The NERDs Project

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Abstract—**NERDs is an acronym for Network-Enhanced Real-Time Drones project. It was a research and development project carried out by Canada's InDro Robotics** (Indro, n.d.) **with technical support from Ericsson and financial support from the Ontario Centre of Innovation (OCI)** (OCI, n.d.). **OCI's mission is to drive economic benefit, job creation and growth in Ontario. Specifically, OCI is committed to helping "Ontario innovators get connected with the researchers, industry partners and funding needed to commercialize the next generation of made-in-Ontario IP and solutions."**

This project took place under the umbrella of the ENCQOR 5G program, which provides SMEs and academia with access to a 5G testbed (the ENCQOR 5G network is a 5G network running through a Quebec/Ontario corridor). (ENCQOR, n.d.)

The NERDs project was based in Ottawa, out of Area X.O, to utilize the ENCQOR 5G network, as well as other infrastructure for Beyond Visual Line-of-Sight (BVLOS) testing. InDro Robotics is an R&D engineering company specializing in advanced Remotely Piloted Aircraft Systems (drones), Uncrewed Ground Vehicles (UGVs) and robotics. The project commenced in the fall of 2020 and concluded successfully at the end of March, 2022.

I.

Ericsson, InDro Robotics, Ontario Centre for Innovation Context

While drone systems have advanced tremendously in the past decade, most commercial and industrial drone systems are operated over Radio Frequency (RF) bandwidths. These frequencies are generally between 900 MHz and 5.8 GHz and limit both the range of the drone's communication system (known as Command and Control, or C2), along with data bandwidth. These low-power networks are created by and exist only within the range capabilities of the controller module/remote control.

Current Canadian and international regulations restrict drone flights, except under approved circumstances, to what is known as Visual Line-Of-Sight (VLOS). This means the aircraft must be seen, unaided, by the drone pilot or a nearby visual observer for the entirety of the mission. The rationale is that operating a drone Beyond Visual Line-Of-Sight (BVLOS) could lead to conflict with traditional aviation, property, or people on the ground. But this also means that long-range drone operations require special permission and are the exception rather than the norm. Although the rules exist for good reasons, they are a significant barrier to the adoption of drones at an industrial scale for inspections, deliveries, etc.

Meanwhile, drone technology has advanced significantly in recent years. Drones can now carry out a multitude of data-intensive tasks useful to industry, including:

- Capturing 4K video
- Inspections using thermal and multispectral imaging
- Non-destructive testing
- Volumetric calculations
- Laser scanning to produce digital 3D "twins"
- Air quality sampling.

Yet two factors impede utilizing these capabilities at scale: The regulatory environment that prohibits most BVLOS flights, and bandwidth limitations that restrict real-time wireless data delivery. (Most data captured is stored onboard drones with MicroSD cards or Solid-State Drives.)

Significantly higher data bandwidths have the potential to overcome both limitations. Greater data throughput enables technologies that enhance drone safety in BVLOS flights and allows for long-range, low-latency teleoperations. A large data pipeline also enables the real-time simultaneous transmission of uncompressed data to the ground and cloud-based servers.

In short, enabling drones to operate over 5G networks (3GPP (3GPP, n.d.) mobile broadband standard) opens the door to safer BVLOS flights that can be teleoperated from great distances, plus more efficient data capture, processing and direct-to-cloud transmission. These are the technological hurdles the NERDs project attempted to solve.

The NERDs project charter states:

> *"The goal of project NERDs is to conceptualize, design and test a 5G compatible module for use with Remotely Piloted Aircraft Systems (RPAS) to allow for remote command and control, as well as aviation radio detection, transmission, and edge processing to increase situational awareness in Beyond Visual Line Of Sight (BVLOS) operations."*

InDro Robotics had previously flown teleoperated BVLOS missions utilizing LTE networks (Cradlepoint, n.d.). While those flights were successful, LTE does not have sufficient bandwidth for dense, real-time data transmission. LTE also poses issues with latency for the drone operator. Minimizing latency to the greatest extent possible is important for the safe operation of BVLOS flights.

II.

Project Requirements

The NERDs project had specific technical requirements. These challenges were designed to fully test the potential capabilities of a 5G-enabled drone. InDro Robotics was selected to develop a state-of-the-art 5G bidirectional module capable of the following (Fig.1):

- Drone Command and Control (C2) over 3GPP cellular link
- Transmission of telemetry back to the control station: altitude, speed, compass heading, high-precision GPS, battery level, ambient temperature, barometric pressure, etc.

- A Software Defined Radio capable of transmitting to nearby private aircraft
- Transmission of RF data back to the control station (signal strength, cell ID, 3GPP SNR, etc.)
- Client-side web integration to back-end drone dispatch service
- Transmission of live adaptive bitrate (720p, 1080p, 4k) video stream from the drone to the control station over 5G. Low-latency transcoding and transmission are key factors to success
- End-to-end video processing latency target of less than 100 ms with 1080p
- Transmit RTK (Real-Time Kinematic) data over 5G cellular link to the drone for high precision positioning (< 5-10 cm).

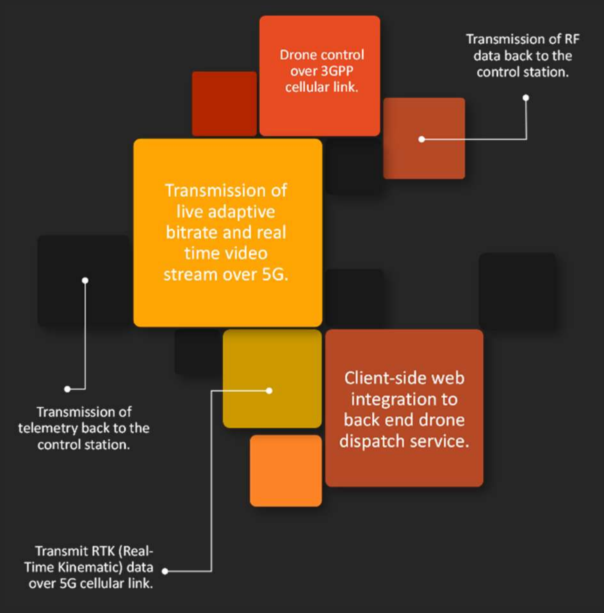


Fig. 1 Major requirements for Project NERDs

III. Multiple components integrated into a single module

The drone airframe for this project was the **InDro Wayfinder** (Fig. 23). The 20-kilogram platform has a lift capacity of 15 kg with a maximum flight time of 55 minutes. InDro has previously carried out BVLOS flights with the Wayfinder over LTE. InDro also had access to some pre-commercial hardware for this project. The module being built for the project would eventually be known as RPAS2.

To enable operations over 5G, a **Quectel RM50XQ-AE** series modem was selected (Fig.2). The 5G module, compatible with both Stand Alone (SA) and Non-Stand-Alone (NSA) 5G networks, has been developed for IoT applications and was responsible for all onboard communications with the cellular network. The Quectel is capable of maximum download speeds of 2.5 Gbps and upload speeds of 650 Mbps under optimal conditions, supporting multiple 5G bands, with fallback to LTE and MIMO (Multi-Input Multi-Output) support with dual transmitter for enhanced upload throughput, with a built-in GNSS (not be confused with drone GNSS0. (Quectel, n.d.).

Mode	RM500Q-AE&RM502Q-AE
5G NR SA	n1/n2/n3/n5/n7/n8/n12/n20/n25/n28/n38/n40/n41/n48*/n66/n71/n77/n78/n79
5G NR NSA	n1/n2/n3/n5/n7/n8/n12/n20/n25/n28/n38/n40/n41/n48*/n66/n71/n77/n78/n79
LTE-FDD	B1/B2/B3/B4/B5/B7/B8/B12(B17)/B13/B14/B18/B19/B20/B25/B26/B28/B29/B30/B32/B66/B71
LTE-TDD	B34/B38/B39/B40/B41/B42/B43/B48
LAA	B46
WCDMA	B1/B2/B3/B4/B5/B6/B8/B19
GNSS	GPS/GLONASS/QZSS/BeiDou (COMPASS)/Galileo

*Fig. 2 **Quectel RM50XQ-AE Frequency Bands and GNSS Type.***

An **NVIDIA Jetson Nano** was chosen as a companion computer for edge processing and was responsible for all drone C2 processing, including telemetry and autonomous flight functions. In addition, the NVIDIA was responsible for 4K video processing, First-Person View video streams used by the pilot, gimbal controls, as well as the modulation and demodulation of Airband communications. The design excluded other types of SBC (Single Board Computer) to enable high processing power while maintaining the form factor and low power consumption, excluding NUCs (Next Unit of Computing) or Jetson Xavier.

Fig. 3 Bayview Yard location and ENCQOR network

The project also required the integration of a **Software Defined Radio**, or SDR. This would carry out the "Hear and be heard" function (Fig.4), transmitting a voice message to nearby crewed (traditional) aircraft. This was a critical piece of the challenge, as the SDR function provides those piloting small aircraft nearby with notification that a drone is flying in their vicinity. Such a function could help ensure the safety of Beyond Visual Line-Of-Sight missions. InDro Robotics had an SDR (bladeRF xA9) onboard enabling bi-directional communications with pilots in the vicinity, and another (LimeSDR) at the Ground Control Station (GCS) to mimic the pilot's radio and receive the NERDs drone communication. The SDR is full-duplex and supports MIMO as well.

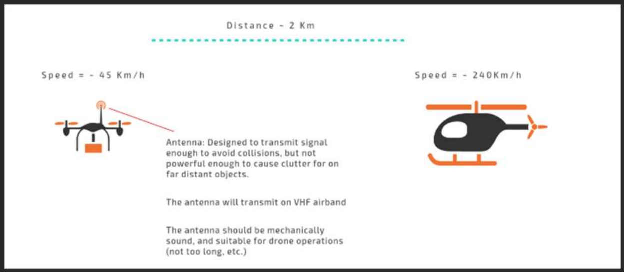


Fig. 4 Collision Avoidance for RPAS2

These SDR boards incorporate Field Programmable Gate

Array integrated circuits, enabling custom programming to alter functionality. We modified the FPGA firmware to InDroSDR, an in-house software written specifically for this kind of application along with the system and antenna design. A special antenna, designed for the frequency spectrum assigned to aviation communications, was used (108-136 MHz).

The Airband communications was complex, requiring detailed calculations and simulations. This helped to ensure the selected antenna would have optimal placement, EMC (electromagnetic compatibility), power, and antenna scattering RCS (Radar Cross-Section). (Tamimi, Antenna Design for NERDs, 2021)

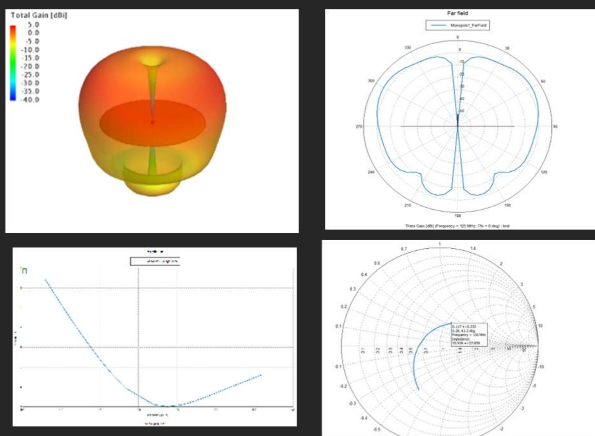


Fig. 5 Antenna analysis and simulation (far field, VSWR, Impedance)

In addition, the team had to ensure the selected antenna would fit the airframe and function properly regardless of the position in space of the drone. This distance (r) determined with Near Field and Far Field Pattern equation:

$r = {2D^2}/{\lambda}$ (1) (Volakis) , where D is the dimension of the antenna, λ is the wavelength.

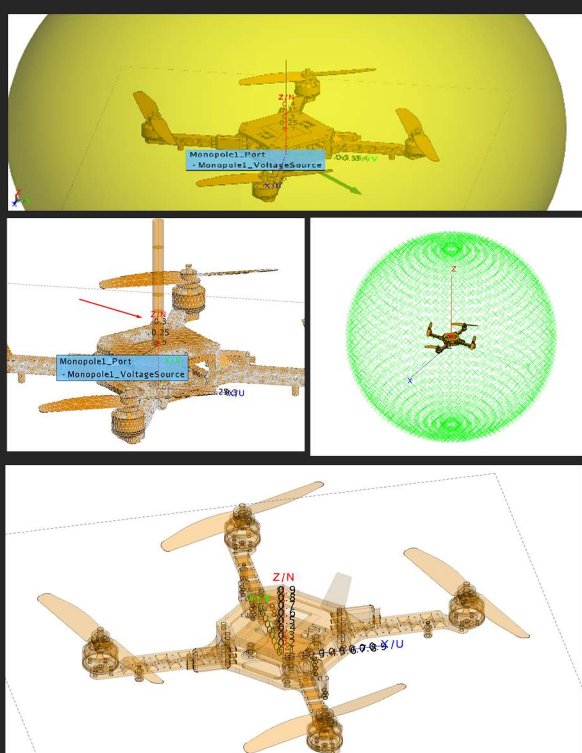


Fig. 6 MLFMM of analyzing and designing the antenna (Tamimi, Antenna Design for NERDs, 2021)

The FEM simulation (Finite Element Method) was not appropriate due to the complexity of the drone's shape. Instead, the Multilevel Fast Multipole Method (MLFMM) was used to determine the best parameters.

Finally, calculations for EM (Electro-Magnetic) compatibility and EM scatter were carried out before selecting the optimal antenna for the project. A blade VHF antenna proved to be the best choice, satisfying all criteria.

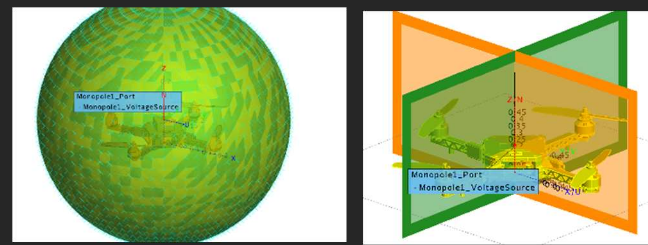


Fig. 7 EMC and EM scatter for the blade VHF antenna

For the 4K video streaming challenge, InDro Robotics selected a Sony A7s III.

This camera features a full-frame CMOS sensor and produces dense, high bitrate 4K video streams. The ability to stream 4K video or other high-bitrate data has two advantages: In the case of 4K video, it enables greater situational awareness for the pilot, who can see surroundings from the sky with far greater clarity than common 720p feeds. (In fact, 4K provides nine times the pixel density of 720p). It also enables, in conjunction with the 5G modem, the ability to stream dense data to the cloud and ground stations in real-time. This has been, until now, a bottleneck that has required many industrial drone operators to record data on MicroSD cards, and then manually upload the data following the missions.

The 4K stream data rates can reach up to 70mbps in real-time, posing the following challenges:

- Network: While 5G is now emerging, most 5G networks are currently NSA (Non Stand-Alone, meaning they share the same LTE backbone). Moreover, cellular networks are fragile in nature (compared to FTTH/Fiber-To-The-Homes, for example). Other factors can further complicate things: Bandwidths can change due to regulations, and multiple UEs (user equipment, like a phone) connecting at peak periods can lead to network congestion. External factors such as weather – even sun coronas and solar flares – can lead to interference or, potentially, a temporary but total outage of the system.

- Limited technology: Because of the drone platform, the only viable option for real-time processing is to use an SBC (single board computer) for real-time processing. At the time of writing this paper, the most current and powerful SBC uses the Tegra architecture (NVENC with 4 cores on an ARM64 chip). This eliminates harnessing desktop/enterprise architecture like Ampere's B-frame, which utilizes previous and forward frames, as well as the support of highly efficient encoders (like AV1). This presents a challenge. In addition, the on-board SBC is also responsible for other tasks while the drone is flying, including C2/Telem (command and control and telemetry) links, positioning, as well as other cameras on the system (including First Person View camera).

- Limited Resources: The drone platform (size and takeoff weight) is a limiting factor – meaning it cannot bear a fully-fledged server rack. So there are limitations to what can be put onboard for real-time data processing, etc.

The ENCQOR network (the private network used for communication to control the NERDs drone) can reach up to 45mbps data rates maximum upload for limited periods of time. This data rate is not sufficient for the low-latency, real-time 4K video streaming to satisfy the NERDs challenge. As a result, InDro Robotics developed its own algorithm for the FEC (forward error correction) based on the draft IETF payload scheme 20 (Qualcomm, n.d.). Though the technicality, development, and implementation of this algorithm is involved, the concept boils down to idea of sending the buffer of the 4K video in a multi-dimensional interleaved pipeline instead of the linear one, allowing the possibility of sending repair packets 'on the fly' (Fig.8).

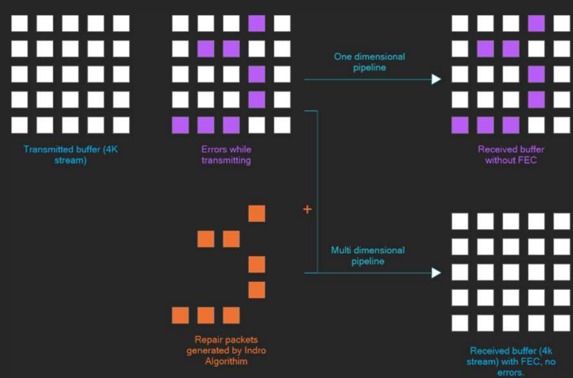


Fig. 8 InDro Algorithm FEC for 4K streams

The Sony A7s III was installed on a Gremsy T3 gimbal, which allowed the pilot to change the camera view from the ground station over 5G (tilt, pan), and within InDro Pilot – the software platform powering the drone.

IV.

RTK Positioning

Positioning accuracy is important for several reasons: It ensures that geo-referenced data is tagged with far greater accuracy, leading to more robust datasets to produce digital twins, etc. Greater accuracy also improves safety for autonomous missions (i.e., centimeter-level precision landings, waypoints, etc.) further contributing to the safety of missions and the confidence of regulators.

V.

System Architecture

NERDs system architecture: We built from the ground-up software platform to enable and extend all project requirements. The platform is called InDro Pilot, within the NERDs system architecture (full one referenced (Tamimi, System Architecture (InDroPilot), n.d.)). It enables all on-board as well as cloud/GCS communication and processing (refer to InDro Pilot section VIII for details).

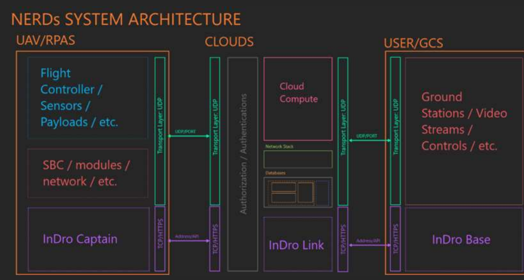


Fig. 9 NERDs Architecture.

VI.

Latency

Latency plays a crucial factor in the NERDs project – and for multiple reasons. On the C2 Link, for example, low latency means a pilot using a real-time joystick to control the drone and camera will have a smooth, responsive, and safe flight over 5G. It's also important for telemetry data and positioning – even for the FPV (First-Person View) camera for real-time viewing or 4K streaming. The pilot needs to have the feel that they are directly in the virtual cockpit, with near-zero latency.

InDro Robotics achieved and delivered very low latency over 5G networks of sub 75ms (vs. sub-400ms over LTE). This enabled low-latency C2/Telem links, as well as video streams for both 4K and FHD in real-time, in addition to the real-time bi-directional communication within the aviation airwaves.

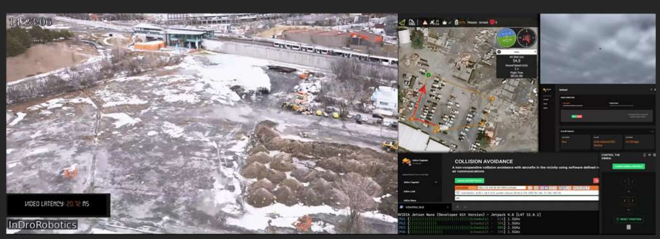


Fig. 10 One of the NERDs missions, and you can see at the bottom-left the latency display.

The low latency achieved by utilizing an InDro Pilot component (InDro Link) first establishes a node in the cloud to authenticate all parties connected to this link. It then enables low-latency peer-to-peer connection with end-to-end encryption (AES-256 cipher with RSA-4096 handshake encryption and SHA-512 hash authentication on both control and data channels). Latency is reported and displayed in real-time within the InDro Pilot platform and updated nearly every second – without adding any extra overhead packets.

Fig. 12 shows the latency over both ENCQOR 5G and Commercial LTE network over time, every second. The first chart shows both latencies, orange one is the LTE and the blue one is the 5G latency. Next charts are the latency over time for each.

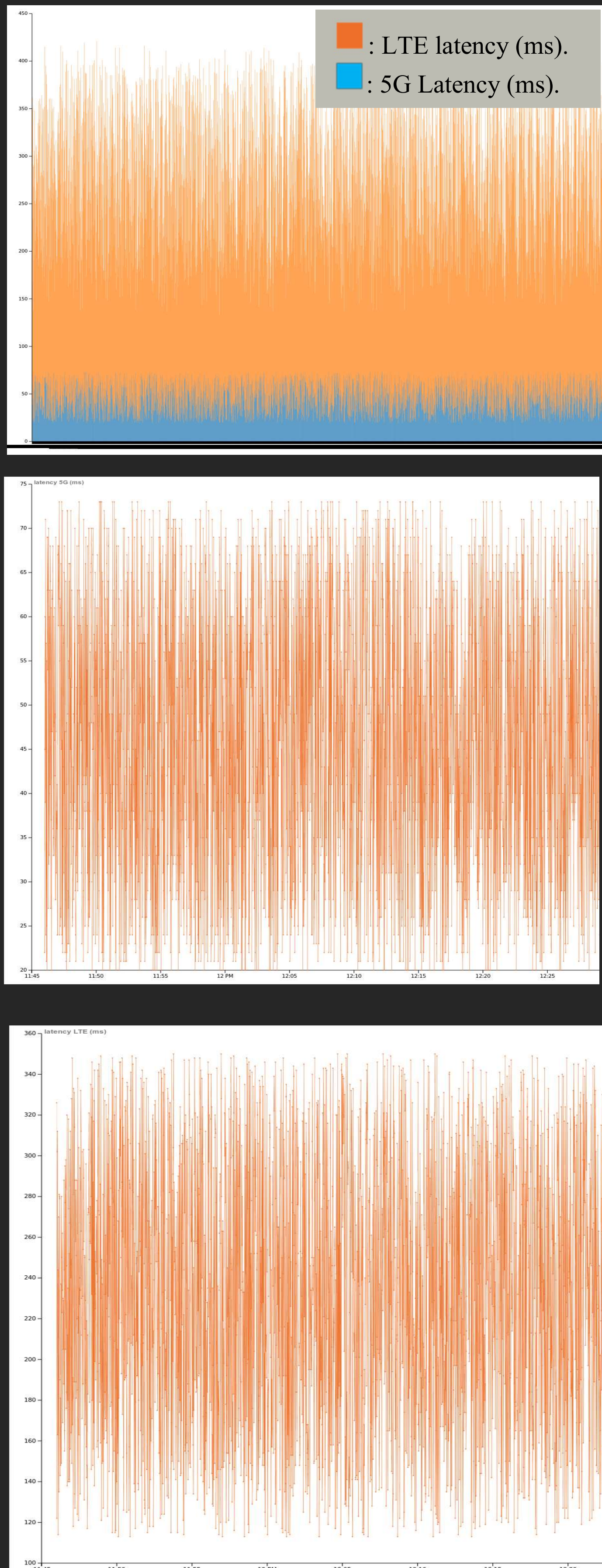


Fig. 11 Latency difference over 5G and LTE

On average, the latency over 5G was around 46ms and 231ms over LTE, graphs below summarize a quantitative distribution with five standard statistics: The minimum value, first quartile, median, third quartile, and maximum value.

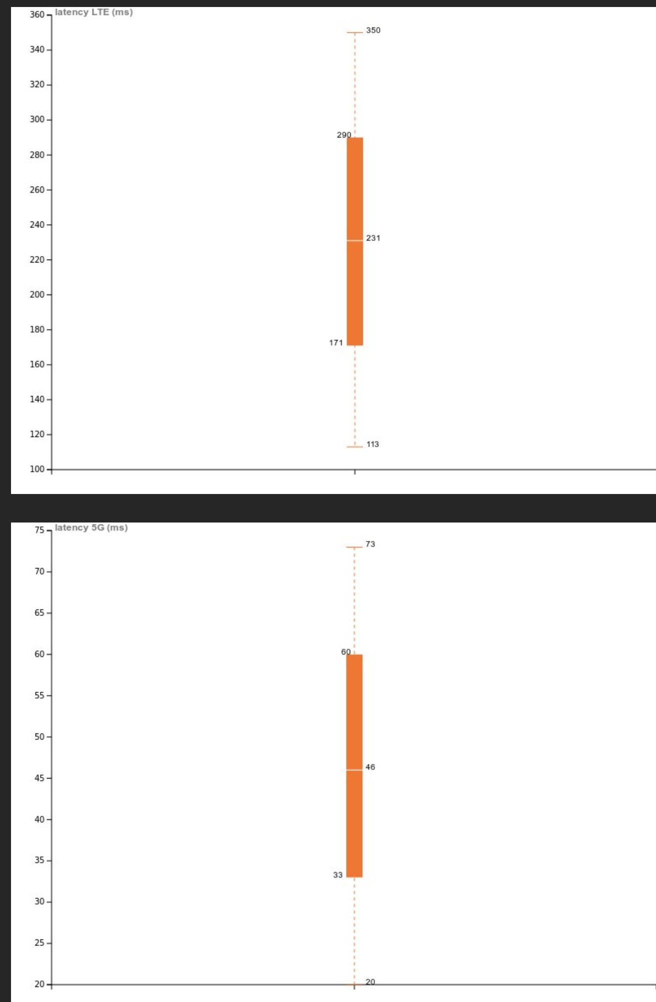
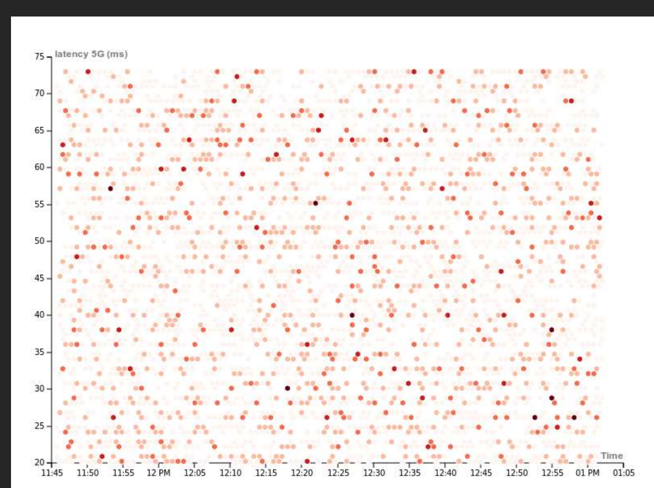


Fig. 12 Average latency over 5G/LTE.

As for the latency correlation and distribution over time, there are many contributing factors. This includes ground station machine performance decoding the 4K stream, plus the on-board edge computing unit. However, overall correlations from the tests were more-or-less consistent.



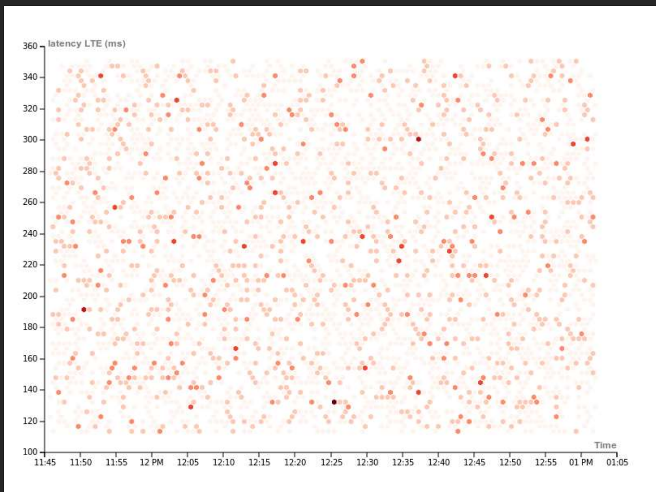


Fig. 13 Latency correlation and distribution over time, dark points mean high occurrence, light points mean lower occurrence

Next is the latency data point cloud with estimated density over time. Darker spots indicate high occurrence compared to light ones.

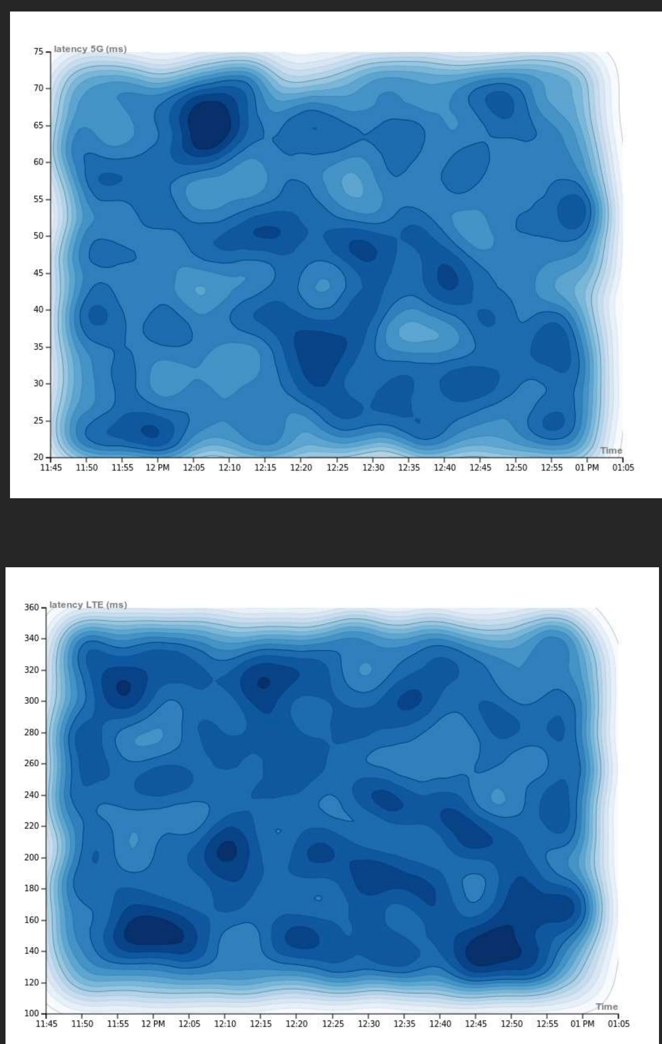


Fig. 14 Data point cloud density.

VII.

Cellular Survey

Cellular networks, in general, have been created for ground-based users (cellphones, etc.). Although surveying the cellular network itself wasn't part of the NERDs project requirements, InDro Robotics felt it was important to "map" cellular strength at altitude for both 5G (SA/NSA) and LTE. This provided a more thorough understanding of network infrastructure, as well as ensuring that no dead zones would be encountered during missions.

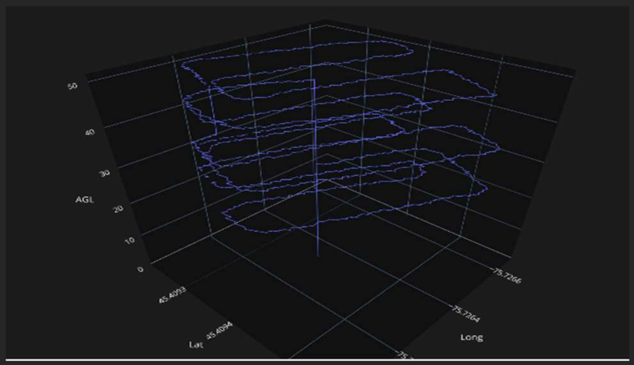


Fig. 15 Drone flight path

While surveying the cellular network, the drone was flown at three levels: 30m, 40m, and 50m AGL (Above Ground Level).

Data was collected every second, resulting in a massive dataset.

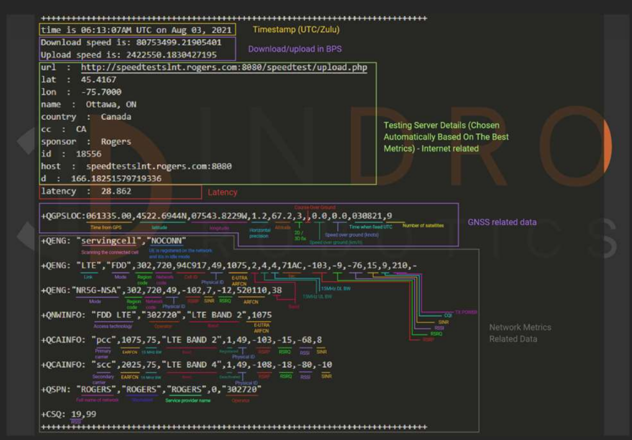


Fig. 16 Data collected every second

The following measurement statistics define the quality of the cellular signal (RSSI): RSRP, RSRQ, and SINR.

RF Connectivity	RSRP (dBm)	RSRQ (dB)	SINR (dB)
Excellent	>=-80	>=-10	>=20
Good	-80 to -90	-10 to -15	13 to 20
Medium	-90 to -100	-15 to -20	0 to 13
Weak	<=-100	<-20	<=0

Fig. 17 RSRP, RSRQ, and SINR thresholds.

RSSI: Received Signal Strength Indicator.

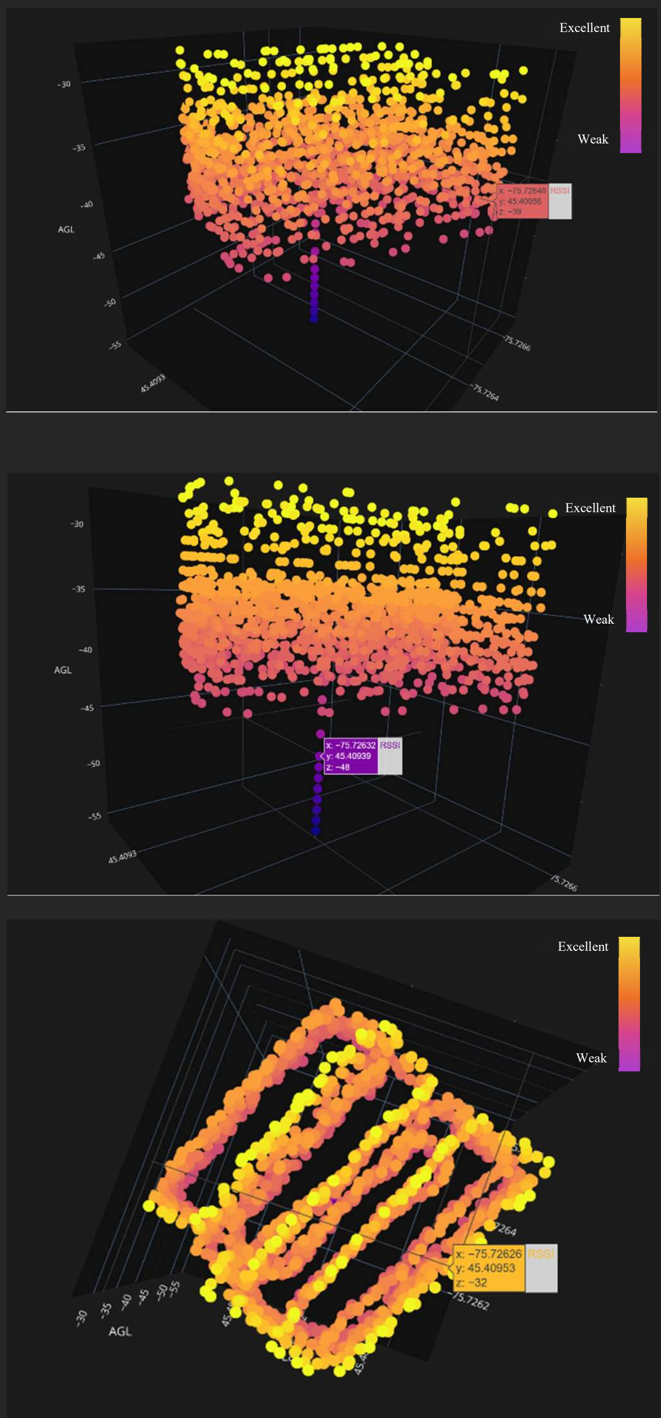


Fig. 18 RSSI data set during the flight, we can see the RSSI gets better the higher the drone fly

RSRP: Reference Signal Received Power.

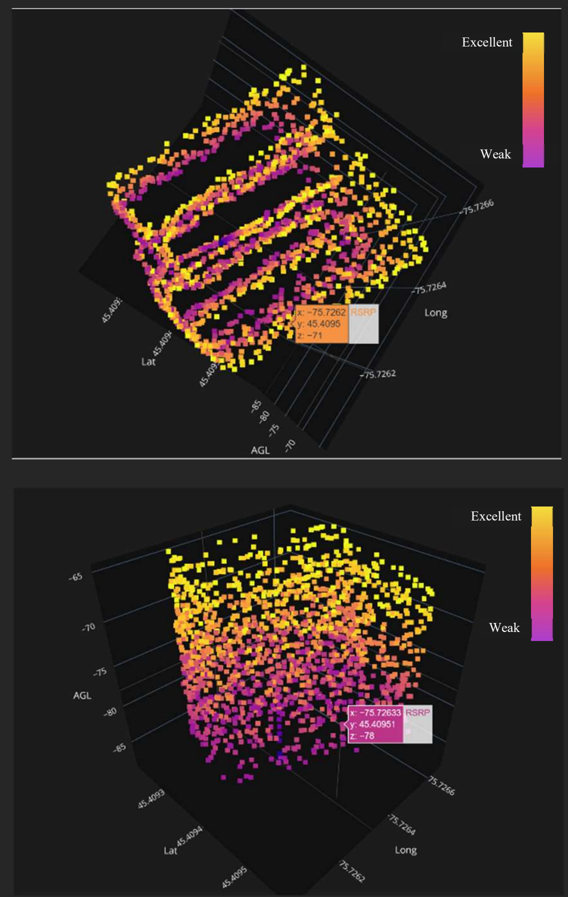
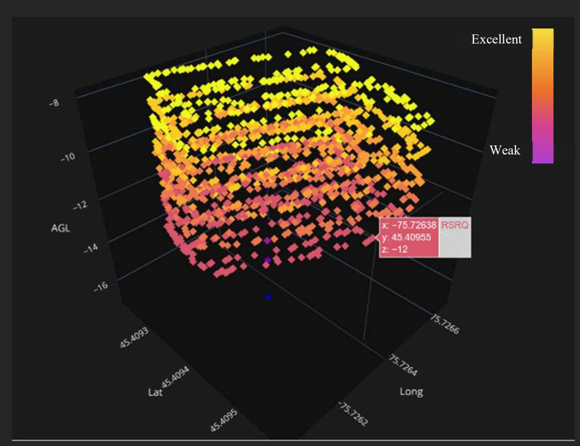


Fig. 19 RSRP mapping in the sky, like RSSI, gets better with higher AGL

RSRQ: Reference Signal Received Quality



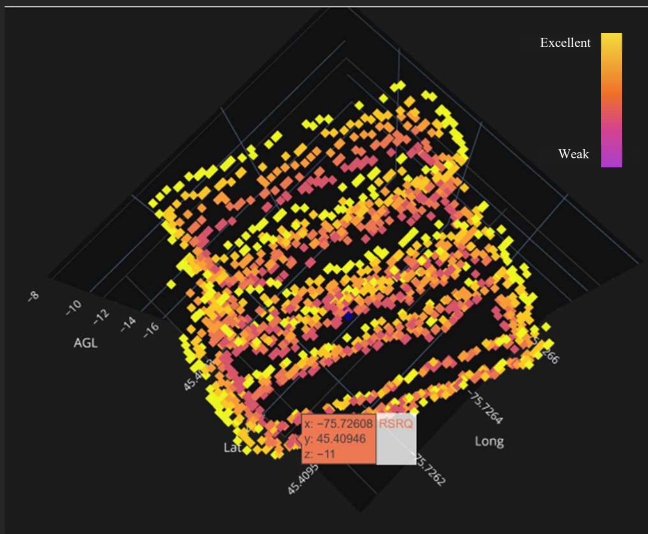


Fig. 20 RSRQ Data as well.

SINR: Signal to Interference plus Noise Ratio

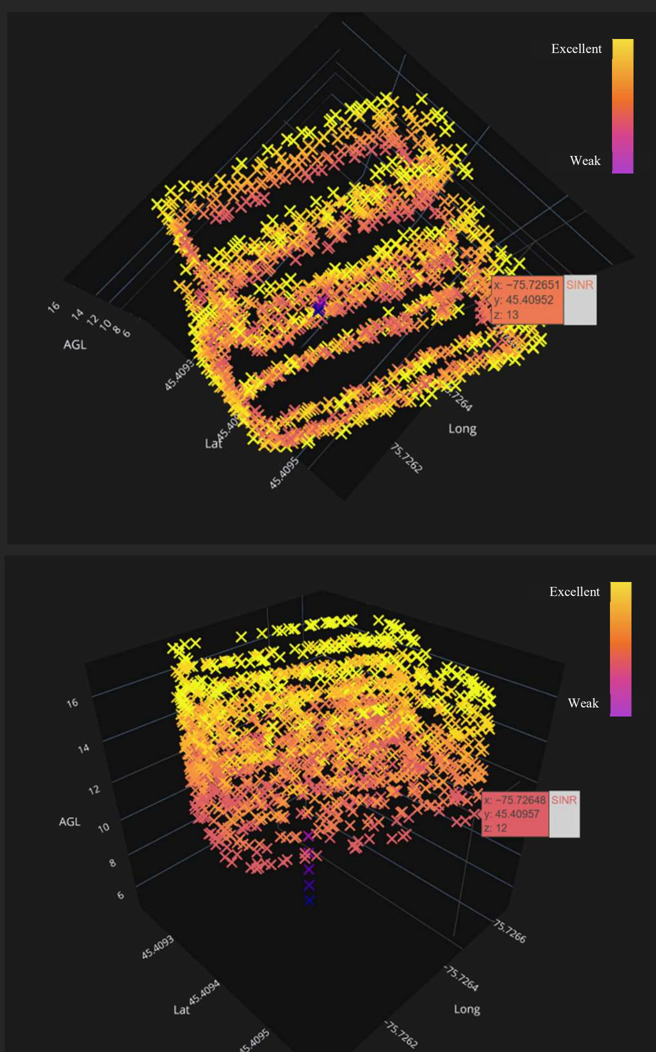


Fig. 21 SINR data, similar to the others, signal quality and power gets better at higher AGL

VIII. InDro Pilot

InDro Pilot is a next-generation modular platform that empowers and enables control over cellular networks (5G/LTE). It can be used on drones for BVLOS flight, and even on Uncrewed Ground Vehicles. InDro Pilot emphasizes modularity, expandability, and reliability while still being user-friendly with minimum configurations required to be up in the air. It enables C2/Telem as well as modular integration of any payload per mission requirements. This will be a commercial product for InDro Robotics soon.

InDro Pilot is an eco-system platform, not a single program. Three major components comprise InDro Pilot:

- InDro Captain: Responsible for on-board, low-level processing, positioning, navigation, and interfacing with payloads
- InDro Link: Establishes secure, low-latency link between the GCS and edge computers for drones or UGVs
- InDro Base: Responsible for the GCS side of the pilot/operator

InDro Pilot high-level features are:

- Next-gen platform empowering the mission with command and controls, telemetry links, and all comms to ground stations with mission autonomy and centimeter-position accuracy (depends on airframe GPS)
- Supports 5G out of the box, both NSA (Non-Standalone) and SA (Standalone), with LTE/3G fallback
- System agnostic, works on all architectures (ARMv8, ARMv7, AMD64, etc.)
- Drone agnostic: Supports all Pixhawk-based drones
- Modular, supports wide range of integrations with different payloads
- Reliable for mission-critical operations and BVLOS
- Ultra-reliable low-latency connection. All links are encrypted with state-of-the-art crypto (AES-256 cipher with RSA-4096 handshake encryption and SHA-512 hash authentication on both control and data channels) and in compliance with ISO27000 and NIST800
- Powerful edge-computing units powered by NVIDIA for AI/ML, real time transcoding, and processing

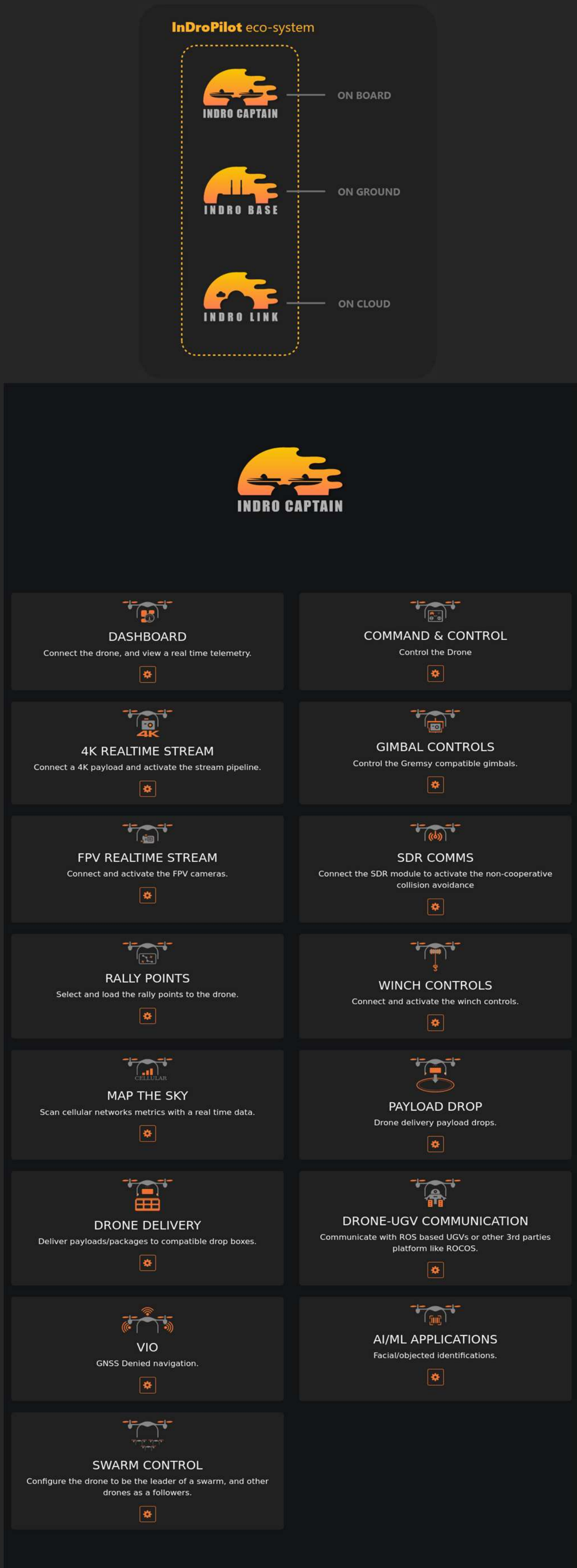


Fig. 22 Indro Pilot components and a screenshot of InDro Captain on-board component that used for NERDs project.

IX. Challenges

In addition to the technical challenges mentioned in this paper, the project also faced other challenges. These are summarized as follows:

- The project was awarded, executed, and delivered during the worldwide COVID-19 pandemic. This impacted the project in multiple ways. Engineering staff were required to work from home in isolation for long periods and faced additional challenges with restricted access to Area X.O.
- The global chip shortage impacted ordering, shipments and deliveries
- The pandemic also closed access to the Bayview Yard, the location of Ericsson's ENCQOR network. This was off-limits until Feb 2022, a month prior to the delivery date. This also meant the team was accessing the network during a month when extreme weather conditions were the norm
- With the project located in Ottawa, flights had to be carried out during sub-optimal weather as the deadline approached.

X. Implications/Conclusion

The successful outcome of this project carries significant implications for InDro Robotics, Ericsson, and the broader drone industry.

As noted, most industrial drones are currently operated within Visual Line-Of-Sight and over the Radio Frequency bandwidths of the remote control. Some manufacturers have just begun to release drones that operate over 4G. 5G is the next territory, and one that will enable greater data throughput and vastly greater efficiencies for industrial applications (i.e. direct cloud uploads of dense data during flight). 5G is the door that will truly make drones and ground robots part of the Internet of Things.

But high-speed, low-latency data uploads are not enough to unlock the promise of Beyond Visual Line-Of-Sight flights. Regulators must be satisfied that drone missions are being operated with a minimal chance of conflict with crewed aircraft, people on the ground or property.

To that end, this project made other significant breakthroughs that work in tandem with the potential of 5G. They are:

- Near-zero latency 4K video streaming, enabling greater situational awareness for the pilot
- Software Defined Radio voice transmissions, alerting pilots of traditional aircraft in the vicinity of the mission of drone operations
- Centimeter-accurate positioning data for autonomous flights and datasets
- The InDro Pilot software suite

Collectively, these are significant achievements for the industry. Improving the safety of situational awareness for both the pilot and crewed aircraft is a solid step toward more routine BVLOS flights. The dramatic improvement in low-latency data transmission will also be embraced by industrial users, who have been searching for a more efficient solution to data handling and cloud processing.

For Ericsson, there are also implications. It can be anticipated that other drone operators, likely using the InDro Robotics module, will be carrying out 5G flights in the not-so-distant future. Many of these flights – at least initially – will be in rural or remote areas, where regulators are more inclined to grant BVLOS permissions. It is likely there will be greater demand for 5G infrastructure, including private 5G networks.

In addition, the 5G/6G promise is not limited to drones. InDro Robotics has also created a module for use in Uncrewed Ground Vehicles (UGVs), allowing for remote and autonomous operations over 5G. Industrial applications such as inspections and surveillance, volumetric calculations at facilities such as cement plants or mining operations, will continue to grow. We have noted significant growth in private 5G networks for industry, and innovations such as those detailed in the NERDs project, will generate even greater demand.

InDro Robotics is already exploring the synergy of deploying ground robots and drones simultaneously over 5G networks, collaborating on a shared mission. InDro Robotics will continue to explore these opportunities.

In summary, the NERDs project was a clear success. It is not an understatement to suggest that, collectively, these achievements mark an inflection point in the sphere of drones as they relate to BVLOS flights and the IoT.

Fig. 23 NERDs RPAS² drone.

XI.

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