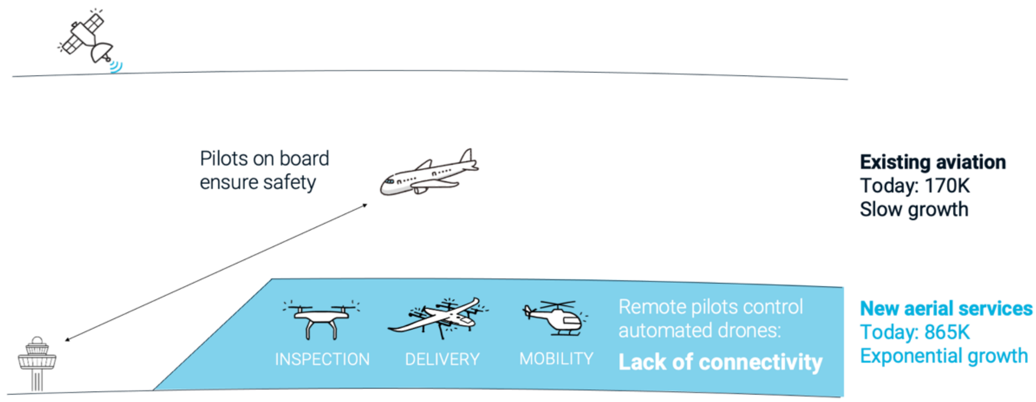
Aerial Cellular Connectivity

January 2023

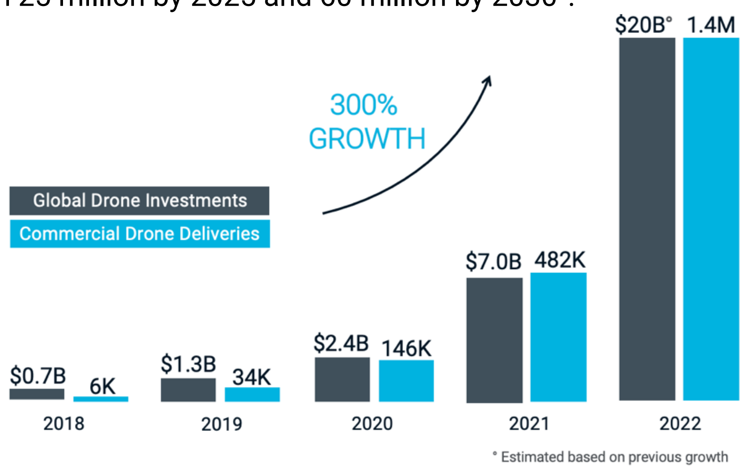
Automated drone services

Drones, also known as uncrewed aerial systems (UAS), have the potential to revolutionize numerous industries by offering cost-effective and transformative solutions for delivery, inspection, agriculture, emergency response, and mapping. In particular, automated drones operating beyond visual line of sight (BVLOS) have the potential to significantly enhance the capabilities and applications of aerial services but require a reliable way to remotely control the drones.

Aerial cellular connectivity refers to the use of mobile networks to provide data connections for drones. As the demand for drone services increases across various industries, the need for reliable and secure aerial cellular connectivity becomes increasingly critical. This paper discusses the challenges and solutions for achieving aviation-grade cellular connectivity.



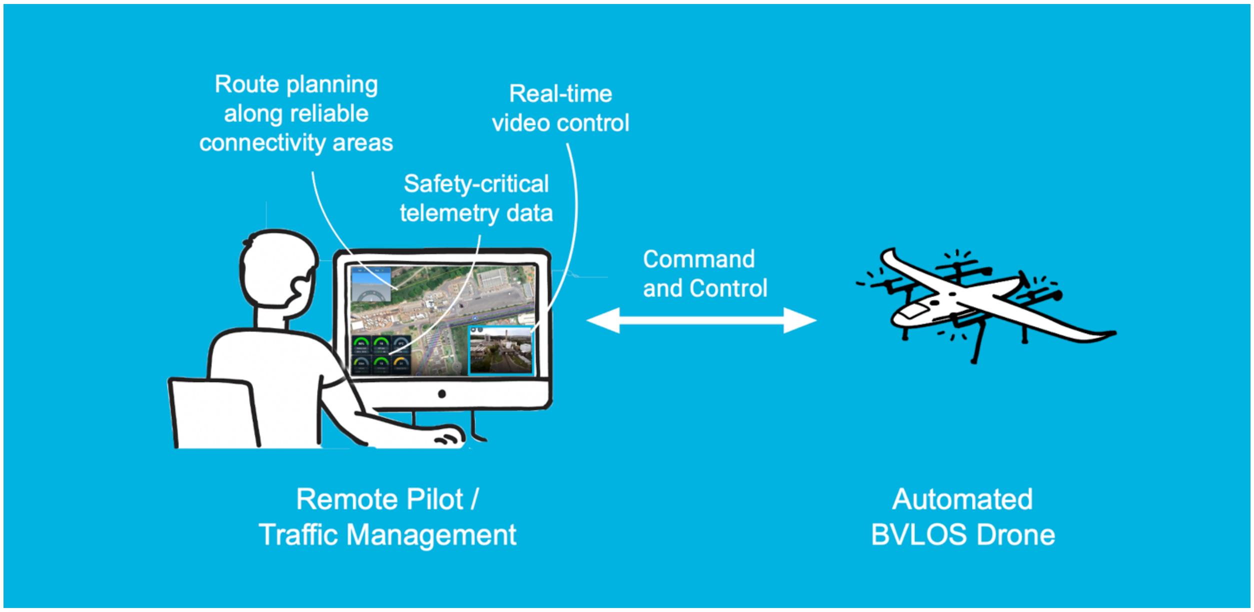
According to a report by McKinsey, the number of drone deliveries has increased at a rate of 300% annually in recent years and reached around 1.4 million in 2022[1]. This growth is also reflected in the increased investment within the commercial drone industry, which has increased 10x over the past 3 years[2]. It is projected that the total number of commercial drones worldwide will reach 25 million by 2025 and 60 million by 2030[3].



[1] https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/future-air-mobility-blog/drone-delivery-more-lift-than-you-think
[2] https://droneii.com/drone-investments-in-2021-break-records
[3] https://www.statista.com/statistics/1234569/worldwide-enterprise-drone-market-shipments/

Assurance of command-and-control connectivity

A command-and-control (C2) connection between the drone and the pilot is necessary for the safe operation of drones. For BVLOS drone operations, a reliable C2 connectivity is essential for the safe integration of drones into the airspace through UAS traffic management (UTM) systems. C2 connections transmit data at a low rate but can require a very high reliability level of 99.999%.



The standardization body RTCA defined requirements for C2 connectivity: availability, continuity, latency, and integrity. Availability refers to the percentage of time that the connection is available to use, continuity refers to the percentage of time that the connection is uninterrupted, latency refers to the delay in data transmission, and integrity refers to the correctness and completeness of transmitted data.

Standards development organizations such as RTCA/EUROCAE are working with industry groups like GSMA[4]/GUTMA[5] to create minimum operational performance standards for aerial cellular connectivity. The RTCA/EUROCAE standard (SC-228/WG-105 Cellular C2 MOPS[6]) will define the necessary levels of cellular C2 connectivity performance for different types of drone operations and is expected to be finalized by the end of 2023 before (most likely) being accepted by FAA/EASA regulations as a Means of Compliance.

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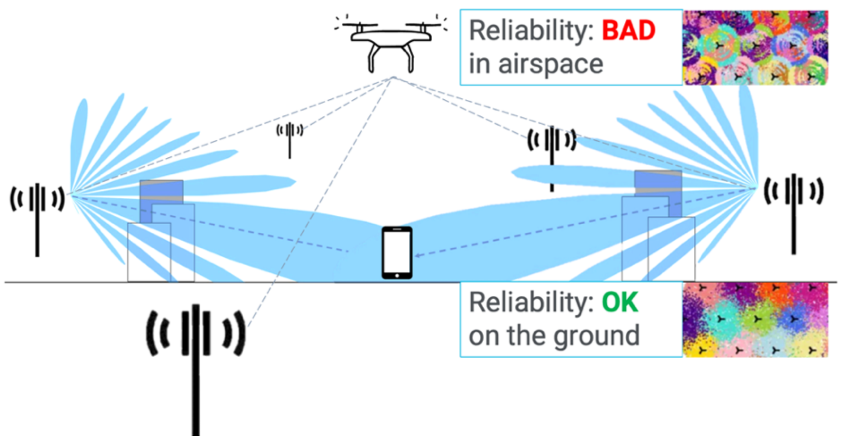
[4] https://www.gsma.com/iot/aerial-connectivity-joint-activity/
[5] https://gutma.org/acja/
[6] https://www.rtca.org/sc-228/

Challenges of using the mobile network for C2

Mobile networks like 4G-LTE and 5G have the potential to provide C2 connectivity for drones, but there are several challenges to aerial cellular connectivity. One of the main challenges of using 4G-LTE/5G mobile networks for C2 is overload and "busy hour" congestion, which are the most common cause of service degradation in 4G-LTE networks[7]. Service degradation occurs when network traffic (i.e., the number of users and their data consumption) approaches the cell capacity. This forces the cell to distribute wireless resources "fairly" among users and store "buffered" data temporarily until sufficient resources are available. Deploying additional infrastructure would solve some of the congestion problems, but network operators deploy base stations (i.e., cells) cost-effectively to maximize the return on investment. This means that networks are never equipped to cope with the "busy hour" scenario and will always solve congestion by fairly distributing resources, resulting in temporary connection losses.

State-of-the-art network infrastructure is typically set up in urban areas, while drones operate in rural areas where older networks are more common. The higher density of base stations in urban environments allows for dynamic offloading to neighboring base stations when cell resources become scarce. In contrast, cells in rural environments serve a large area without the ability to connect users to a neighboring cell, which results in more frequent cell capacity problems and potential losses for regular data connections.



Aerial cellular connectivity has fundamental differences compared to regular ground-based network usage, including radio line-of-sight (LOS) visibility to base station antennas, the ability to connect to far-away base stations, and an entirely different propagation scenario due to "antenna sidelobes". These unique propagation characteristics lead to a distinct 3D network coverage in airspace, increased downlink interference with lower signal-to-interference-and-noise ratio (SINR) and throughput degradation, as well as sudden power drops and potential connection losses due to sidelobe propagation nulls. Frequent and chaotic cell handovers consume additional network resources, lead to challenging network behavior, and increase the risk of handover failure. On the positive side, aerial LOS paths constitute a deterministic propagation process, which allows for accurate prediction of network availability and performance along predefined drone routes.

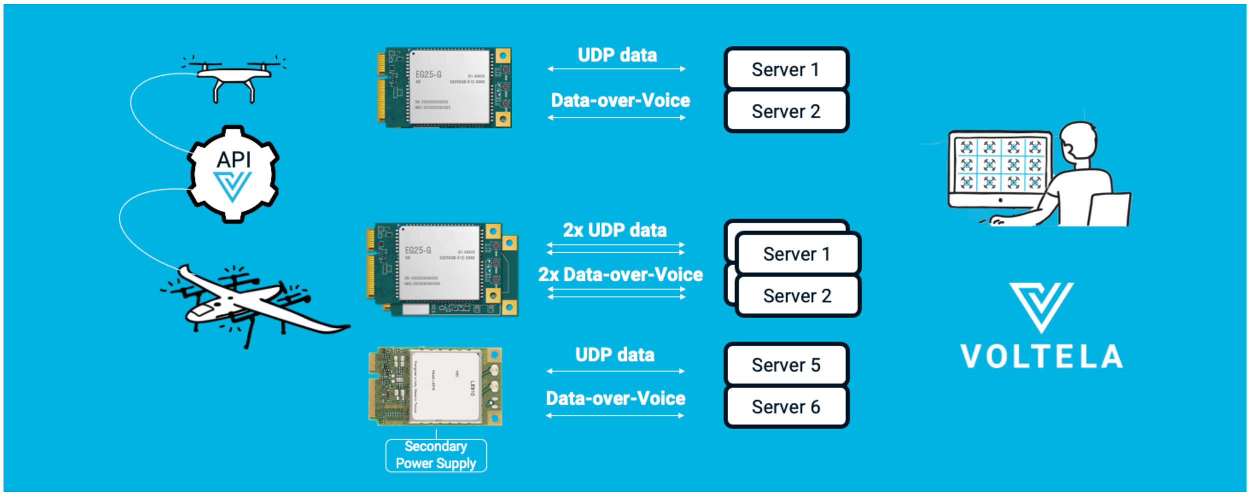
[7] https://www.spirent.com/assets/wp/wp_mobile-network-outages-service-degradations

Solutions for aerial connectivity

Satellite communication systems such as Iridium or Starlink provide reliable global coverage, but latency (up to 1800 ms round-trip[8]), operational costs (300,000x more $/bit, Iridium[9] vs. LTE[10]) or hardware requirements (flat panel antenna[11]) limit their applicability for drones. Iridium Circuit-Switched Data[12] provides low latency and affordable ($1/min) connections but would only be worthwhile where mobile networks are not available. However, a lack of mobile networks indicates a lack of people (low ground-risk) and reduces the need for high-performance C2 links.

4G-LTE networks offer "best-effort" connectivity by sharing wireless resources (frequency band slots and time slots) among all users in a cell. While 4G-LTE can achieve up to 99%[13] reliability (i.e., packet success rate), it is prone to congestion and connection losses. “Regular 5G” is not a solution for aviation-grade connectivity either, as it operates like 4G-LTE with best-effort connectivity. "5G Network Slicing" has the potential to provide low-latency and prioritized links but won’t be available for drone applications in the near future given the investment required for its widespread deployment. "Private 5G Networks" with uptilted antennas could also serve aircrafts at 10,000 ft or higher along busy airspace routes, but the viability of this approach still needs to be verified.

3GPP, the standards organization for mobile communication, has proposed several approaches to address the challenges of aerial cellular connectivity (TR 36.777). However, implementing these solutions is not economically viable for either modem chipset manufacturers or network operators given the required investments for this nascent industry ("chicken and egg problem"). Similar problems were observed in the car-to-car communication industry for over a decade.



8 http://www.dodccrp.org/events/10th_ICCRTS/CD/papers/233.pdf
9 https://satellitephonestore.com/iridium-sdb
10 https://www.statista.com/statistics/994913/average-cellular-data-price-per-gigabyte-in-the-us/
11 https://www.starlink.com/specifications
12 https://www.iridium.com/services/iridium-circuit-switched-data/
13 Verizon/FAA Memorandum of Agreement Cellular Technologies to Support UAS Activities Report

Software solutions that utilize commercial off-the-shelf modems and connect to existing network infrastructure provide cost-effective and reliable drone connectivity today. Basic solutions for link redundancy include combining multiple modems connected to different network providers. Advanced solutions include data-over-voice technology for prioritized, low-latency C2 connectivity. More advanced software solutions involve innovative network reporting schemes for guaranteed connection reliability using regular data channels (e.g., User Datagram Protocol - UDP) or to select the most suitable base stations along the drone route.

Data-over-voice for C2 connectivity assurance

The C2 data-over-voice technology, developed at the Fraunhofer Institute, leverages the superior Quality-of-Service (QoS) of voice channels in any mobile network. Unlike best-effort data channels, voice channels have a high priority and a guaranteed low latency. While network congestion can cause regular UDP data to buffer, data streams sent over voice channels continue at a low, constant latency. This is critical for BVLOS operations, as unstable C2 latency can result in an uncontrollable flight situation for a remote pilot. These QoS advantages apply to 4G Voice over LTE (VoLTE) and the upcoming Voice over 5G (Vo5G) technology.

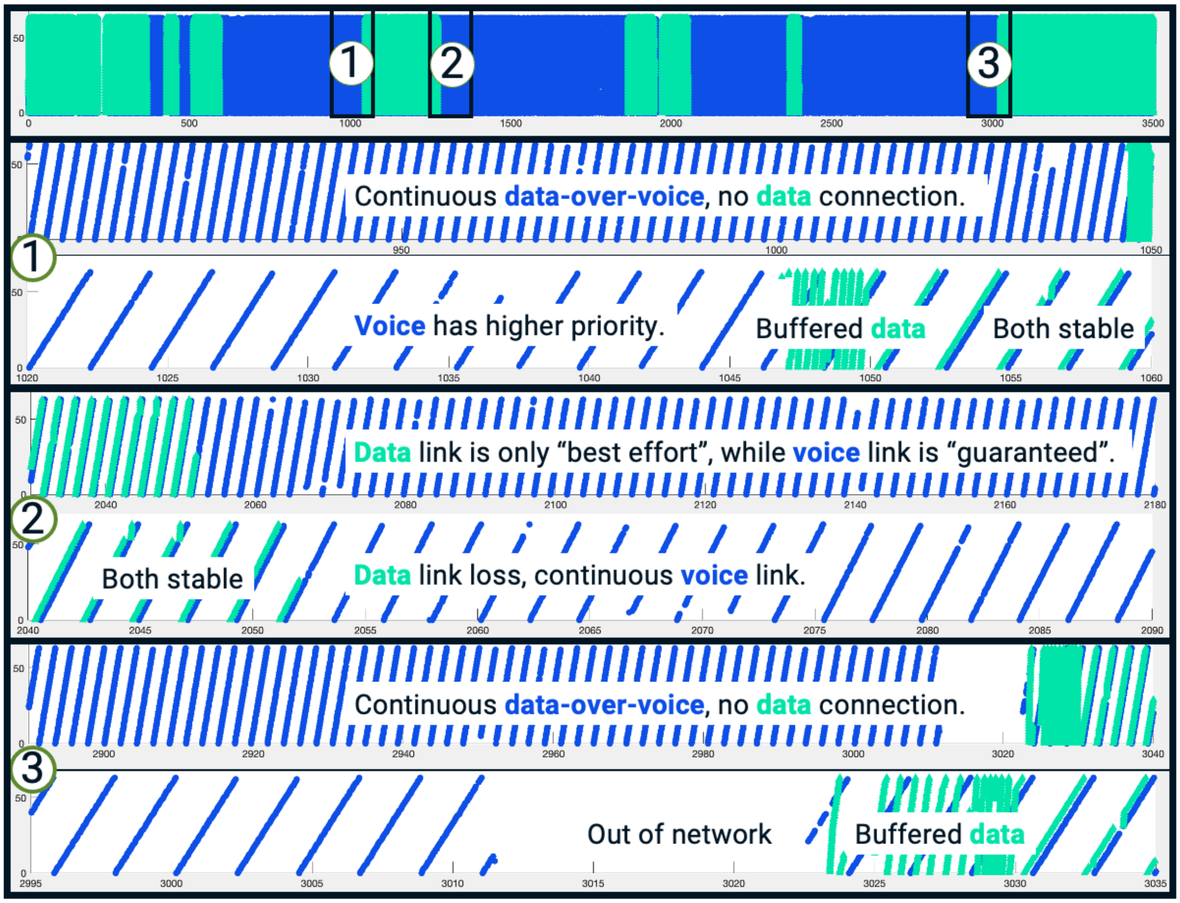
3GPP defined 27 Quality-of-Service (QoS) classes with various network priorities and latency levels. The highest priority is given to signaling classes, which are needed to keep the network running. Other service classes, designed for use cases in Vehicle-to-X (V2X), Intelligent Transport Systems (ITS), and Discrete Automation, provide high network priority and low latency. Some of the classes also provide a Guaranteed Bitrate, meaning that data is not buffered but received within the given latency (not "best-effort"). While V2X/ITS QoS classes would be ideal for C2 connections, they come at a high cost due to the required deployment of new network infrastructure (and updated modems). In fact, providing these QoS classes for drone applications on a widespread basis would require a substantial investment in network infrastructure.

Service Example	*Resource Type*	*Priority Level*	*Packet Latency*	*Packet Error Rate*	*Quality Identifier*
Voice	Guaranteed Bitrate	20	100 ms	10^{-2}	1
V2X	Guaranteed Bitrate	30	50 ms	10^{-3}	3
Regular Data	No Bitrate Guarantee	60	300 ms	10^{-6}	6
V2X	Guaranteed Bitrate	25	50 ms	10^{-2}	75
V2X	No Bitrate Guarantee	65	50 ms	10^{-2}	79
Discrete Automation	Guaranteed Bitrate	19	10 ms	10^{-4}	82
ITS	Guaranteed Bitrate	24	30 ms	10^{-5}	84

Relevant 4G/5G Quality-of-Service Classes[14] [15]

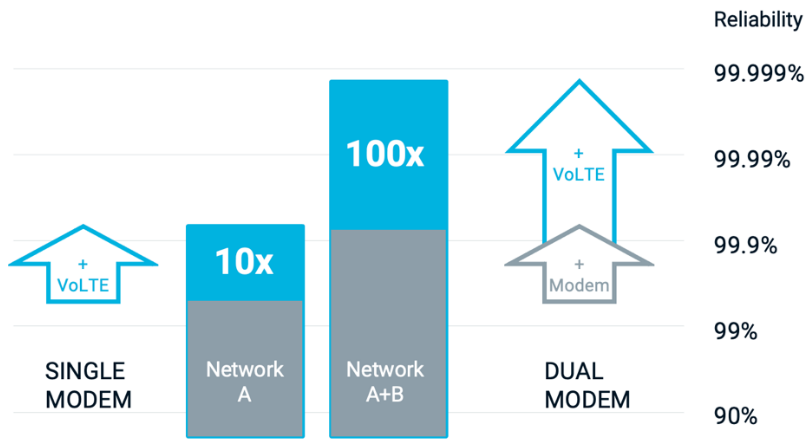
[14] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3144
[15] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=810

The C2 data-over-voice technology establishes a redundant voice connection (QoS Identifier 1) alongside the regular data channel (QoS Identifier 6) through a phone call between the drone's modem and a virtual phone server. This parallel connection is then used for C2 communication by translating drone telemetry data (such as position, altitude, and battery status) into audible signals that mimic the human voice, allowing the data to bypass audio codecs in mobile networks. This C2 connection is full duplex, meaning that commands from the pilot to the drone can be sent simultaneously. By combining telemetry data received via both the data channel and the voice channel, an even higher QoS can be achieved, exceeding the performance of the individual channels.

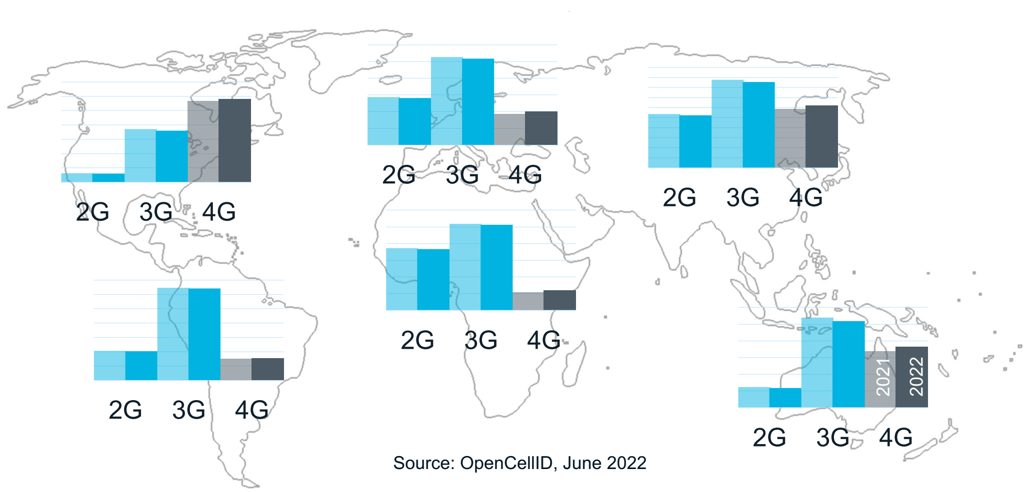


Mobile network operators constantly monitor the quality of their services to enforce 3GPP Quality-of-Service requirements (QoS control in TS 23.203). "Busy hour congestion" is a major contributor (37%) to network outages, which often occur in the radio access network (37%) due to bandwidth consumption that exceeds the limited available spectrum. In contrast, degradation in VoLTE service performance is rare. To ensure a good user experience during times of network congestion, VoLTE packets are prioritized, and latency is managed in both directions[16].

[16] https://www.spirent.com/assets/wp/wp_mobile-network-outages-service-degradations



Measurement data collected over 10,000 minutes from flights in rural and urban scenarios showed that data-over-voice (i.e., VoLTE) connections resulted in a 10x reliability improvement compared to regular 4G-LTE data channels. Integrating data-over-voice technology with a dual-modem solution leads to a 1000x improvement and a reliability level of 99.999%[17], the performance requirement for C2 connectivity assurance.



Mobile networks were originally designed for phone calls, with little or no data connectivity. These older 2G and 3G networks will eventually be replaced with VoLTE technology, but this transition will probably be slow for most parts of the world[18]. Today, 2G/3G still make up a large part of the global infrastructure[19]. Data-over-voice technology operates on any mobile network generation ("XG") delivering reliable C2 connectivity.

[17] https://www.nsf.gov/awardsearch/showAward?AWD_ID=2126616&HistoricalAwards=false
[18] https://data.gsmaintelligence.com/research/research/research-2021/the-sun-sets-on-2g-and-3g-networks-as-operators-look-to-the-future
[19] https://opencellid.org/stats.php

Conclusion

Mobile networks were not designed for aerial services. This shortcoming can be overcome with new solutions, such as 5G Network Slicing, V2X/ITS QoS classes, and other drone-specific 3GPP standards. While these solutions have the capability to provide high priority and low latency C2 connectivity, they all require changes to the current network infrastructure and a substantial investment from network operators in the still nascent drone industry.

Modem-centric software solutions and special modem firmware that utilize existing networks can bridge the gap until infrastructure-dependent solutions are widely available. C2 data-over-voice technology meets aviation requirements at an affordable cost and can play a positive role in the growth of the global BVLOS industry. In the long-term, repurposing voice channels for safety-critical applications provides a cost-effective redundancy layer that can be beneficial for multiple autonomous industries.

- ✓ Prioritized data connections - Continuity
- ✓ All networks worldwide - Availability
- ✓ Guaranteed Quality-of Service - Low

Latency