National Aeronautics and Space Administration

Flying Drones Beyond Visual Line of Sight Using 4G LTE: Issues and Concerns

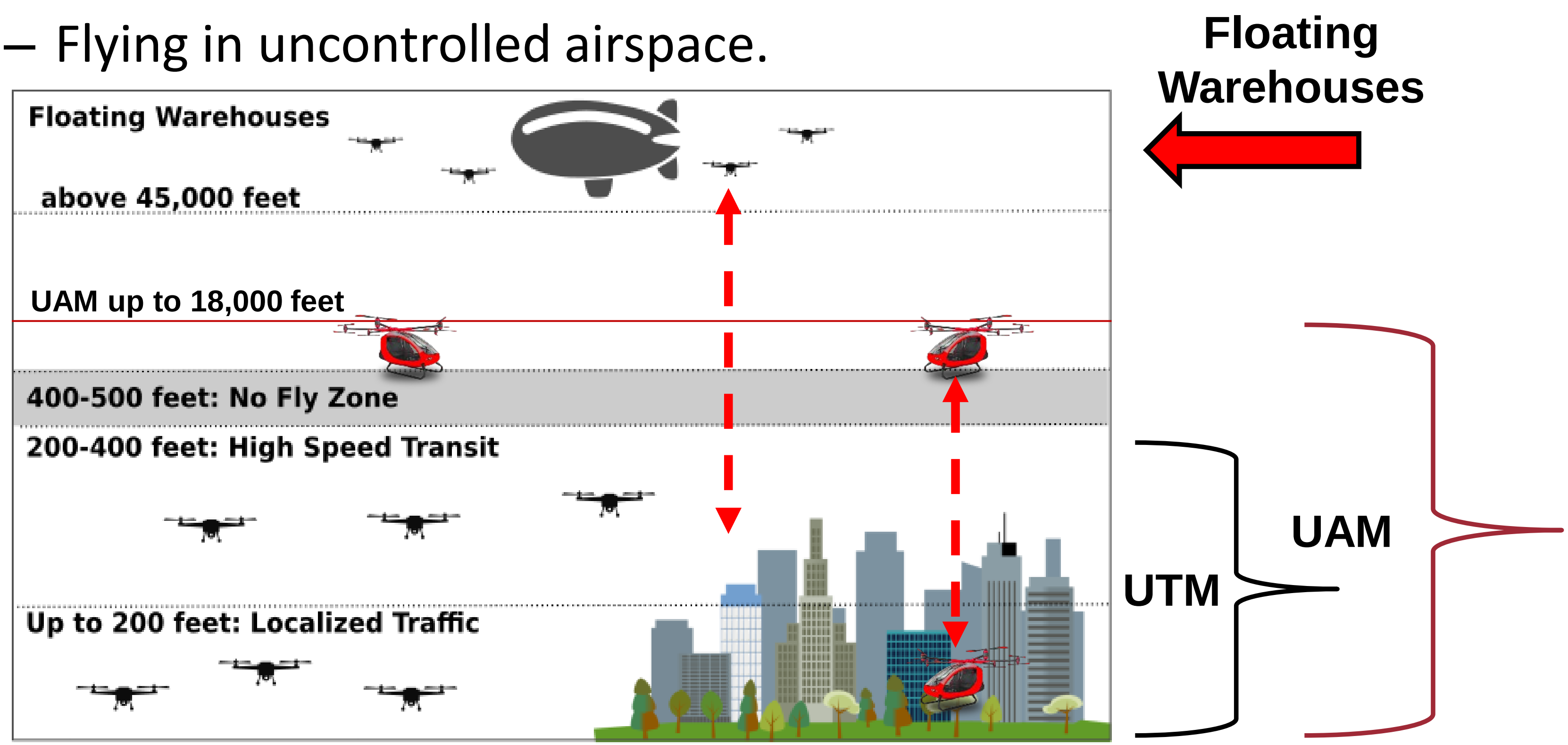
I-CNS 2019

April 9-11, 2019

William D. Ivancic, Syzygy Engineering LLC
Robert J Kerczewski
Robert W. Murawski, MTI Systems Incorporated
Konstantin Matheou, Zin Technologies Incorporated
Alan N Downey, NASA Glenn Research Center

UTM Project – the first step

- Unmanned Aerial System (UAS) Traffic Management (UTM)
  - UAVs with a total weight including cargo of under 55 pounds
  - Flying under 400 feet
  - Speeds of up to 100 mph
  - Flying in uncontrolled airspace.



Amazon's Airspace Design for Small Drone Operations with Floating Warehouses

Purpose

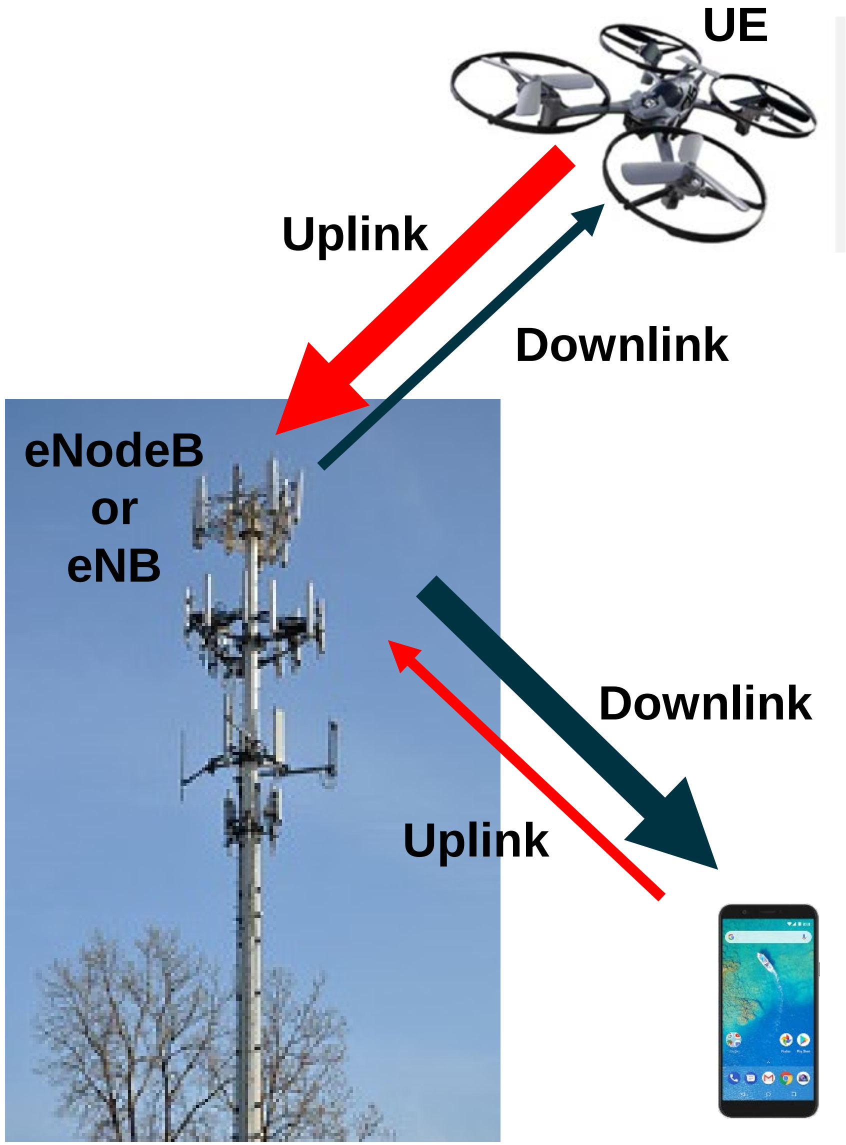
- Can 4G LTE can be used for air traffic management of small Unmanned Air Vehicles (sUAVs) as well as support user applications.
  - Applications include: mapping, surveying, newsgathering, surveillance, agricultural and marketing (videos and imagery) and package delivery
- If so:
  - What are the limitations?
  - What enhancements may be necessary?
  - What are the major issues and concerns?

NASA GRC Focus

- Most international government agencies responsible for Airspace Safety want to know if current and future cellular telecommunications systems and in particular 4th Generation, Long Term Evolution (4G LTE) can be used to provide communications necessary to ensure that sUAVs can fly safely beyond visual line of sight (BVLOS)
- Can LTE be used to provide the uplink applications communication needs and the uplink/downlink command and control communications necessary to ensure sUAVs can fly safely beyond visual line of sight (BVLOS)?
  - Command and control implies reliability
  - Uplink applications stress the LTE network
    - Examples: High-definition video or high-quality imagery

Terminology

- User Equipment
  - Cell phone, smart phone, UAV with 2G, 3G, LTE, 5G radio ***and associated protocols***
    - Radio Access, Network Registration, Handovers, Service Level Agreements (e.g. data rates and data quantity), Billing
- Downlink: the unidirectional radio link for the transmission of signals from a UTRAN (base station) access point to a UE (User Equipment - e.g. cell phone). In general the direction from Network to UE.
- Uplink: the unidirectional radio link for the transmission of signals from User Equipment (UE) to a base station



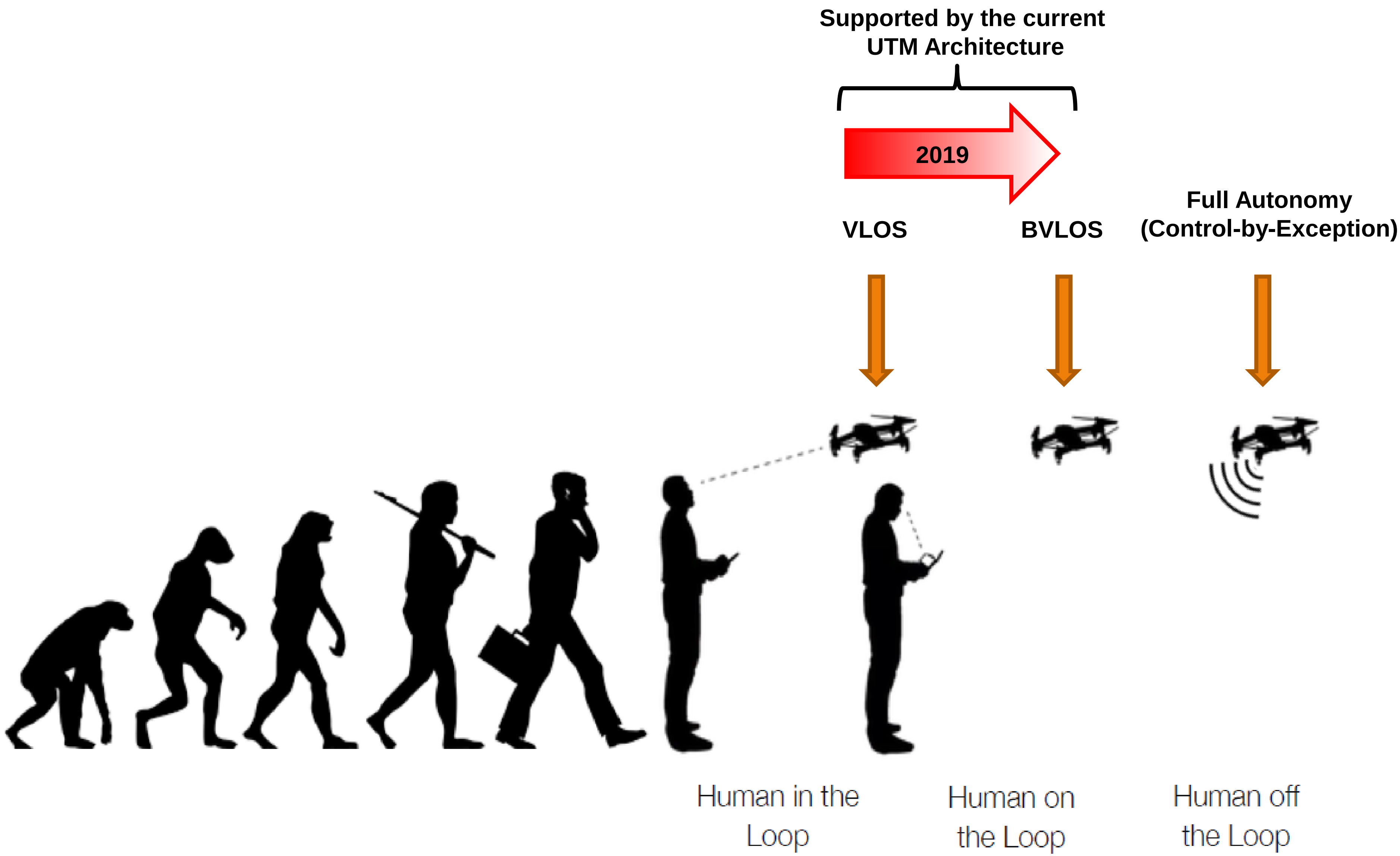
Air Traffic Management Trends and Evolution

- Pre 1956 – managed aircraft into and out of airports, else see and avoid
- Current ATM – Active Control system with air traffic controllers communicating directly with pilots
- Corridors (highways in the sky)
  - Pro: one of the ways to help ensure separation of aircraft.
  - Con: can increase flight distance (fuel) and time and reduces scheduling flexibility, scaling issues
- Free Flight – Pilots could fly paths that are more direct to their destinations rather than flying in corridors.
  - Yet to be instituted.
    - Security concerns
    - Flexible, but difficult scheduling problems – particularly coexisting with current practices
- Control-by-Exception
  - pilots and aircraft with the use of new situational awareness technologies can generally maintain self-separation
  - Air traffic controller only needs to be involved when situations become abnormal

UAS Traffic Management

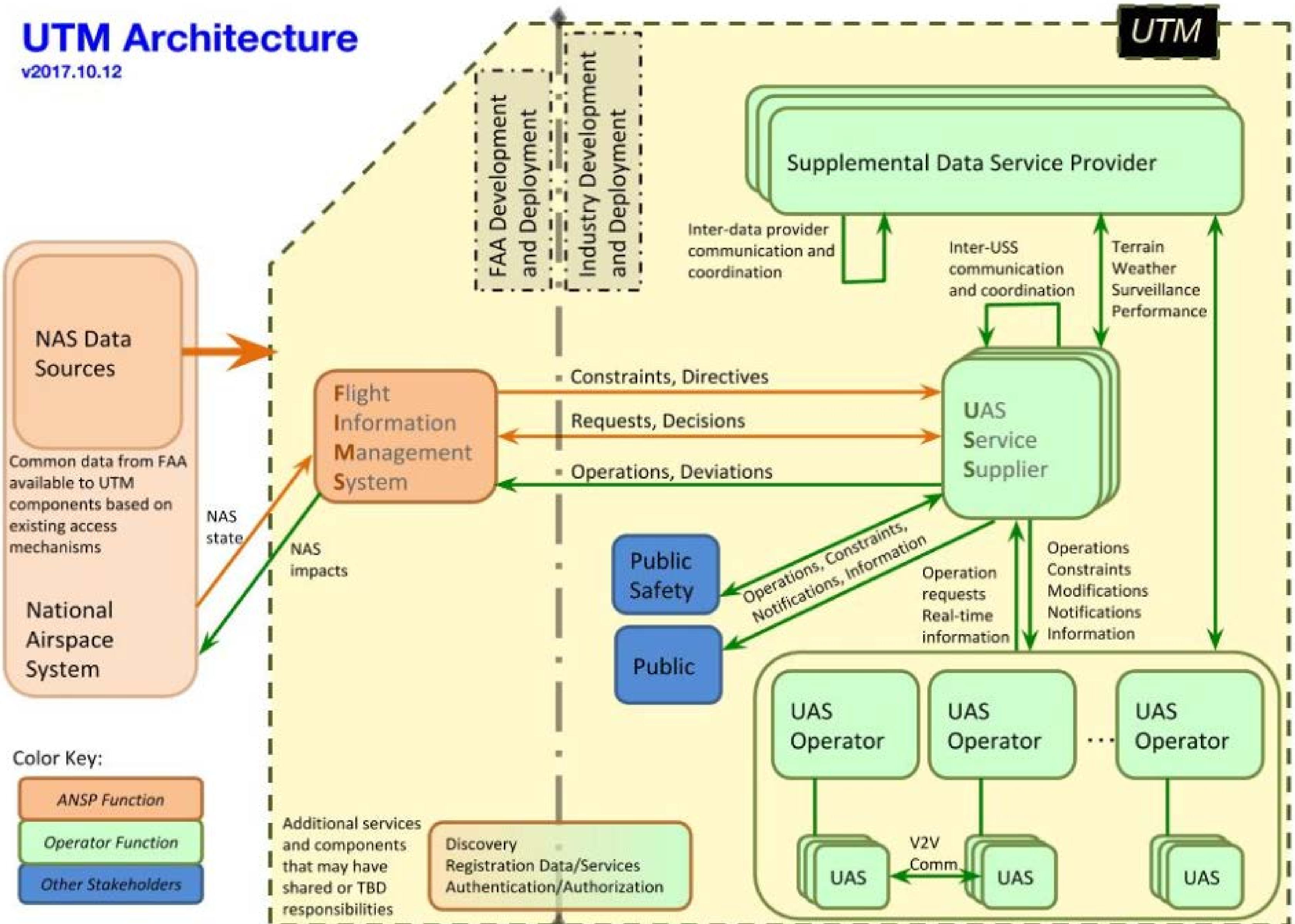
- Operating principles for small UAS
  - Only authenticated UAS and operators are allowed to operate in the airspace
  - UAS stay clear of each other (clear is a vague term)
  - UAS and manned aviation stay clear of each other
  - UAS operators or support systems have awareness of all constraints in the airspace and of people, animals and structures on the ground and UAS will stay clear of them
  - Public safety UAS (e.g. police, first responders, government agencies, and military) should be given priority over other UAS and manned aviation.
- Solution must address Scalability Issues.
  - Currently about 5,000 commercial flights in the air over the US at any one time
  - Forecast 250,000 to 1.6 million ***commercial drones*** in the US by 2021
- Free flight for most operations with Geo-fencing
- Corridors expected to be used for high density areas

UTM Evolution



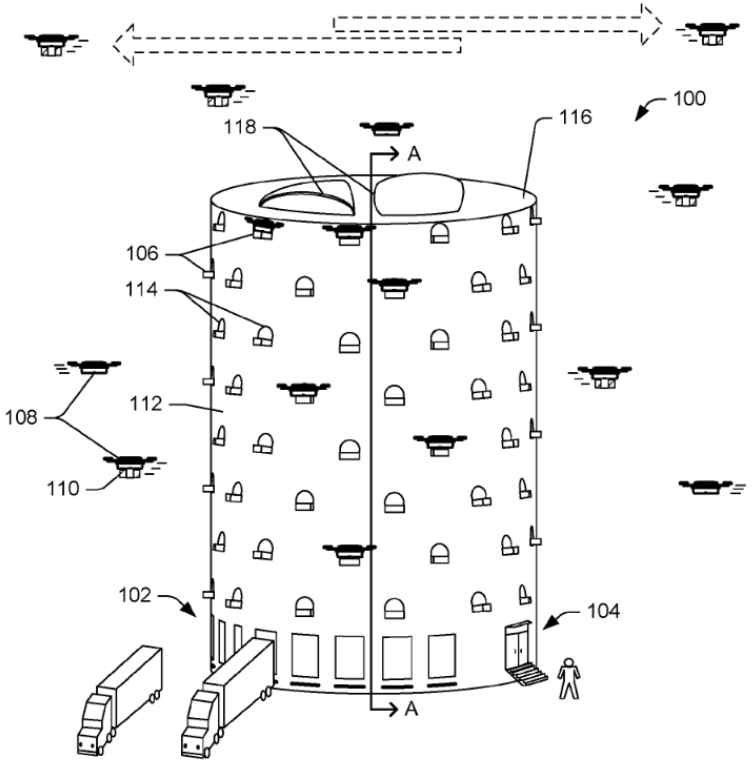
Source: Dr. Marcus Johnson

UTM Architecture



UTM Architecture and Autonomous systems

- Current architecture is sufficient for operator in the loop
- Architecture needs to evolve to accommodate autonomous operations such as package delivery
- Package delivery may be the largest application for sUAVs
- Amazon®, FedEx®, UPS, Wal-Mart, Domino's Pizza and others are expected to use drones for package delivery



Amazon Patent Multi-Level Fulfillment Center for Unmanned Aerial Vehicles

Managing Autonomous System

- Terrestrial motor vehicle transportation system
  - Corridors (roads … sometimes one-way)
  - Coarse regulators (e.g. traffic lights, traffic cops)
  - Speed limits
  - The vehicle operating system.
    - o Breaks, steering, accelerator
    - o Sense and avoid system (currently human)
      - Blind spot sensors
      - Lane changing
      - Dynamic Cruse Control
      - Driver assist / autonomous parking
      - Automatic breaking
- Self-driving cars
    - o Vehicle-to-vehicle communications
      - Secure and fast (enabled with 5G cellular technology)
    - o Coordination between groups of vehicles (i.e. eliminate traffic lights or make them dynamically controlled)
    - o Situational awareness only has to be local (Scalability)
      - Applicable for sUAVs in UTM airspace, at least for localized traffic below 200 feet and traveling at relatively low speeds.

Applications and communication loading

- Command and Control Requirements are currently undefined … at least by FAA or ICAO. Why?
  - Different operation scenarios and traffic management systems requires different types and amounts of communication.
  - The traditional centralized control system requires communication between the aircraft and the controller.
  - Autonomous systems may only require communication between localized vehicles
- Commanding and control (C2) is expected to put minimum strain on the system
  - Note: Latency requirements may be quite different depending on whether one is commanding to maneuver a UAV vs. commanding to update waypoints.
- Applications can place a heavy load on the LTE **uplink** portion of the network – particularly high-quality video.

Current BVLOS Operational Systems

- Current regulations for most major countries can be found on the ICAO UAS Toolkit website
- A 2017 report by the RAND Corporation entitled "International Commercial Drone Regulation and Drone Delivery Services" provides the latest BVLOS regulations of most major countries
  - Most of the information in this report is from 2016 to 2017.
  - Laws are constantly being reevaluated;
  - Generally, drone laws are moving toward a more-permissive approach to regulation.
- Most countries have yet to approve BVLOS operations except via waivers
- As of 2017, the only countries that have enacted relatively unrestricted legislation on commercial drone are: Costa Rica, Iceland, Italy, Norway, Sweden and the United Arab Emirates
- As of October 2018, many, if not most, current operational systems are in counties that have rural access needs.
  - 4G LTE infrastructure is not often available if at all. Here, the use of satellite communications is likely necessary.
- Global UAV has been operating mainly in Europe for over 2 years BVLOS exclusively using LTE.
  - Mostly of the users are Government and law enforcement as government agencies are cleared for such operations
  - Uplink rates are advertised at 8Mbps, but with video compression, only 1.5 to 2.0 Mbps is required.

3GPP Study on Enhanced LTE Support for Connected Drones

- 3GPP – 3rd Generation Partnership Project
- Objectives:
  - verify the level of performance (need requirements),
  - identify supportable heights, speed, and densities of aerial vehicles,
  - investigate and develop air-to-ground channel models, and
  - study performance enhancing solutions for interference mitigation, interference detection, identification, handover, and positioning.
- Requirements (developed by 3GPP by necessity)
- Field trials and simulations by at least 7 different entities (Qualcomm, Nokia, Ericsson, ZTE, Huawei, NTT, Docomo)

3GPP developed requirements / metrics

Requirement developed by iterative consensus process among team members

Items	Value
Data type	1. C&C: This includes telemetry, waypoint update for autonomous UAV operation, real time piloting, identity, flight authorization, navigation database update, etc. 2. Application Data: This includes video (streaming), images, other sensors data, etc.
Latency (NOTE)	1. C&C: 50ms (one way from eNB to UAV) 2. Application data: similar to LTE UE (terrestrial user)
DL/UL data rate	1. C&C: 60-100 kbps for UL/DL 2. Application data: up to 50 Mbps for UL (High Definition Video)
C&C Reliability	Up to 10^{-3} Packet Error Loss Rate (99.9% reliability)

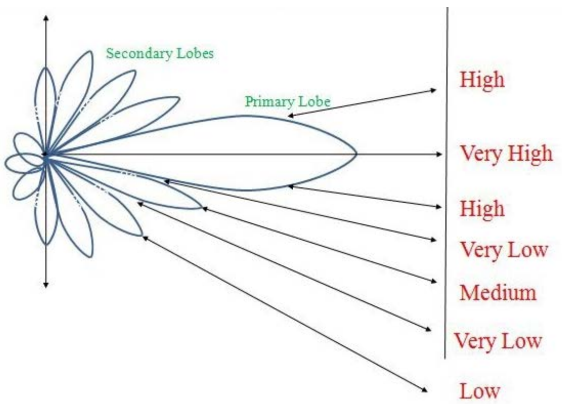
Performance metrics for HO and RLF simulations

KPI	Unit	Description
Handover rate	HO/UE/sec	Number of HO attempts over time (including HOF)
HOF rate	%	Number of HO failures/Total number of HO attempts (including HOF)
Radio Link Failure (RLF) rate	RLF/UE/sec	Number of RLFs over time
Time in handoff	%	Fraction of time a UE is in HO procedure including time for successful HO (HO execution delay) and HOF (reestablishment delay)
Time in Qout	%	Fraction of time a UE is in Qout state
Ping pong rate (NOTE)	%	Number of ping-pongs/Total number of successful handovers (excluding handover failures)

Key Findings – Field Trials

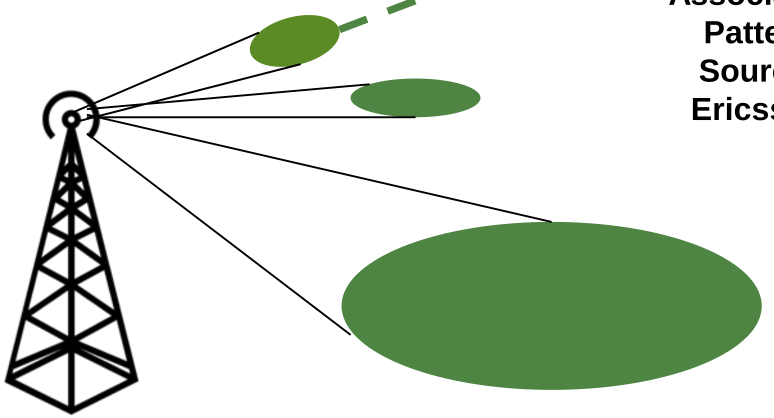
- At elevation, the RF signals experience free-space propagation
- Inter-cell interference increases significantly at higher altitudes leading to a decreased Signal to Interference Noise Ratio (SINR) at the airborne receiver.
- Reference Signal Receive Powers (RSRPs) for Aerial User Equipments (AUEs) are higher than the RSRPs for Terrestrial User Equipments (TUEs)
- Reference Signal Received Qualities (RSRQs), at the higher altitudes are lower than the RSRQs at ground level.
- SINR, RSRP and RSRQ are used to determine handovers and thus affect handover operation.
- **UE at altitude produces more uplink interference in the network than ground UEs (3X in 700 MHz band)**
  - **Results in poor resource utilization.**
  - **The presence of UAVs has a negative impact on the UL performance of the TUEs**

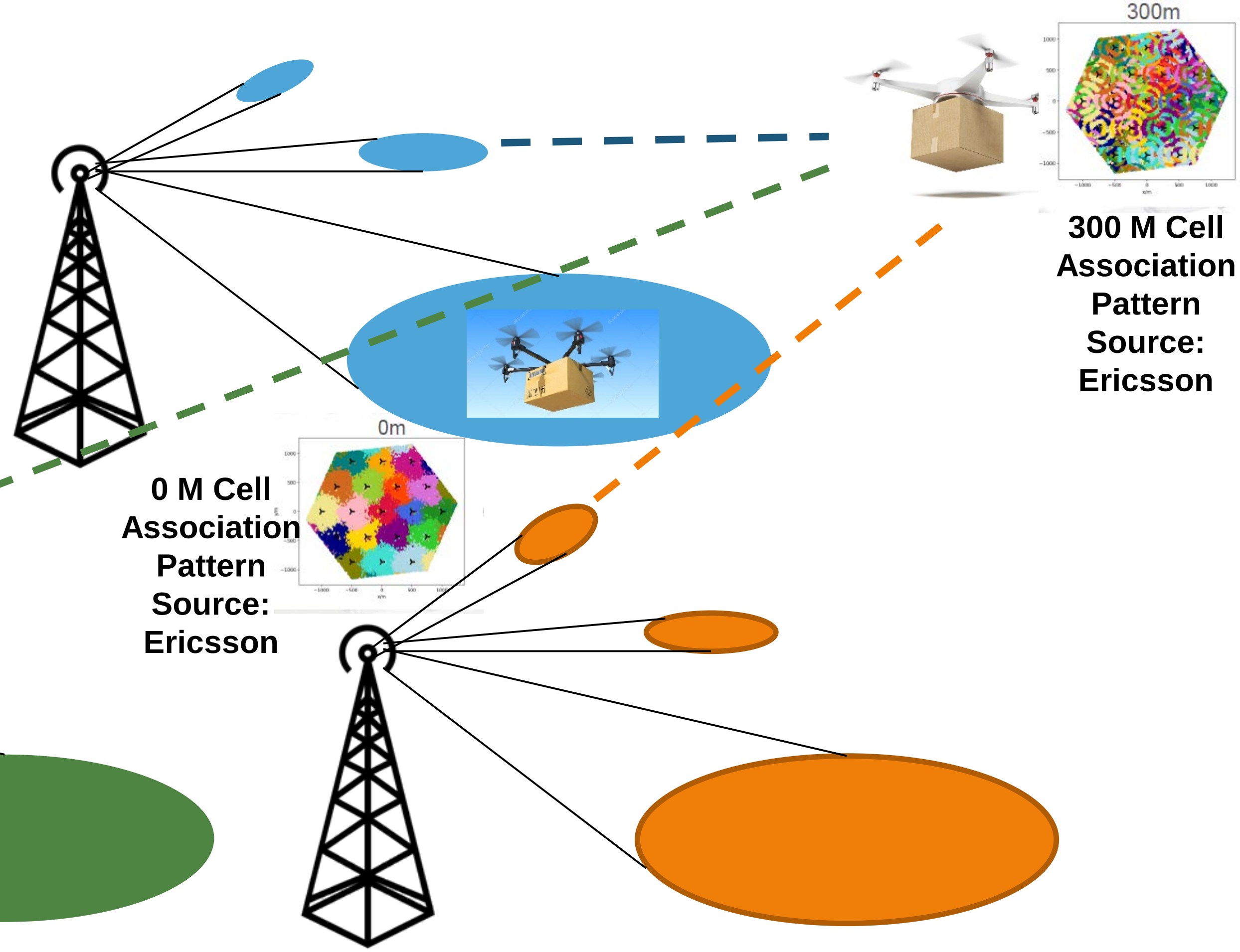
The Problem - sidelobes



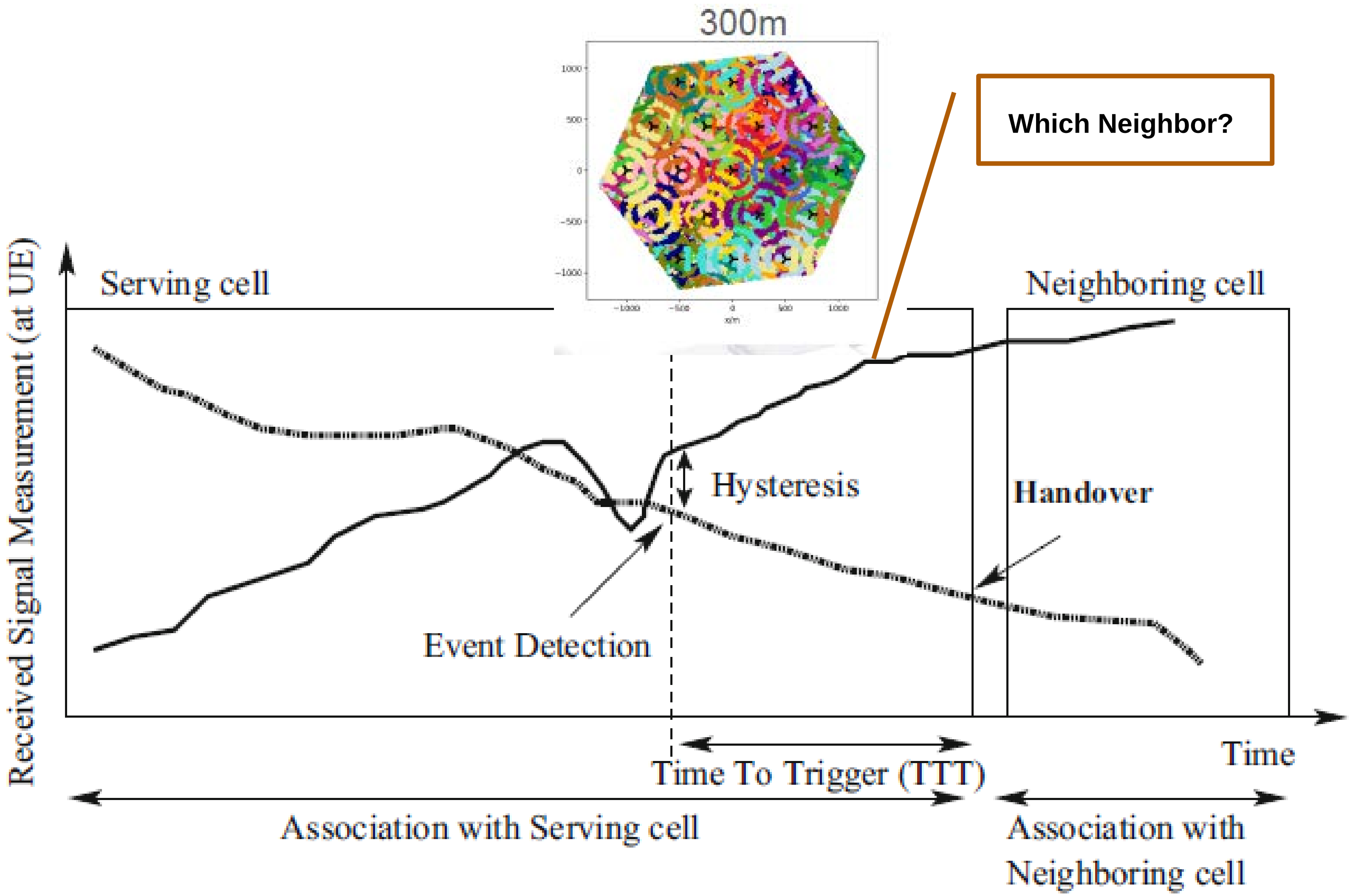
Source: Naha Kumar

Urban Macro (Uma)





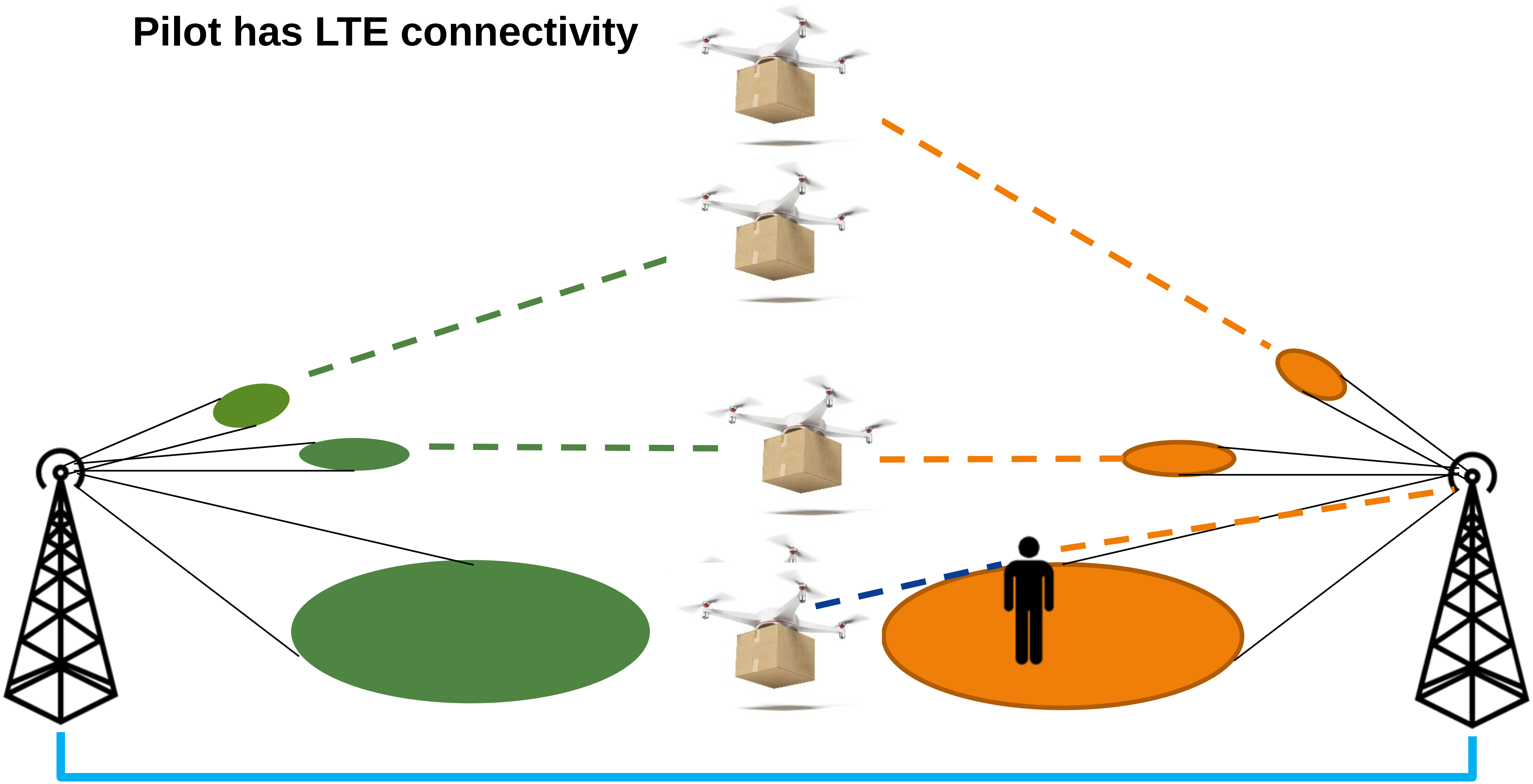
Mobility Management at Altitude



Source: IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

Rural Macro (Rma)

Scenario Requires:
Local Radio Control while on the ground
4G LTE BVLOS in the air
Pilot has LTE connectivity



Items that will improve Aerial Use

- Improved interference detection
- Uplink interference mitigation
  - Improves utilization of system resources
  - Enables increased uplink data rates
- Downlink interference mitigation
  - Expected to improve mobility management
- Mobility performance improvement and
  - Possible new or different algorithms for AUEs and eNodeBs
- Aerial UE identification
  - Enables AUEs to be place in restricted channels thereby mitigating interference with TUEs
  - Can trigger different mobility algorithms and power control algorithms
  - Improves security (rouge AUEs can have service terminated)

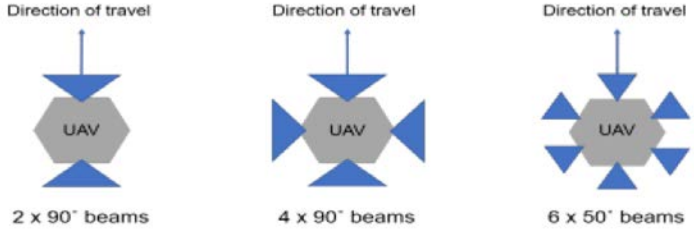
Power Control Algorithms - simulations

- Optimized Open Loop Power Control (OLPC) is proposed by Qualcomm (Note, Qualcomm is a EU manufacturer)
- Extremely attractive solution for interference mitigation, as it does not require any changes to eNodeB
- Can be employed by all UEs (terrestrial UEs and aerial UEs – AUEs) without differentiation of airborne and ground UEs.
- Issues related to field trials:
  - Can one change the power control in current commercial UEs (this may require cooperation by UE manufacturers;
  - Does one have to develop a software defined radio (SDR) that operates in real-time in order to manipulate the power control algorithms in the UE?
  - Scalability is hard. It is significantly more challenging to make systems work on a global scale than it is for small-scale deployment.
  - How can this be flight tested, as a single AUE or a few AUEs may not provide sufficient loading to demonstrate much of anything?

Pattern Diversity Multi-sector Antennas

- Nokia simulations indicated that pattern diversity (a.k.a. angular diversity using 4 or 6 fixed sectorized beams, for both rural and urban areas, the achieved reliability is higher than the target 99.9%.
- The amount of interference received in the downlink is limited to the beam width of the beam, leading to a reduced overall outage.
- The receiver simply picks the beam direction with the best signal quality (RSRP or RSRQ) without adjusting the orientation of the drone
- In the uplink, the antenna provides a gain for the drone and limits the interference impact on terrestrial users

Multi-sector fixed beam Antennas concept



Average uplink throughput gains with a grid of fixed 6 beams in medium - high load traffic conditions

Environment	Terrestrial UE	Drone at 120m
Rural	+20%	+35%
Urban	+51%	+56%

Multi-sector Antennas - Issues

- Developing a 6 sector antenna system and integrating that with a UE requires coordination of the UE with the antenna control system
- Determining which sector to activate is a complex problem
  - One possible algorithm is for the system to turn all sectors on for scanning to determine handover criteria
    - Some analytical method must be used to determine from which sector the best neighbor is being received.
  - Another possibility is to quickly activate each sector to 'scan' for towers and then turn the selected beam on for UL transmissions
- The gains provided by Pattern Diversity can be field tested by just using one directional antenna and performing network measurements to validate the simulation results.
  - ***A field test was under development by NASA GRC, but not completed due to reprogramming of funding in February 2019. The antenna (single sector) is tested and could be made available to interested parties.***
  - The critical measurements are the Interference-over-Thermal (IoT) at all eNodeBs in view.
    - These measurements are needed to determine the overall interference generated by the UL transmission and the interference mitigation effects provided by the single sector directional antennas.

Handovers

- A limited amount of field testing has been done regarding drones at elevation
  - Results have been mixed and reasons unclear
    - Qualcomm field trials in an Urban Macro area showed "Handover performance (success rate of handovers, and lower frequency of handover events) is superior for airborne UEs than for ground Users
    - Test by KDDI in Japan over a 100m square route in an Urban Macro area showed that above altitude 50m, some handover failures occurred. This is likely because of the interference from many neighbor cells. There were no failures at ground level.
- Six different 3GPP companies performed a number of simulations to evaluate handover issues with mixed results
  - The results for Source 1, source 2 and source 3 for mobility rates of 3km/h and 30km/h, the handover rate of TUEs was higher than that of AUEs.
  - Source 4, source 5, source 6 and source 3 at mobility rates of 60km/h and 160km/h, the handover rate of TUEs was lower than that of AUEs
  - The majority of the companies observed higher HOF and RLF rates for aerial UE than that for terrestrial UE in most cases.
    - The higher the speed or the height of aerial UE, the higher HOF and RLF rate was observed.
  - The Majority of the companies observed higher RLF rate for AUE in most cases.
    - The higher the speed of AUE, the higher the RLF rate.
  - In general, a better mobility performance was observed in rural area networks compared to urban area networks. This is likely due to a limited number of eNodeBs and therefore less interference.

Conclusions – page 1

- 4G LTE can be used to command and control drones and for drone applications, but it depends on where the drone is operating and what the application is.
- 4G LTE is not ubiquitous. One cannot use LTE where it is not available. Other services such a satellite may be required.
- It is highly unlikely that a drone operating in a UMa area would be able to obtain significantly more coverage area by using two service suppliers
  - In high service areas, such as Urban Macro (UMa) areas, different service providers tend to cover the same areas and also tend to NOT cover the same areas.
- In highly rural areas with low population densities, there may be only one service provider
- Better solutions are needed to address the mobility issues of the AUEs and that handover algorithm can be further optimized to better support AUE mobility performance.

Conclusions – page 2

- Studies indicate that for today's 4G LTE networks in Urban Macro setting where LTE is ubiquitous, 3GPP performance criteria can be achieved when only a few AUEs are operating. However, ***as the number of AUEs increases, without some modifications and optimizations of the LTE network or drone antenna technology (for interference mitigation), these goals may not be achievable.***
- Servicing AUEs using the existing 4G LTE network and associate drone antenna technology has significant impact on the terrestrial users.
  - Providing efficient and effective connectivity to the aerial UEs while minimizing the impact on terrestrial devices requires a rethinking of many of the assumptions, models, and techniques used to date for cellular systems.
- Applications and operations have to be designed to work within the limitations of the network.
- One certainty in drone operations is that, for some drone somewhere, the radio link will fail. Sufficient mechanisms must be in place to ensure safe operations when radio link failure occurs.