences against Air or Maritime Safety, Breaking and Entering, Mischief, the province's trespass act laws related to voyeurism and privacy, and the privacy rights of others.

Implications for spectrum monitoring

The weight limit for drones (less than 25kg including payload) is a significant simplifying factor for using drones in any environment in Canada. In fact, most of the drones we have surveyed for monitoring purposes fall in this category. For example, the Tarot T-18 weighs 7.4kg and can carry a payload up to 8kg.

Spectrum compliance activities will likely be considered Advanced operations since they may be conducted in controlled airspace such as downtown core of a city, areas with bystanders, or places close to airports, or flying over people. Advanced operations also have requirements on pilot certification and drone registration. While pilot certification is not a particularly lengthy or expensive process, the longer-term practicalities of ensuring regular practice for pilots does add operational burden to the pilots and the organization. For certain monitoring scenarios, such as in a built-up area and flying above the 400 feet height for tower inspection, an SFOC will be required, which may require defining the area of operation of the drones. In this case, it may be necessary to use ground-based sensor measurement results to determine the area of interest and whether it is in a zone that requires SFOC.

The current process of obtaining an SFOC is lengthy and typically takes a couple of weeks. For interference detection applications, this process is too long to be practical. The application needs to be expedited in a timely manner. The spectrum regulators could have a drone operation waiver from Transport Canada that would entitle them to fly over certain urban areas without going through the application process. Recently, DGEPS (Director General Engineering, Planning and Standards Branch) within the Spectrum Telecommunications Sector (STS) of ISED and Transport Canada are collaborating on the RTM (Remote Piloting Aircraft System Traffic Management) project to test the use of various technologies to provide air traffic management services to RPAS. The technologies include mobile and satellite network technology as a command and control (C2) link to relay data between RPASs and the remote pilot for BVLOS (Beyond Visual Line of Sight) applications in rural areas, and radar for object detection and collision avoidance. With RTM, flight authorizations could be expedited in a timely manner in order to quickly detect and localize interference in the area of interest.

2.2 The United States

Currently, within the United States, most users operate small, unmanned aircraft due to their affordability and ease of operation. For this reason, many regulations summarized on the Federal Aviation Administration (FAA) website pertain to this type of drone. The FAA define small, unmanned aircraft (sUAS) as any aircraft weighing 55 lbs. (25 kg) or less in its entirety, i.e., systems, cargo, and payload and can operate without a pilot on-board. There are four categories of sUAS operators: recreational hobbyists, educational users (teachers and their students), certified civilian or foreign remote pilots, civilian or foreign, and public safety and government organizations. The FAA is adding regulations to require drones to continuously broadcast the drone ID and location, including the controller location.

Both recreational hobbyists and educational users must fly their sUAS solely for personal enjoyment or educational purposes. Civilian and foreign operators who wish to become certified pilots, must pass required knowledge tests, training programs and formally register their aircraft. Law enforcement, fire fighters, and other public safety and government users, have two options. The first option allows individual organization members to become FAA certified remote pilots. The second option allows the organization itself to become a "public aircraft operator" by obtaining a certificate of authority from the FAA granting them the right to "self-certify" remote pilots. In most cases, public safety and government organizations choose the former option All four categories of operators must adhere to the following FAA rules:

- must not operate outside visual-line-of-sight (VLOS) of the pilot,
- must not operate above 400 ft above-ground-level (AGL),
- allowed to operate within controlled airspaces B, C, D & E with Air Traffic Control (ATC) permission,
- allowed to operate in uncontrolled airspace G without ATC permission
- The Operations Over People rule became effective on April 21, 2021. Drone pilots operating under Part 107 may fly at night, over people and moving vehicles without a waiver as long as they meet the requirements defined in the rule. Airspace authorizations are still required for night operations in controlled airspace under 400 feet.
- must not operate under a covered structure or within a covered stationary vehicle,
- must not operate from a moving aircraft,
- must not operate from a moving vehicle, unless operating in a sparsely populated area,
- must not operate carelessly, recklessly, or carry hazardous materials,
- must not fly more than one sUAS at a time.

Certain objectives, industry requirements, research experiments and other uncommon situations necessitate exception to the federal restrictions outlined above. Exceptions are granted on a case-by-case basis by providing the FAA with a detailed proposal. Essentially this includes a completed waiver application accompanied by supporting documentation which is used by the FAA to validate the information outlined in their application.

Individual states vary in degree of government involvement. Most states impose restrictions in addition to federal rules and regulations. These restrictions typically concern law enforcement, civil procedure, and the creation of "no fly zones." A few states choose not to impose further restrictions on unmanned aircraft usage so as not to impede technology development or restrict related commerce.

Implications for spectrum monitoring

Applications for exception to the federal restrictions can be granted on a case-by-case basis by providing the FAA with a detailed proposal.

Many institutions working closely with the FAA receive multiple Certificates of Authority (COAs) allowing them to certify their own remote pilots, enjoy access to hundreds-of-thousands of square miles of airspace, and can operate multiple UAVs simultaneously within the same airspace.

2.3 The European Union

The new EU regulations for flying drones came into force On January 1, 2021, which standardizes drone regulations across the continent. The new rules replace each EU state's existing laws and apply to all drone operators.

- The new European regulatory framework classifies each technology into three separate categories: Open, Specific and Certified. Additional criteria such as weight, certification, operator qualification, and operations will also help determine the category that drones fall into.
- The Open Category is considered low risk and applies to most consumer drones and drones that don't transport goods. Drones operating in this category will not require authorization from a national aviation authority (NAA) for standard operations that fall within its defined scope. The open category is further divided into subcategories A1 (< 250 g), A2 (< 2 kg) and A3 (< 25 kg) depending on the danger posed by its intended operation. Note: all masses specified are mass at take-off including payload and fuel.
    - A1 applies to drones that weigh less 250g. In the operations, drone must not fly over people.
    - A2 applies to drones between 900g and 4kg. In addition to A1 restrictions, the drone operations must take place at a safe horizontal distance of at least 30 meters from uninvolved persons.
    - A3 applies to drones that weigh less than 25 kg. The operation must reasonably ensure the safety of uninvolved people and must be at a safe horizontal distance of at least 150 meters from residential, commercial, industrial or recreational areas.
- The Specific Category applies to drone operations where flights pose a level of risk greater than the Open Category. Advanced operations such as BVLOS fall into this category. There are three ways to operate in this category:
    - The operation is conducted under a Standard Scenario published by the European Union Aviation Safety Agency (EASA) or NAA. A declaration needs to be submitted to the NAA for the operation.
    - The operation is not conducted under a Standard Scenario. Drone operators must perform a risk appraisal according to the Specific Operations Risk Assessment (SORA) or a Predefined Risk Assessment (PDRA) or other alternatives accepted by their local NAA. Authorization will be provided if the mitigations put in place are considered enough to ensure the safety of the operation by the authority.
    - The operation is conducted under the responsibility of an operator with a Light UAS Operator Certificate (LUC).
- The Certified Category applies to operations that are considered the highest risk. For example, a drone flight that involves the transportation of people or dangerous goods would fall into this category.

<u>Implications for spectrum monitoring</u>

Spectrum monitoring operations typically involve drones above 4 kg and less than 25 kg and take place both in urban and suburban area. They would likely fall into the Open Category (A3) and the Specific Category. This requires operators to submit declarations to their NAA and perform proper risk appraisal.

2.4 The United Kingdom

On the 1st January 2021 a new Regulation came into effect in the UK which creates manufacturer standards (class C0 to C6) for any drones placed into the market from 1st January 2023. The following descriptions focuses on Legacy Drones, *i.e.*, drones that are already on sale and operating within the UK.

In the UK, drone flights are classed into OPEN, Specific, and Certified categories according to the level of risk they pose to the public and other airspace users. The Categories dictate where drones of a certain weight and type can fly, and how close they can fly to uninvolved people, crowds and built-up areas.

- The OPEN category: general limitations for (Legacy) drones flying in the OPEN category include the following:
    - Drones must have a take-off mass less than 25kg.
    - Drones must not fly over any assemblies of people.
    - Drones and their surrounding airspace must have direct, unaided VLOS of the drone during the flight.
    - Drones must not fly within the Flight Restricted Zone (FRZ) of a protected aerodrome, or in any other restricted airspace, without the appropriate permission.
    - Drone must not fly close to or inside an area where an emergency response is ongoing, without permission from the responsible emergency service.
- The OPEN category further splits into three subcategories: A1, A2 and A3, and further conditions and limitations apply.
    - The A1 Subcategory is available to Legacy drones with a maximum take-off mass of less than 250g (known as *A1 Transitional drones*). These drones are allowed fly over people.
    - The A2 Subcategory is available (until 31st December 2022) to legacy drones with a take-off mass of less than 2Kg (known as *A2 Transitional Drones*). These drones are allowed to fly close to (50 metres away horizontally from) people.
    - The A3 Subcategory is available to Legacy drones with a maximum take-off mass of less than 25Kg (known as *A3 Transitional Drones*). These drones must fly far (at least 150 metres horizontally) from people.
- The SPECIFIC category: any drone operations outside of the OPEN category must apply to the Civil Aviation Authority (CAA) for permission to operate in the SPECIFIC category. If granted, an Operational Authorisation will be issued, which sets out the parameters within which the drone operations may take place. Standard conditions for flying in the Specific Category include:
    - Drones must have a maximum take-off weight of less than 25 kg.

  - Drones must be maintained within VLOS with a maximum distance of 500m horizontally. Pilots can be assisted by a single Unmanned Aircraft Observer next to the pilot and they must maintain VLOS of the drone and its surrounding airspace during the flight.
  - Drones must not fly more than 120m from the surface.
  - Drones must not fly within the FRZ of a protected aerodrome without the appropriate permission.
  - Drones must not fly within 50m horizontally of any assemblies of people, and within 50m of any uninvolved person, except that during take-off and landing this distance may be reduced to 30 metres.
  - Drones must be equipped with a mechanism to land in the event of disruption to or a failure of any of its control systems, including the radio link, and the remote pilot must have ensured that this mechanism is in working order before the aircraft commences its flight.
- The CERTIFIED category: any drone that has UAS Operations that are very complex or that present the same high risk as manned aviation must apply to the CAA for permission to operate in the CERTIFIED category.

Implications for spectrum monitoring
Spectrum monitoring operations typically use drones that weigh between 5 and 25 kg and are required to fly over and/or near people. Thus, they will not comply with all conditions set out by the OPEN and SPECIFIC categories. This requires operators to be in possession of a non-standard Permission/Operational Authorisation granted by the CAA which exempts them from complying with any of the above.

3 Case Studies in Spectrum Compliance

In this section, we survey the spectrum activities of industries, regulators and academia.

3.1 Industry

There are a few companies offering commercial drone solutions for spectrum monitoring. There are also other companies with mature capabilities and extensive domain knowledge of wireless that could be adapted for spectrum monitoring applications. This section does not specifically cover manufacturers of consumer-oriented drones (e.g., DJI, Parrot, Intel). However, we reference them when end user companies or regulators use them in spectrum monitoring applications. The same applies to specific purpose commercial drone manufacturers (e.g., Boeing, BAE systems).

3.1.1 LSTelcom

LSTelcom AG is a provider of a number of wireless products and services including spectrum monitoring (www.lstelcom.com). Their spectrum monitoring service includes fixed and mobile monitoring devices along with the LS Observer software platform to collect measurements and provide visual intelligence. Their LS Observer platform includes a spectrum monitoring service provided by purpose-specific spectrum monitoring drones. The two drone platforms provide a spectrum measurement capability with direction finding from 20MHz to 6GHz or 32GHz depending on the models.

https://www.lstelcom.com/fileadmin/content/lst/marketing/brochures/LS_Brochure_OBSERVER_AMU_106w_en.pdf

https://www.lstelcom.com/fileadmin/content/lst/marketing/brochures/LS_Brochure_OBSERVER_AMU_132s_en.pdf

How the drones are used is not specified by LSTelcom, rather it seems to be part of the service that they provide.

Implications for spectrum monitoring

LSTelcom provides a wide range of spectrum monitoring products and services of which drones are a part. The company has created Colibrex subsidiary specifically to develop and produce drones targeting the spectrum measurement market.

3.1.2 Colibrex

Colibrex GmbH – a wholly owned subsidiary of LSTelcom AG – specializes in producing specific-purpose drones for RF measurements. The company appears to have two major lines of business: airport wireless systems (e.g., Instrument Landing Systems, Air-Traffic Control, etc.) and RF monitoring for verifying RF links such as pointing errors in microwave backhaul systems, spectrum utilization monitoring, and transmitters localization. The Colibrex drones are fully integrated with LSTelcom's LS Observer product (see above).

The COL-X8 drone by Colibrex is a fully-integrated RF signal measurement system permitting measurements from 20MHz to 50GHz. While details are not readily available, it seems that issues such as weight and EMC have been addressed.

Implications for spectrum monitoring

Colibrex and LSTelcom together have created an integrated solution for spectrum monitoring and interferer localization based on LSTelcom's LS Observer platform. Their solution has been adopted by two spectrum regulators: the Belgian Institute for Postal Services and Telecommunications (BIPT) and the German Federal Network Agency (BNetzA)

https://www.lstelcom.com/fileadmin/content/lst/marketing/spectrum/LS_Spectrum_Broadcast_2019_EN.pdf).

The Colibrex drone does not seem to be network connected which would mean that it is limited to VLOS operation. Also, it means that an RF engineer will need to be physically present with the pilot to interpret spectrum measurements in real-time and guide the pilot to ensure the correct measurements are taken.

3.1.3 Nokia

Nokia Networks has created a drone division: Nokia Drone Networks. A Brochure describing their drone capability at a high level can be found here:

https://onestore.nokia.com/asset/201633

Nokia does not currently offer a spectrum monitoring or interference localization product or service. The main focus of Nokia's drone work is to create a range of LTE and 5G connected drones which can be piloted remotely, even BVLOS. The primary application aims at emergency response situations. Nokia has a modular payload system so that it is possible to swap out cameras, loudspeakers, environmental sensors, etc. depending upon application. Their applications include: 1) search and rescue using visual light and infra-red cameras, 2) public safety alerting using a loudspeaker, 3) visual inspection using cameras, 4) environmental monitoring using various sensors, and 5) delivery of small emergency aid packages (e.g., medicines or an Automated External Defibrillator (AED)). The payload capacity is not specified, but a small AED weighs around 2kg, which may give some indication of potential payload limitations. The drones can be controlled locally or from a central command centre.

Implications for spectrum monitoring

Nokia's solution is a highly flexible platform with options to swap payloads. Given the customizable payload and flexible control options, an additional payload for spectrum monitoring and localization is an easy step to imagine. Nokia's engineering expertise could easily integrate a spectrum measurement payload of less than 3 kg which seems to be within the payload capability of the Nokia drone as well make any necessary upgrades to EMC shielding on the drone itself. Given the modular nature of the payload, perhaps a third-party company could also perform the work.

Nokia's focus is on remotely piloted drones using on-board LTE, or more recently, 5G radios. A network connected drone opens up the possibility of flying a drone BVLOS which is permitted in Canada as long as there is a local "visual observer", which has significant operational implications for spectrum monitoring.

Piloting a drone requires licensing and therefore training and subsequent practice for the pilots to retain their skills. However, remote piloting BVLOS would potentially allow DGSO to employ a smaller number of trained pilots at a centralized location or at a small number of regional centres. The licensed pilots could be augmented by a team of regionally based, non-pilot visual observers who would be responsible for deploying and collecting the drones in the field and remaining within VLOS during the flight. Data streamed back from the drone includes 3D positioning, signal measurements, and time. The data could be interpreted by a centrally located engineering team who would use the data to guide the pilot to ensure that enough data is collected to localize an interferer. Synthesizing the measurements into a likely location for an interferer will require some processing which can be done much more readily in a central location with experts to interpret the emerging signal strength map in 3D.

3.1.4 Ericsson

Ericsson, like Nokia, has developed a drone capability called Ericsson Drone Mobility (https://www.ericsson.com/en/ericsson-one/drone-mobility) which is a "cloud-based platform that enables safe, secure and efficient drone fleet operations". The drones are network connected using on-board LTE or, more recently, 5G radios. Ericsson, also like Nokia, does not provide a spectrum monitoring/interference localization service and their solution seems to be mainly aimed at site inspections using drone-mounted cameras and a cloud-based AI to analyze the imagery of cell towers and installed equipment.

Implications for spectrum monitoring

Ericsson drone could carry an RF measurement payload, then a network connected drone opens up the possibility of flying a drone BVLOS. Depending upon a country's regulations for remote piloting of UAVs, that would potentially allow an organization to employ a smaller number of trained pilots at centralized locations supplemented by a number of regionally located "visual observers". The visual observer's role would be to deploy the drones in the field and remain within VLOS during the flight. Data streamed back from the drone includes 3D positioning, signal measurements and time. The data could be interpreted by a centrally located engineering team who would use the data to guide the pilot to ensure that enough data is collected to localize an interferer. Synthesizing the measurements into a likely location for an interferer will require some processing which can be done much more readily in a central location with experts to interpret the emerging signal strength map in 3D..

3.1.5 Other equipment manufacturers/service providers

Spectrum monitoring using drones is a niche market. The companies above are providing a spectrum monitoring service or have the necessary capabilities to develop one using their existing drone investments. How the market will develop is hard to predict. However, with the proliferation of new wireless deployments and an increasing emphasis on spectrum sharing, there will likely be a growing need for fast-to-deploy, low-cost spectrum monitoring and interference localization solutions.

A closely related market segment is the military's requirement to remotely detect enemy locations based upon radio emissions. It is reasonable to expect that developers of military drones will develop spectrum measurement drones which should, with some modification, be applicable to the needs of a spectrum regulator's role for illegal interference localization and neutralization. For example France's Ministry of Defence recently closed an RFI for a drone to detect and localize RF emissions: https://www.defense.gouv.fr/aid/appels-a-projets/appel-a-projets-pour-une-mini-charge-utile-d-appui-electronique-sur-drones (only available in French).

3.2 Spectrum Regulators

In this section, we survey the activities by spectrum regulators on the use of drones for spectrum measurement, which include the ITU-R, ANFR in France, Ofcom in the United Kingdom, BIPT and FCC in the United States.

3.2.1 ITU-R

ITU-R Study Group (SG) 1 specializes in the areas of spectrum management. SG 1 Working Party (WP) 1C is responsible for studying questions relevant to the area of spectrum monitoring. This includes the development of techniques for observing the use of spectrum, measurement techniques, inspection of radio stations, identification of emissions, and location of interference sources. One of the current topics for WP 1C is spectrum monitoring evolution (e.g., the use of drones and small satellites) [07].

In June 2017, WP 1C established a Correspondence Group (CG) on the use of commercial drones for spectrum monitoring and measurements. The CG is responsible for developing working documents toward a preliminary draft Report and Recommendation. This report details the functional components of drone-based monitoring systems, considerations and limitations, experiments, and use cases. According to the ITU-R report, the functional components of a drone-based monitoring system can be described as having four parts: 1) the drone flight system, 2) radio monitoring and measurement system, 3) the radio mission control, and 4) radio mission remote control.

the drone flight system includes flight control with/without collision avoidance, location and altitude control, horizontal and vertical position control (hovering) and homing (origin) control.

radio monitoring and measurement system includes both equipment for receiving and measuring radio waves and equipment capable of transmitting signals.

radio mission control coordinates the drone as well as the radio monitoring and measurement system to perform one or more tasks. It has a communication link for transferring telemetry and other data to the remote (ground) control station.

radio mission remote control manages the drone radio monitoring and measurement stations during the process of radio monitoring via the mission control link.

The report discusses the considerations for the use of commercial drones monitoring including prerequisites to operation, measurement uncertainty factors, and current limitations of commercial drones. Two experiments and use cases are described in the report. The first use case is the use of drones for measuring radio signals for terrestrial broadcasting. The results are compared with measurements made with a traditional fixed monitoring system. The second use case is the use of drones for detecting and locating VSAT uplink satellite signals.

Highlights of ITU-R activities

The ITU-R WP 1C is in the process of developing a report on the use of unmanned aerial vehicles for spectrum monitoring and measurements. The report details the common elements, considerations on the uncertainty, possible missions as well as use cases of spectrum monitoring and measurement procedures that are assisted by commercial drones.

3.2.2 ISED Canada

ISED Canada's Engineering, Planning and Standards Branch (DGEPS) and Transport Canada are collaborating on the RTM project to test the use of various technologies to provide air traffic management services to RPAS. RTM is also known as Unmanned Aircraft Traffic Management (UTM). The technologies include mobile and satellite network technology as a command and control link to relay data between RPASs and the remote pilot for BVLOS applications in rural areas. Other technologies that are being examined include radars for object detection and collision avoidance. With RTM, flight authorizations could be expedited in a timely manner in order to quickly detect and localize interference in the area of interest.

3.2.3 ANFR

ANFR (http://www.anfr.fr/en/home/) in France manages all radio frequency spectrum in France. ANFR has been experimenting since 2017 on the use of drones for spectrum measurement activities. Their main objective is to study the usefulness, feasibility and practicability of the use of drones for spectrum control activities. They have used both DJI and Yuneec drones A DJI S900 drone was outfitted with an Anritsu spectrum analyzer and 4G modem.

They conducted radio site surveys for different towers heights using drones for visual inspection of antennas and radio stations. A precision barometer was imbedded on the drones to measure the height of the antenna. Different transport flying rules were applied depending on the location of the various sites. They also used spectrum analyzers on-board drones for checking power emissions of microwave links notably at Super High Frequency (SHF) 3 GHz to 30GHz and

Extremely High Frequency (EHF) 30 GHz to 300 GHz bands. Base station antenna patterns and Radio Local Area Networks(RLANs) power levels to ensure compliance. Compact Spectrum analyzers were used at 40 to 80 GHz for frequency analysis of microwave links as shown in Figure 1.

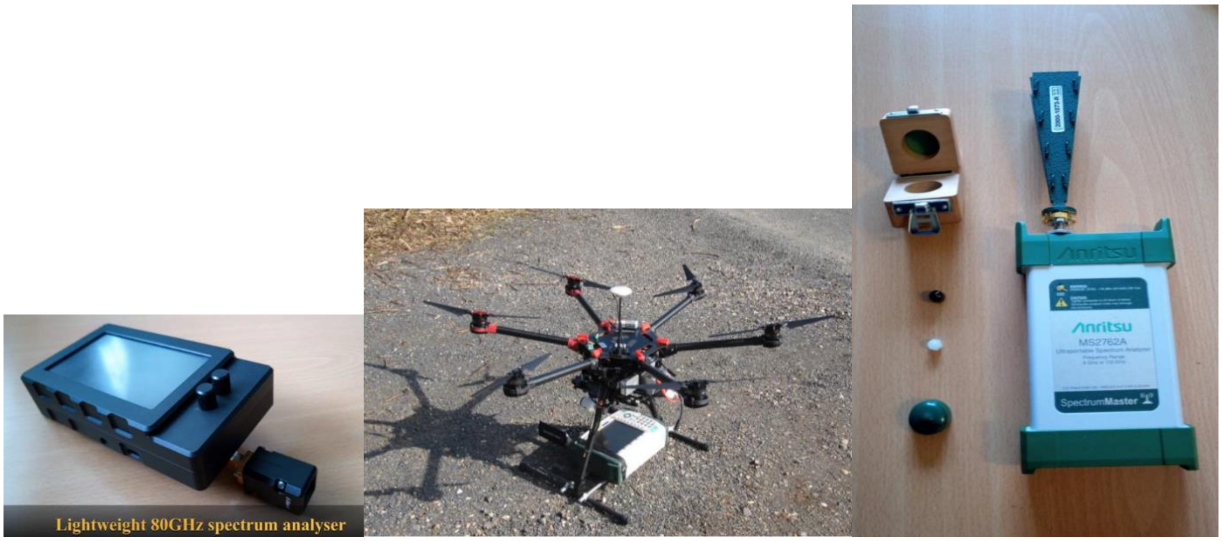

Figure 1: Compact spectrum analyzers and drone used by ANFR.

Additional experiments were performed on localization of Global Navigation Satellite System (GNS) jammers. The use of drones facilitates the localization of jammers in complex areas.

Moving forward ANFR will be studying the feasibility of a "light" measurement drone (e.g., below 4kg including payload) to automatically measure and record frequency, transmission power level measurements, position of drone (position, azimuth, elevation), and time of reception during a flight.

In general, using drones to conduct electromagnetic field measurements is safer than having professionals climb antenna towers, enter fenced zones around towers and rooftops, or expose themselves to high-power radiation from antennas. The use of drones can also reduce the time required to inspect the towers.

Highlights of ANFR activities

- The use of drones is operational for site survey and compliance assessment.
- Interference localization is still at an early stage. GNSS jamming is an issue in France.
- ANFR's preference going forward is to use drone less than 4 kg including payload due to considerations of risk classifications.
- ANFR is currently studying the new EU drone regulations and their impact on the use of drones for spectrum monitoring. The new law came into effect on January 1,2021 and aims to standardize drone regulations across the EU.

3.2.4 Ofcom

Ofcom in the United Kingdom (http://www.ofcom.org.uk) is the government-approved regulatory and competition authority for the broadcasting, telecommunications and postal industries of the United Kingdom. Ofcom has been experimenting with the use of drones for spectrum management activities for the last 5 years. Ofcom is using drones in low-populated areas since British drone flight restrictions are quite rigid. Ofcom can't fly in urban areas without having a special certificate unless there is a park nearby. These certificates are expensive and take time to acquire. They are therefore using drones mainly for verifying coverage and carrying out antenna pattern measurements in rural areas. This is a good use case for using predetermined flight paths and ensuring that there are no gaps in the coverage area between the drone and the pilot. They are also using drones to cost effectively inspect the integrity of their tower masts. Their drones can make thousands of measurements in a short time and in small areas. Previously, they collected such data which relying on a truck that is equipped with a mast and moves very slowly when making measurements. Essentially one can perceive the drone as a super "mobile mast". In practice, Ofcom found that the 20-minute flight time is sufficient to make the needed measurements.

Ofcom purchased a DJI commercial drone and upgraded it to mitigate electromagnetic interference (EMI) issues when flying near high-power emitters. They enhanced it with other upgrades to safely carry a spectrum analyzer and antenna payload.

Highlights of Ofcom activities:

- They have found drones useful and efficient for checking coverage and verifying antenna patterns.
- They would like to use drones for interference localization, but that would be mainly in urban areas and flight regulations restrict that. (Note that the new European drone regulations do not apply to Great Britain).
- They found it more effective to stream data back to the ground in addition to having the data stored in the spectrum analyzer.

3.2.5 FCC

FCC (http://www.fcc.gov) regulates interstate and international communications by radio, television, wire, satellite, and cable in the United States. It is an independent federal agency responsible for implementing and enforcing communications law and regulations in the states. According to communications with staff in the Office of Field Director, Enforcement Bureau (EB), the EB Field Office does not currently have any present drone applications or drone equipment. However, they haven’t ruled out use of drones and are monitoring the latest technology developments. They see the benefits of using drones in situations where elevation is required to detect interference.

3.3 Research Program

Academic institutions are making significant contributions on a broad range of research interests. These contributions benefit a variety of industries including aerospace and defense, national defense, public safety, conservation, manufacturing, materials, technology, and health. In the following, we only include academic research activities that are focused specifically on the use of drones for spectrum monitoring purposes.

3.3.1 Spectrum Monitoring to Detect Radio Interference

In [03], researchers from Yonsei University and Kyung Hee University, South Korea, studied the application of drone technology in spectrum monitoring to detect radio interference. They conducted interviews with experts and literature studies to confirm the feasibility of frequency monitoring using drones. The results of the interviews include:

- for spectrum monitoring using drones, the spectrum analyzer needs to be light weight and capable of analyzing signals in the range of 9 kHz to 6 GHz.
- in addition to the advantage of mobility, drones can be used to identify spectrum characteristics that are currently not utilized in analysis.
- drones can create 3D maps for precise search for interference sources.
- the use of drones is more effective and efficient than ground-based sensors for use cases such as monitoring inter-mountainous base stations, tower Effective Isotropic Radiated Power (EIRP) measurement, and canyon intrusion detection.
- drones with portable detectors can be used in the high-density apartment complexes in the downtown area for detecting interference sources more efficiently than ground-based sensors.
- There are two methods of using drones: 1) the receiver is placed in the vehicle with antenna installed in the drone, and 2) the complete system is installed on a drone. Each has its own advantages and disadvantages.

In 2017, they concluded that there are still technical limitations to be solved including battery life, equipment (spectrum analyzer and antenna) weight and privacy issues. However, the rapid development of the drone technology makes it possible to use drones for spectrum monitoring. When combined with existing spectrum monitoring vehicles and antennas, efficiency is expected to increase in monitoring range and frequency.

3.3.2 Spectrum monitoring using drones and cognitive radio

Researchers from the Institute of Telecommunications Management, National Cheng Kung University in Taiwan developed a prototype of an aerial spectrum monitoring system in 2017, which consists of a ground control station and a four-rotor UAV [12]**Error! Reference source not found.**. This UAV uses a software-defined radio (SDR) receiver to perform spectrum monitoring tasks including signal strength, frequency occupancy, and signal analysis. The lightweight and low cost SDR-based dongle sensor consists of a Realtek RTL2832U chip and a Rafael Micro R820T tuner. It uses the open-source GNU Radio development platform.

The aerial monitoring system can detect radio signals in the frequency range of 25–1700 MHz covering the FM and DVB bands. The authors measured signal strength, and provided waterfall display and demodulation for identifying FM stations. They concluded that the proposed aerial monitoring system is more cost-effective and flexible than land-vehicle monitoring stations.

3.3.3 Radio frequency interference measurements using drones

In [13], researchers from the Centria University of Applied Science, the Finnish Transport and Communications Agency, and the University of Oulu collaborated in 2019 on a trial of an unmanned aircraft for monitoring spectrum usage and interference localization. The aim of the study was to clarify whether there are differences in the capability of finding the interference source from the ground or air.

A fourth-floor flat was selected for the measurement location and the interference source was located on the fourth floor. The commercial UAV DJI S900 Spreading Wings was used. The flight duration was about 15 minutes. A hand-held spectrum analyzer and a log directional antenna were used as a measurement system for determining the power of an interfering signal in all measurements. The trial used a two-phase process: 1) a premeasurement phase that is used to determine the dominating polarity for the RF source, and 2) a second phase that refines the location estimate of the RF interference. Reference measurements were performed at a distance of 45 meters from the RF source on the ground level. The results of the reference measurement on the ground level were compared with the results of measurements in the air using both numerical values and a visual waterfall format.

The comparison showed that the drone-based method was able to determine the height and the floor of the interfering device much more accurately and quickly compared to the use of hand-held devices in a monitoring van. The drone-based method was able to determine the floor of the RF source with an accuracy of two floors while the method using ground-based sensors was unable to determine the height of the RF source. They concluded that drone-based RF measurements are beneficial for national authorities as a tool for airborne mobile monitoring. In addition, the use of drones could be especially useful in challenging urban environments.

3.3.4 Interference Assessment for Private 5G networks using drones

Researchers from Tampere University, Ericsson, and the Centria University of Applied Science in Finland published a paper in 2020 on challenges and solutions in UAV-aided interference assessment for private 5G New Radio (NR) deployments [14]. They outlined the challenges of practical interference assessment of local indoor 5G networks including local licensing regulations, drone operations, regulatory aspects for flying drones, and data acquisition and processing. They concluded that UAV-based measurement systems are ready for interference management, but it would be a major breakthrough if commercial aerial applications could obtain regulatory waivers to operate in BVLOS autonomously and potentially using multiple drones.

They used a proof-of-concept system to illustrate the feasibility of drone-based measurements for estimating outdoor interference from indoor 5G NR systems. An indoor 5G NR base station (BS) is located approximately in the center of the building and is equipped with a directional antenna pointing toward the east wall of the building. The BS operates at 3.55 GHz with a fixed transmission power of 2 watts. The drone carries a mobile network scanner capable of simultaneously measuring signals of different radio access technologies (e.g., LTE and 5G NR). Both an omnidirectional and a directional logarithmic periodic antenna were installed on the drone. The scanner was controlled and monitored by a tablet over Wi-Fi links. The UAV was programmed to follow six pre-defined three-dimensional routes. The study includes four different test cases to explore various antenna beams including main lobe, side lobe, and back lobe. They concluded that data collection would have been significantly more difficult without the aid of a drone for these scenarios. The proposed system offers a more informative interference picture than with the traditional approaches. They also concluded that, as drone hardware technology advances and drone flight regulations become more flexible, drone-based systems will be able to generate larger volumes of data, making it possible to optimize the network in real time based on spectrum monitoring results.

3.3.5 Drone-Based GPS Jammer Localization

In [16], researchers from Stanford University in 2016 demonstrated the use of a drone capable of autonomously localizing the source of GPS jamming in a live jamming exercise hosted by the Department of Homeland Security (DHS). Their system, called Jammer Acquisition with GPS Exploration and Reconnaissance (JAGER), has been developed to address the challenges of rapid localization. JAGER consists of a modified DJI S1000 airframe with a Pixhawk flight control computer. JAGER has GPS, Global Navigation Satellite System (GLONASS), and Locata for navigation. The source of jamming was a COTS GPS jammer provided by DHS. For RF direction finding, JAGER carries a directional antenna and rotate the platform to obtain the bearings to the jammer.

Under the scenario of a single static jammer in an open field, JAGER successfully located the jammer autonomously from various distances using several different algorithms. JAGER reliably determined the direction of the jammer from 800 metres, which is well beyond the effective range of the jammer. The system was shown to be able to rapidly localize a jammer in a large search area. GLONASS and Locata were both used for navigation during the test. JAGER was able to have GLONASS navigation with high availability in the air, but experienced difficulties in close proximity to the jammer. JAGER flew autonomously using Locata probably due to shielding of the antennas of the navigation systems. It was demonstrated that JAGER can locate a jammer from a distance that is greater than effective jamming radius on JAGER and perhaps other GNSS equipment. This result is profound in that it means that JAGER could navigate on GNSS from a standoff distance and still localize the jammer given an appropriate algorithm.

3.3.6 Research Activities by Academic institutions in the United States

Academic institutions in the United States, with established aeronautics research programs, receive significant funding from National Aeronautics and Space Administration (NASA), the Department of Defense (DOD), the Defense Advanced Research Projects Agency (DARPA), the National Science Foundation (NSF), the National Institutes of Health (NIH), military branches and various corporate partners. Many institutions working closely with the FAA, such as the University of Colorado-Boulder, receive multiple Certificates of Authority (COAs) allowing them to certify their own remote pilots, access hundreds-of-thousands of square miles of airspace and can operate multiple UAVs simultaneously within the same airspace. Table 3 lists the institutions in the United States, including programs and goals, that currently carry out research related to drones.

Table 3: Academic Institutions in the United States Currently Carrying Out Drone Research

Institution	Research Programs	Research Goals
Carnegie Mellon University ***Pittsburgh, PA***	• Air Lab, • CI2CV Lab, • CREATE Lab • Microelectromechanical Systems Lab, • NavLab • Intelligent Sensor, Measurement & Control Lab, • Resilient Intelligent Systems Lab • Illumination & Imaging Center,	• Autonomous helicopter obstacle avoidance & landing • fly indoors in visually degraded environments, • develop intelligent semantic mapping, • develop novel illumination & imaging technologies, • enhance computer vision & machine learning capabilities, • further human-robot interactions,

	• NREC • Human-Robot Interaction Group	• develop miniature sensors & actuator systems, • improve autonomous aerial inspections, • perform in real-word scenarios
Marshall University ***Huntington, WV***	• Unmanned Vehicle Laboratory (UVL)	• Enhance wireless communications by developing, integrating & evaluating lightweight digital signature protocols, • improve structural health monitoring (SHM) services, • improve ad-hoc coverage for 5G and beyond
Texas A&M University ***Bryan, TX***	• TEES Center for Autonomous Vehicle & Sensor Systems (CANVASS)	• Unify research & development to better serve state and nation, • enable collaboration across departments, • leverage strength in infrastructure, vehicle systems & algorithms
United States Air Force Academy ***CO***	• The Center for Unmanned Aircraft Systems • Aeronautics Research Center	• Allow one operator to control multiple UAVs at a time that autonomously search, find, identify & track various targets
University of Cincinnati ***Cincinnati, OH***	• Unmanned Aerial Vehicle Multi-Agent Systems Technology Research Lab (UAV Master) • Intelligent Robotics & Autonomous Systems Lab • UC Simulation Center • (5) COAs from FAA	• Unite academia with emergency response teams to assess viability of drones for enhanced situational awareness (Project SIERRA), • locate specified targets in GPS denied environments (Project SUAVE), • provide telehealth services regardless of location
University of Colorado ***Boulder, CO***	• Research & Engineering Center for Unmanned Vehicles (RECUV) • Site for the NSF Center of Unmanned Aircraft Systems • The Unmanned Aircraft System & Severe Storms Research Group • (28) COAs from FAA, Access to 100,000 sq mi of airspace; allowed to operate more than one UAS simultaneously in the same airspace	• Engineer new mobile sensing systems, • promote thoughtful discussion between academics, governments & industry leaders, • facilitate adoption, • increase public awareness, • enhance learning environment
University of Florida ***Gainesville, FL***	• Unmanned Aircraft Systems Research Program (UASRP)	• Save lives of wildlife biologists, • enhance aerial imagery, • optimize data acquisition methodology, • provide valuable scientific data to improve the quality of biologists' research & help administrators make key decisions
University of Michigan ***Ann Arbor, MI***	• Autonomous Aerospace Systems (AASL) • Aerospace, Robotics & Controls (ARC) • Michigan Exploration Lab, • Noise, Vibration & Motion Control Lab	• Develop systems that pilot or aid piloting of UAVs, • research & develop key technologies for the collaborative control of swarms, adversarial strategies, operator-machine interaction, advanced mission planning & other aeronautical control sciences,

	• Constellation University Institutes Project • François-Xavier Bagnoud Flight Vehicle Institute • Michigan/AFRL Collaborative Center for Control Sciences • Dynamics & Control Research Group • Computational Fluid Dynamics Group	• develop methods to calibrate & optimize sensors & systems on small satellites for space exploration, • develop suitable hardware configurations for implementing feedback control algorithms & robust, non-linear, adaptive control algorithms;
University of North Texas ***Denton, TX***	• Unmanned Aircraft Systems (UAS) Research	• Develop quickly deployable networks for emergency responders, • develop systems for traffic: management, communication, reliability & security, • develop approaches for flight safety & controls, • develop lightweight materials embedded with sensors, • develop cost-effective manufacturing for UAV prototypes, • high-fidelity modeling of flight dynamics using in-house IP & computing center

4 Simulation Tools for Spectrum Monitoring

Drones are likely to play a key part in spectrum monitoring in the future and thus evaluating their effectiveness is a priority. However, wide-scale field testing is impractical. Even a large investments of resources would cover only a small number of possible drone scenarios. An alternative would be to use software simulation.

Simulation is a low-cost solution that requires no special equipment or flying/spectrum usage permits. A wide variety of drone monitoring scenarios can be designed, developed and tested in a controlled, virtual environment that does not require constant access to physical equipment. These simulated scenarios could be quickly developed to represent the operational use cases encountered in real-world spectrum operations and could then be validated against a small number of field tests using drones.

One of the key issues with any simulated virtual environment is the choice of software tool and its simulation capabilities for drones. Requirements for simulating spectrum monitoring using drones include: 1) an ability to simulate RF propagation in a 3D environment and 2) a capability to model the mobility of transmitters and receivers including drones. An ability to visualize both the scenarios and the spectrum simulation results would be highly valuable.

Two types of tools are discussed. The first type of tool specializes in RF propagation and can precisely model the characteristics of point-to-point or point-to-multipoint RF propagation within a static 3D environment. Snapshot based simulations can then be analyzed on a set of grid points to simulate the flight path of a drone. The second type of tools are network simulators. These simulators have simpler propagation models but can also simultaneously simulate mobility of multiple transmitters and receivers within a dynamic 3D environment.

4.1 CRC COVLIB

CRC COVLIB is an advanced software package that performs RF coverage prediction, transmitter network design and interference analysis for broadcast and radio communication systems. COVLIB was developed at CRC over many years and enhanced continuously. It includes a group of tools and applications that can be used in different operational systems and in different programming languages. It supports customized high-fidelity terrain data and has excellent performance and accuracy. While COVLIB is good at predicting long-range radio communications, it does not have ray tracing capability. Although it provides good point-to-point RF propagation estimations including those high in the air such as drones, it lacks the full functionality for simulating drones.

COVLIB does not directly support mobility for transmitters or receivers. However, it can still be used for RF modelling on a single case-by-case operation as part of a larger simulation system. In general, COVLIB, when used alone, lacks the full functionality required for simulating drones.

4.2 CRC PathTracer

The CRC developed propagation tool is based on Monte-Carlo ray-tracing leveraging nVidia's RTX GPU technology of GPUs for simulation acceleration. It was developed with mmWave as the primary use case. Currently, PathTracer predicts only the received power level. Future releases may add support for impulse response. Path tracer is designed for short distances and high frequencies (e.g., mmWave and indoor environments). Complex environments can be modeled by combining multiple "snapshots" at the expense of additional simulation time.

Like or COVLIB, PathTracer can be used as part of a larger simulation system. It is not suitable simulation tool, by itself, for simulation of high mobility of drones in outdoor environments.

4.3 InfoVista Planet Engine

Infovista Planet provides RF planning, geodata, network testing and optimization covering an entire wireless-network planning project from indoor to outdoor. In the latest release, Planet also supports Dynamic Spectrum Sharing (DSS) usage of 4G LTE spectrum with 5G NR, both indoor and outdoor design, and crowdsourced data that allows access to a massive dataset for geolocated sample measurement. The Planet Distributed Radio Propagation Engine (DRPE) supports distribution of radio prediction calculations over multiple machines. However, Planet does not support mobility modeling for transmitters and receivers.

Like the two previous simulators, Planet could be used as the propagation model as part of a larger simulation system.

4.4 GnuRadio (OpenSource)

GnuRadio is a free & open-source software development toolkit that provides signal processing blocks to implement software radios. Most blocks are implementations of physical layer components (e.g., filters, decoders, demodulators, etc.). It supports spectrum capabilities not provided by many simulators including In-phase and Quadrature (I/Q) data generation.

Not intended as a standalone system simulator, some features such as mobility modeling and ray-tracing are not supported in GunRadio. It would be best used as part of a larger simulation system to support spectrum capability requirement.

4.5 NS3 (Open Source)

Network Simulator 3 (NS3) is a most popular open-source discrete-event network simulator intended for research and educational use. NS3 can create sufficiently realistic simulation models to be used as a wireless network emulator. It focuses on wireless internet protocol (IP) simulations but is capable of both time and mobility-based modelling. Interfaces exist for NS3 to use more sophisticated physical-layer tools such as GnuRadio.

NS3 is well supported by an active research community and could be combined with a more advanced propagation tool (if needed). Though no specific drone projects are active at this time adding such a capability would be possible.

4.6 OMNeT++ (Open Source)

Omnet++ is an extensible, modular, component-based C++ discrete-event simulation library and framework primarily intended for building network simulators. An advantage of OMNeT++ over NS3 is that it can natively import maps from OpenStreetMap and Sumo. Like NS3, OMNeT++ can generate statistical data on drone operations from any part of the simulation, which include histograms, line graphs etc. OMNeT++ provides visualization of the simulation results in a time-series manner with support for mobility features for ad-hoc or Land Mobile Radio (LMR) networks.

OMNeT++ is well supported by an active user base and could be combined with a more advanced propagation tool if needed. Omnet++ currently has projects devoted to both vehicular and drone-based scenarios.

4.7 Recommendations

Since the CRC drone simulation study will be aiming to investigate the benefits of using drones in spectrum monitoring in terms of improvements of timeliness and accuracy in comparison to ground-based sensors, two types of building blocks must be considered for the selected simulation tool: 1) a propagation modeling and 2) a network simulator with mobility modeling capability.

The choice of a propagation modeling tool depends heavily on the drone scenario. If fine grained accuracy is not required, propagation models such as COVLIB or even the Longley-Rice model would be sufficient to accomplish a coverage analysis at a fixed height without incorporating drone mobility. If more detailed terrain models are available and higher frequency spectrum (such as mmWave) is required, PathTracer or Planet can be applied to provide more accurate results.

Network simulators are needed in order to generate time and space varying (mobility influenced) spectrum data from dynamic drone scenarios. An open-source tool should be considered when investigating the use of drones for interference detection and localization in urban scenarios as they are better connected to academic research and reflect the most recent development of technologies. The open-source network simulator OMNeT++ currently has working drone models and is highly extensible, but has only simplistic propagation models built in.

Overall, it is recommended that OMNeT++ be used for investigating the use of drones as part of a spectrum monitoring and measurement system for the scenarios outlined above. The lack of granularity and precision of the built-in propagation models in OMNeT++ can be enhanced by replacing the existing models with a fast tool such as COVLIB or slower but more detailed tool such as PathTracer or Planet Engine if needed.

5 Considerations and Observations of Use of Drones for Spectrum Monitoring

Like most conventional ground vehicle-based spectrum monitoring systems, a spectrum monitoring system using drone is a complete RF receiving system that includes an antenna (and/or other types of sensors such as cameras, barometers), receiver, storage, networking, and online analysis. The only difference is that all the equipment is mounted on drones with limited payload weight and access to power supply. In the following we will discuss some considerations and requirements for the use of drones in spectrum monitoring.

5.1 Regulations for Flying Drones

There is currently no universal set of unified rules for all countries, and each country may have different specific laws and regulations. Each nation has regulations limiting flight regions, time of day, and flight controls for each type of drone. It is necessary to contact the appropriate national regulatory authority in advance of flying. Pilots must clearly understand the categories that the planned drone flight falls into and follow all regulations. In most countries, no special approval (e.g., SFOC in Canada) is required if the drones weigh less than 25 kg, the flight will not be operated in controlled space, and the drone will not fly over or close to bystanders. Otherwise, special authorizations will be required and the length of time to receive an authorization to fly inhibits the effectiveness of drone use for spectrum monitoring.

5.2 Drone Type

There are various types of drones, the majority of which can be categorized into two types: fixed-wing and rotary. Fixed-wing drones use fixed, static wings while rotary-wing drones use one or more rotor-blades or rotor-wings. Each has its own advantages and disadvantages. Multi-rotor drones have the unique feature that they can tightly navigate around infrastructure and remain stationary (hovering) and are probably the only and suitable option for spectrum monitoring applications. In Canada, the 25 kg weight limit including payload significantly simplifies drone use. Most drones identified in this survey are 25 kg or less. Current drones have limited range and endurance due to power supply constraints but are expected to with improve with technology advances.

Transport Canada has list of drones that meet safety requirement and can be used for advanced operations.

5.3 Drone Operation Cost

The cost of purchasing a drone platform for spectrum monitoring purpose is far below that of the most basic mobile sensor system [08]. However, additional costs for drone operations should be considered including training of the pilots and maintenance of the equipment. Future autonomous drone technology will remove pilot licensing costs.

5.4 Sensor Payload

Virtually all kinds of payloads can be attached to drones with the only restrictions being the weight and size of payloads. For spectrum monitoring, RF sensors are required. Cameras will be required in visual inspection applications. The frequency range and sensor sensitivity should also be considered. Since drones are a relatively small, there are many structures around the antenna that may interfere with signal reception from certain directions. In some cases, it may be necessary to mount a laser reflector to achieve more accurate positioning.

A sensor payload for spectrum monitoring comprises a spectrum analyzer, antenna, a computer for control and analysis, and optional radio links to send results back to the ground stations. There are two types of RF systems that are appropriate for drones. The first are the small or handheld spectrum analyzers commercially off-the-shelf (COTS). They can measure spectrum well into the mmWave range and weigh generally between 0.5 and 3.5 kg. A representative selection can be found at the Newark site (https://canada.newark.com/c/test-measurement/rf-test-equipment/spectrum-analyzers?spectrum-analyzer-type=handheld). The Tektronix RSA306B weighs only 0.75kg and can measure RF signals from 9 kHz to 6 GHz. The SAF Tehnika analyzer weighs 0.57 kg and can be configured to measure from 300MHz to 87GHz.

The second type are software defined radio (SDR) receivers. SDRs have the advantage of changing system configurations dynamically during a flight. They can be remotely configured during an operation. There are many well-developed software development platforms available for facilitating the design of SDR-based receivers. National Instrument's Ettus Universal Software Radio Peripheral (USRP) B200 provides a fully integrated single board platform with continuous frequency coverage from 70 MHz to 6 GHz with up to 56 MHz of instantaneous bandwidth. The B200 weights 350g with a size about the size of a deck cards. CRC has been developing B200-based sensors for spectrum monitoring for a number of years.

Small and lightweight antenna options for use with drones also exist. For example, the Aaronia Hyperlog 7060 antenna AG weighs 270 g and has a frequency range of 700 MHz to 2.5 GHz (https://downloads.aaronia.com/datasheets/antennas/HyperLOG/Aaronia_HyperLOG_70_Logper_Antennas.pdf##)

The COTS equipment available today have the right capabilities to meet the basic requirements for sensor payload on drones for spectrum monitoring. Further optimization of the payload is also possible but does not seem to be requirement given the state of COTS equipment capabilities. The optimization includes integration with the drone avionics, reduction in weight, and harden EMC etc.

5.5 EMC Shielding and Close Proximity Monitoring

We consider Electromagnetic Compatibility (EMC) shielding a critical requirement in using drones for spectrum monitoring. EMC shielding is any method used to protect a sensitive signal from external electromagnetic signals or preventing a stronger signal from leaking out and interfering with surrounding electronics. Colibrex drones are designed with EMC capability. They consider EMC influences and limitation of interference to measurements. However, most commercial drones do not have EMC considerations. Experience in the field has found that with general purpose commercial drones, it is necessary to improve EMC shielding for close proximity measurements. In monitoring applications, drones and payloads may be exposed to high strength electric fields caused by high-power transmitters and high voltage power converter stations. The electronic systems onboard a drone may also experience EM interference from the electric motors and power supplies onboard the drone. EM interference may degrade the system performance and can damage onboard electronic systems. In worst case, it can cause the drone to crash. EMC shielding is achieved by using a metallic screen to block electromagnetic interference, which will affect overall drone weight.

Close proximity spectrum monitoring refers to operating drones close to a powerful transmitter (e.g., radio or television (TV) broadcast stations) without overdriving the receiver or damaging the antenna while being able to maintain a certain level of sensitivity of the sensor payload. RF receivers have a maximum RF power allowed at the receive antenna. This is the maximum input power level allowed before damage occurs to the low noise amplifier at the front-end. In close proximity interference detection and localization, the transmitter locations are unknown to the operator and it is likely that drones may fly close to the transmitters. To mitigate such situations, capabilities such as pre-selection (filtering banks or pre-filter) and automatic gain control (AGC) can be used. AGC allows for weaker signals to be monitored within a pre-selected band.

5.6 Path Pre-configuration

The capability of a drone to follow a pre-configured path using optimized path planning algorithms is desirable for spectrum monitoring. An optimized path can be computed before an operation using path-planning algorithms based on the goal of the operation. Benefits of this approach include: 1) minimizing battery drain and extending operation range, 2) improved statistics through the collection of multiple samples along repeated paths, 3) reduced accidental collisions, and 4) avoidance of known high power transmitters to avoid being overloaded. Currently, most manufacturers use simple waypoint GPS navigation. Future dynamic in-flight path planning may become common particularly for BVLOS operations.

5.7 IMU and Flight Control

Inertial Measurement Unit (IMU) and flight control technologies are essential for the use of drones for spectrum monitoring. They are used to ensure that drones fly smoothly and in controlled orientations. This is particularly important for drones equipped with camera and directional antennas. Most drones are equipped with GPS systems that provide location data necessary to perform functions such as position hold, autonomous flight, return to home, and waypoint navigation. However, GPS may not always be available in urban areas or in areas with irregular terrain. In addition, GPS is susceptible to jamming and interference.

IMUs are the main component of an Inertial Navigation System (INS), which allows the drones to determine their position, velocity, and attitude without relying on GPS. An INS it is not susceptible to jamming. The flight controller receives information from both the IMU and GPS, and fuse them to control the movement and altitude of the drone. If some of the sensors are denied or fail, the flight controller can still position the drone.

5.8 BVLOS Capability

BVLOS operations allow drones to fly beyond the pilots' visual range. This is particularly important for using drones for spectrum monitoring in urban scenarios. BVLOS operations require additional technologies and connectivity including:

cameras provide an first-person view (FPV) to pilots. BVLOS require high-bandwidth, long-range, low-latency, high-reliability datalinks between the drone and the operator to transmit video.

various onboard sensors are required to gather data that allow drones to fly autonomously. The acquired data require a long-range telemetry and command & control link with a ground station, via radio, cellular or satellite connections.

detect-and-avoid (DAA) or sense-and-avoid (SAA) capabilities allow drone to avoid nearby obstacles and air traffic by rapidly adjusting their navigation. These capabilities may be provided by onboard sensors such as acoustic, LiDAR, radar or visual cameras.

However, the most pressing challenge for BVLOS operation is regulation. Transportation Canada is currently testing RPAS Traffic Management (RTM) services that could link communication networks and sensors with traffic management to enable the integration of BVLOS drone operations. With RTM, Transport Canada can expedite the authorization of BVLOS operations.

6 Use Case Summary

From the survey studies, we have found that drone measurements are currently used to perform installation verification of radio station towers (e.g., antenna pattern measurements etc.) and high-power transmitters (e.g., broadcast stations) for compliance verification activities.

6.1 Radio Tower Inspection and Compliance Verification

Radio tower inspection and compliance verification is currently done visually from the ground. If a problem exists, it is hard to track or identify. Drones can easily fly to the problem area and identify any issues using either visual methods (camera) or by using a directional spectrum receiver (currently used for measuring of sectorization).

In order to verify the physical integrity of towers and tower installations it is currently necessary to use a combination of visual inspections from the ground supplemented by tower-climbing personnel. These visual inspections can determine tower rusting issues, missing cable retentions, broken mounting brackets etc. A drone equipped with a high-resolution camera can replace the expensive and time-consuming climbing of towers.

6.2 Cellular Radio Tower Emissions Compliance

For cellular tower installations, EIRP antenna azimuth and down tilt are important compliance considerations. Depending upon the location of the tower, it may be impossible to perform verification measurements using vehicle-mounted or hand-held monitoring equipment (e.g., an antenna mounted on the roof parapet of a high-rise office building). A drone equipped with a directional receiver can quickly map out the 3D emission profile of an antenna in order to confirm compliance or detect non-compliance.

6.3 Broadcast Station Compliance

Broadcast towers are some of the highest impact interferers. They operate at high power and are designed to reach a wide area. Current spectrum monitoring is achieved using stationary ground terminals and sometimes ground-based vehicles. Drones can perform a faster and more flexible compliance verification of such high-power transmitters.

6.4 High Power Tower to Tower Interference

Checking interference from high-power towers is currently done using vehicles that have masts of limited height. Drones can fly directly between towers into the beam to measure actual signal within the first Fresnel zone. This capability is especially useful for finding interferers at the height at which the interference is happening.

6.5 Microwave Link Monitoring

Drones have been shown to be useful for microwave link parameter measurements especially at high frequency (i.e., SHF and EHF) bands since ground-based sensors won't be able to carry out such measurements. Traditionally, helicopters are used for such tasks at considerable cost, and the use of drones may be able to significantly lower the cost of such measurements.

6.6 Interference and Localization for 5G networks

Industrial automation has created a high demand for private 5G networks to provide indoor connectivity. The private network's access to licensed spectrum is obtained either through a service-level agreement, spectrum leasing, or local license directly from the regulator. In any case, spectrum regulators limit the maximum transmit or receive power levels outside the dedicated coverage area of a network to prevent interference with incumbent users. Traditional solutions for measuring outdoor interference include collecting real-world data by walking or driving. The use of drones offers an attractive alternative due to their flexible mobility and adaptive altitude that allows producing a full 3D picture of the interference. In addition, drones can be programmed to repeatedly travel along the same routes in order to collect more detailed statistics or assess the changes in private network configurations.

A similar use case is the interference assessment for the 6 GHz band. ISED is currently considering making this band available for license-exempt RLAN (e.g., Wi-Fi 6E and 5G NR-U) use [15]. One proposed class of RLANs that do not require to operate under an Automated Frequency Coordinator is the low-power indoor RLANs. The regulators will need to ensure that the RLANs comply with the regulatory emission limits and the incumbent users are protected.

6.7 Above Ground Interference Detection

More advanced use cases are being considered that deal with vertical sensing as a complement to ground sensors. For instance, the detection of a source of interference to aircraft is difficult to detect from the ground, while raising up the sensor or spectrum analyzer is an effective way of using drones instead of helicopters where the wind disturbance can cause damage. Another interesting use case for using drones is LTE "jammers" caused by cellular repeaters, often located on roof tops. The increasing prevalence of cellular repeaters is a consequence of higher thermal efficiency windows with metallic coatings that block external radio signals from entering the building.

Other use cases that have been discussed include flying drones over and around the back of buildings, as well as into "cavities" (e.g., courtyards), top of buildings, or hard to reach places in urban areas and rural areas.

7 Conclusions

It is noteworthy that as new technologies such as onboard detect and avoid (DAA) systems are being applied to improve the safety of drones, the aviation authorities are opening the sky for more complex operations. In 2020, Transport Canada granted the first SFOC to MVT Geo-solutions in Quebec for drone flights for power line inspections. In the U.S., after years of debate, the FAA has recently allowed more types of drone delivery flights across the country. Under the new rules, commercial drone pilots can fly at night or over vehicles without needing to apply for a special waiver from the FAA and flights over people are now also permitted in many circumstances. All these examples point to a trend that, as new drone technology continues to develop, the rules for flying drones in the future will become less restricted making the use of drones practical for spectrum monitoring.

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