ANALYSIS OF SPECTRUM SHARING FOR UNMANNED AERIAL SYSTEMS

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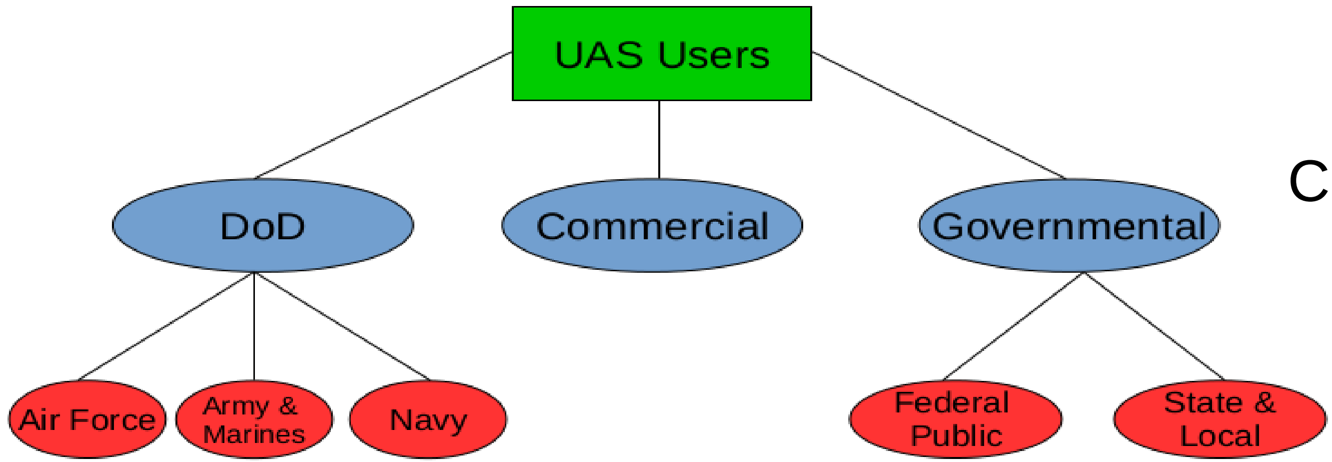
Introduction

- Unmanned aircraft system (UAS) is the **aggregation** of multiple systems:
  - Unmanned aircraft subsystem
  - Ground control station (GCS) subsystem
  - ATC subsystem
  - Sense & Avoid subsystem
  - Payload subsystem (e.g. video camera, etc.).

- The physical aircraft is the unmanned aerial vehicle (UAV) or, simply, unmanned aircraft (UA)

- **Well-developed** UAV technology
- Significantly **lower costs** than that of traditional manned aircraft systems [1]

Projected and Current Applications



Categorization of UAS Users

Application Examples

Role	**Commercial**
Media	- Event filming - Aerial photography - Information services
Transport	- Cargo planes
Monitoring	*Security* - Pipeline *Inspection* - Power and rail line
Communications	- Relay - Remote sensing - Disaster eNBs
Agriculture	- Crop spraying/dusting - Forestry operations

Role	**Governmental**	
	Federal	**State & Local**
Science	*Earth & Environment* - Pollution and land monitoring - Meteorological services - Biological services - Research	
Security	- Coast line - Border patrol - Anti-terror fight - Search & Rescue - Disaster and catas-trophe management	- Police support - Fire fighting - Traffic spotting - Forest fire avoid-ance
Humani-tarian Support	- Famine relief - Medical support - Emergency relief	

Classification of UAVs [2]

- Useful UAV Classification are mean takeoff weight (MTOW) based

Name	**MTOW** [kg]	**Operating Altitude** [m]	**Mission Radius** [km]	**UAV Examples**
Nano	< 0.5	< 120	1.6	Hummingbird
Micro	$0.5 - 2$	< 915	< 8	Raven A/B
Small	$2 - 25$	$< 3,050$	< 40	T-Hawk
Ultralight Aircraft	$25 - 115$	$< 4,570$	< 120	Integrator
Light Sport Aircraft	$115 - 600$	$< 5,500$	< 160	Shadow
Small Aircraft	$600 - 5,670$	$< 7,620$	< 320	Reaper
Medium Aircraft	$5,670 - 18,600$	$< 30,500$	TBD	Global Hawk
Large Aircraft	$18,600 - 136,000$	?	?	Pegasus

Nano UAV: Hummingbird

Micro UAV: Raven A/B

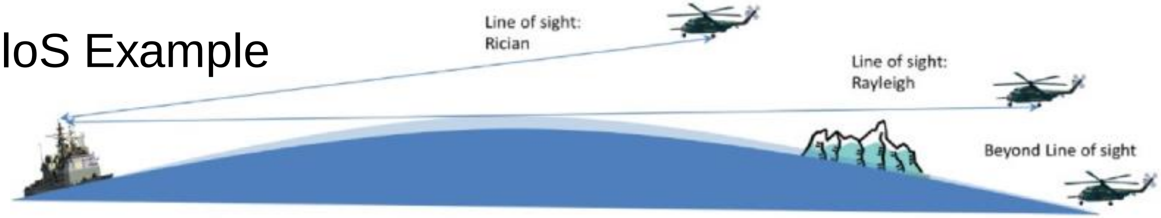
Small UAV: RQ-16A T-Hawk

Small UAV: RQ-16A T-Hawk

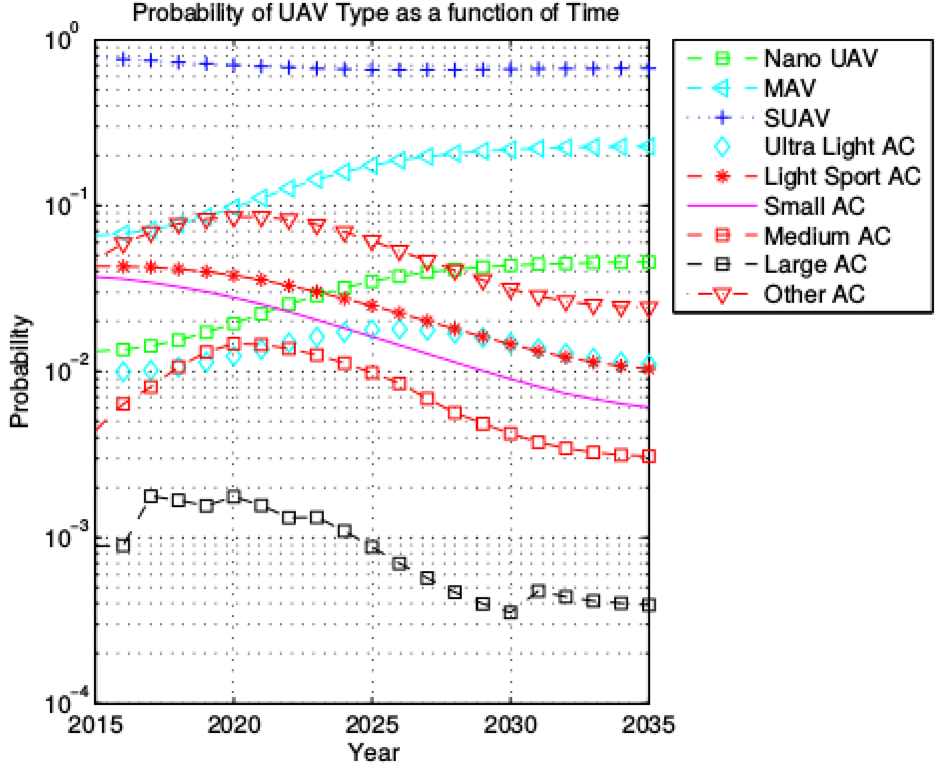
Projected Relative UAV Quantities

- Around 22% and 67% will be of type MAV and SUAV by 2035
- SUAV and MAV communication typically LoS radio communication [3] (and not BLoS)
- BLoS is the **indirect** radio communication between the UA and a UACS using **satellite communication services**

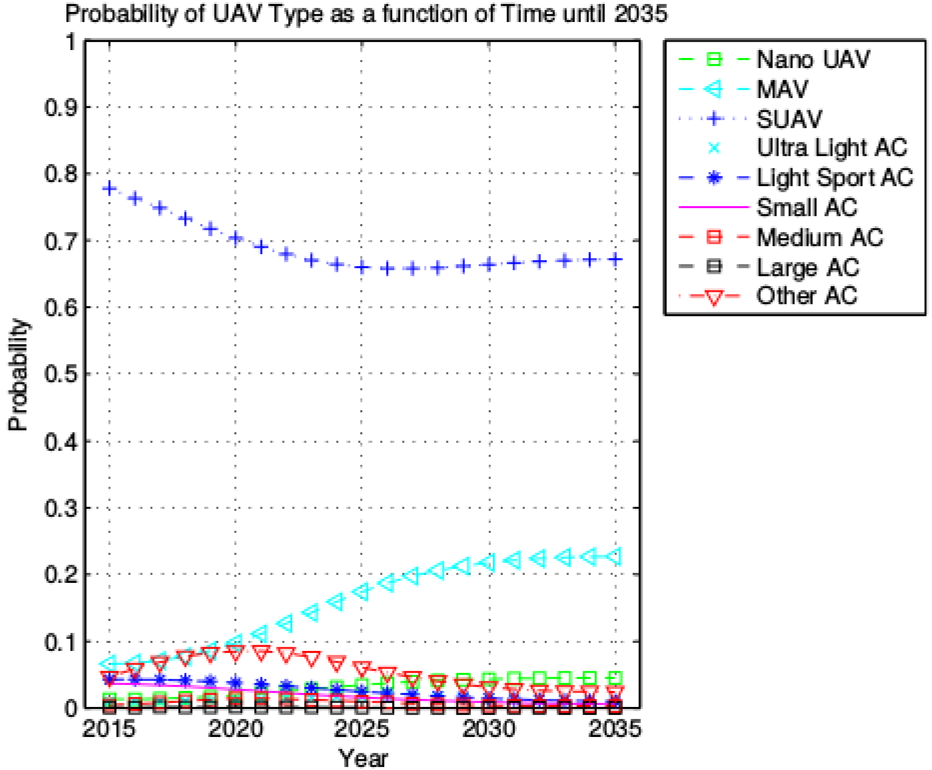
LoS and BloS Example



PMF of UAV Quantities

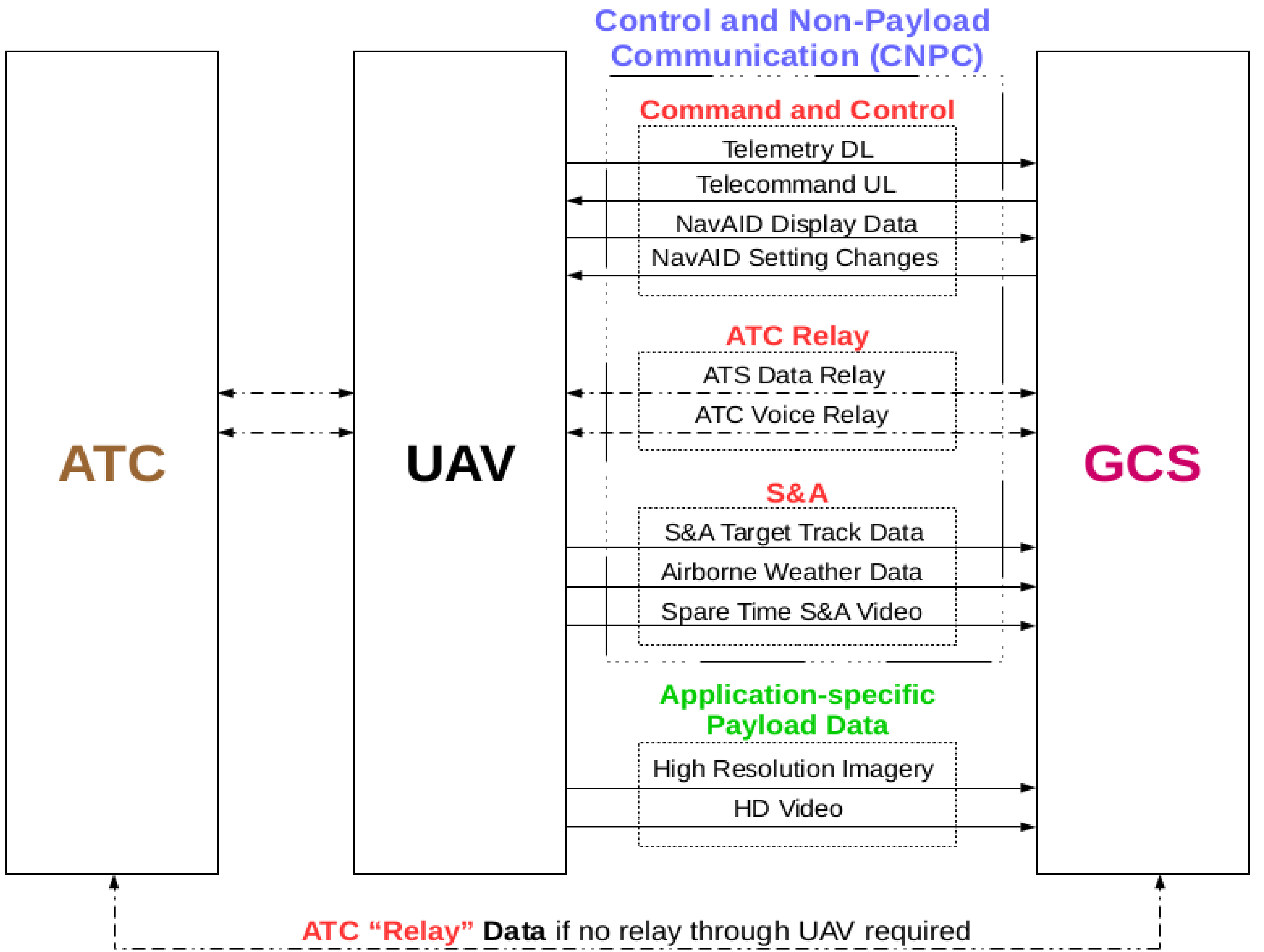


(a) Log-scaled PMF of UAV types



(b) Linear-scaled PMF of UAV types

Control and Non-payload Communication (CNPC) and Payload Links



Computed Spectral Requirement

- Bandwidth Requirement for any link: $W = K \cdot B \cdot M \cdot R/(U \cdot E)$
- Computation is based on Methodology I of ITU-R [4]
- Only 34 MHz of spectrum for LoS CNPC is intended to be allocated
- Increase of Spectral Efficiency to 1.45 bps/Hz

	C2	**ATC Relay**	**S&A Low Latency**	**S&A Medium Latency**	**Video/Weather Radar**
R	2	2	2	1.5	1
U	0.5	1	0.5	0.75	1
E [bps/Hz]	0.75				
Ratio $R/(U \cdot E)$	5.33	2.66	5.33	2.66	1.33

Cell Type	**M**	**K**	$\mathbf{B \cdot R/(U \cdot E)}$ [kHz]			**Spectrum Need** [MHz]		
			DL	UL	Overall	DL	UL	Overall
Surface	3	1	451.2	36.1	487.3	1.35	0.11	1.46
A	5	7	451.2	36.1	487.3	15.79	1.26	17.05
B	70	4	102.5	22.9	125.4	28.69	6.42	35.10
C	24	3	102.5	22.9	125.4	7.38	1.65	9.03
D	8	3	102.5	22.9	125.4	2.46	0.55	3.01
Total						55.67[21]	9.99[19]	65.65[22]

Air-to-Ground Propagation

- Cell Planning in Spectrum Computation is utilizing radio horizon as link range
- For LAPs high shadowing effect at low elevation angles

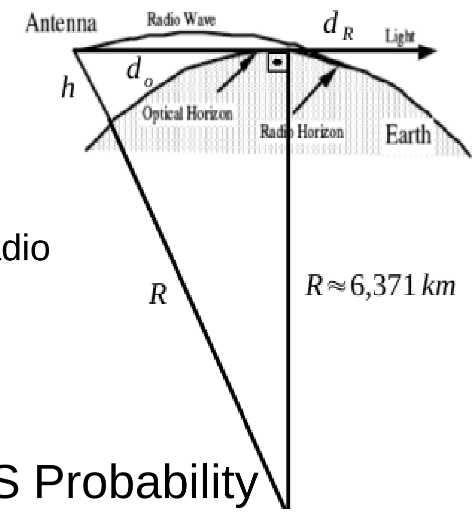
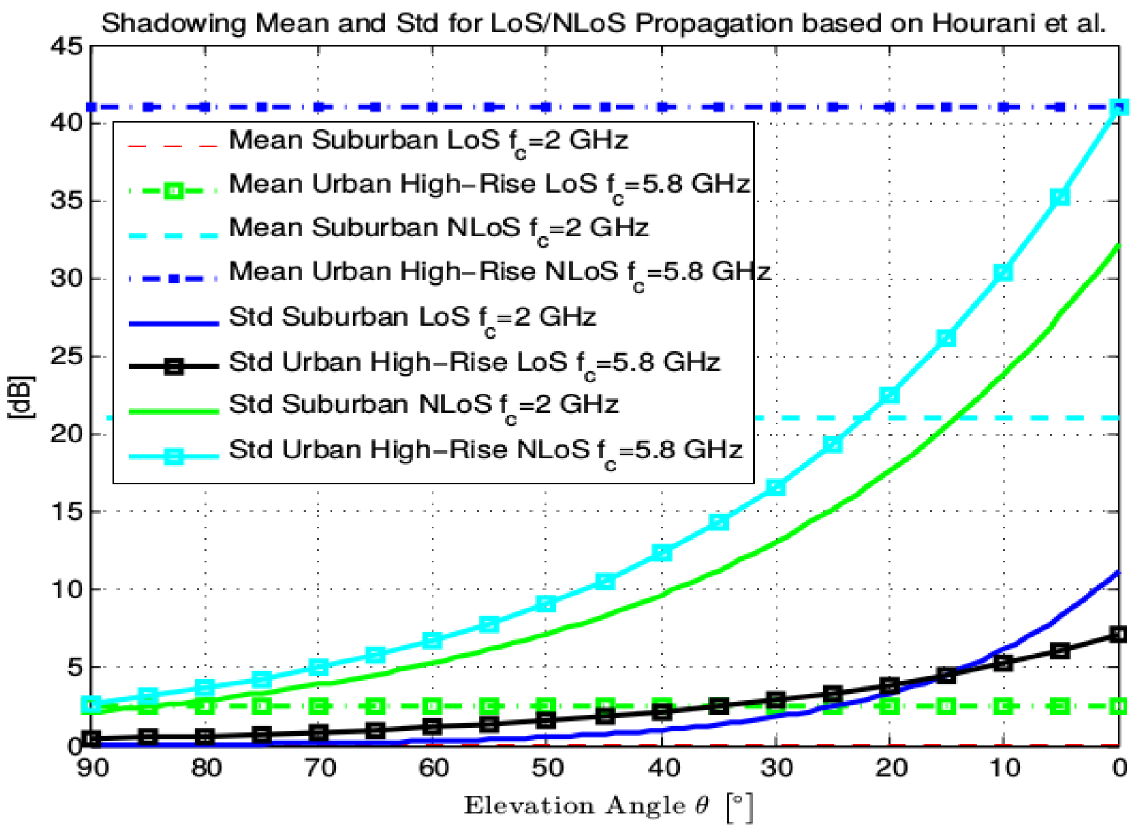
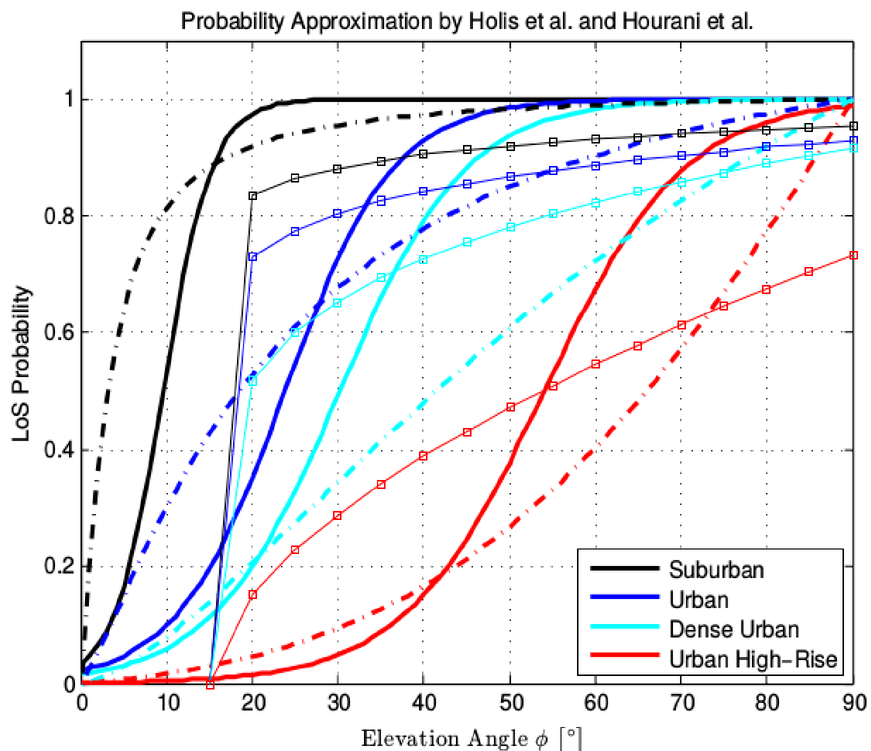


Illustration of Radio Horizon

Shadowing of LAP [5]

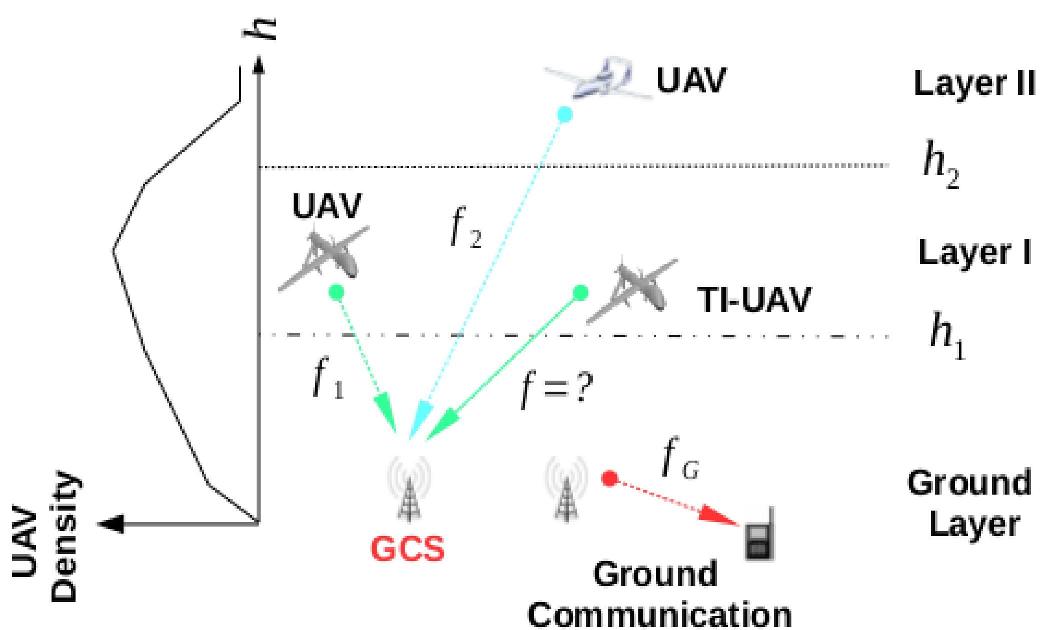


Radio LoS Probability



DL Spectrum Sharing Scenarios

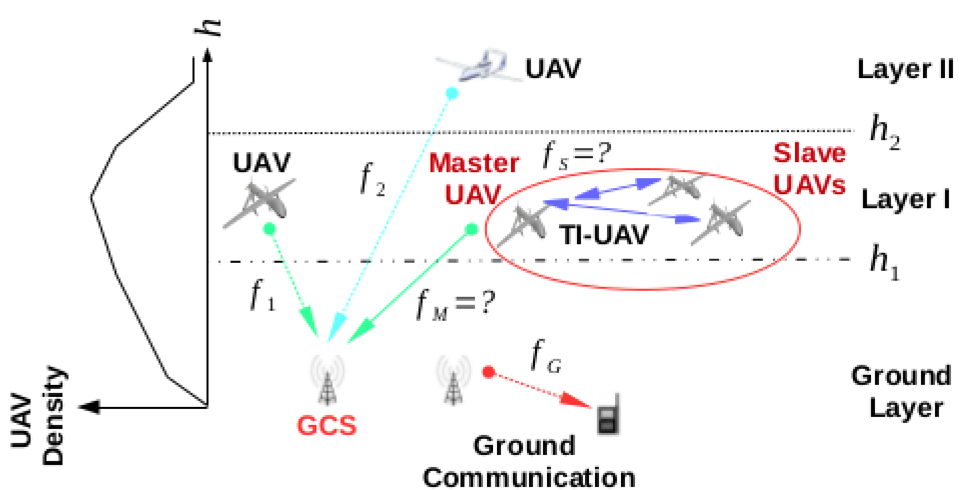
- UAV missions can be either of **individual** or **cooperative** nature
- Routes are either pre-planned (point-to-point or aerial-based) or unplanned



1. CNPC Spectrum from Higher Layer Available (Video/Weather Radar)
2. Intra-tier Spectrum Sharing
3. Unused spectrum from terrestrial communications systems (e.g. 3.5 GHz)

DL Spectrum Sharing of Cooperative UAV Swarms

- Similar concepts apply for Cooperative UAV Swarms
- Choose the “best” Master UAV to optimize throughput [6]



Conclusion

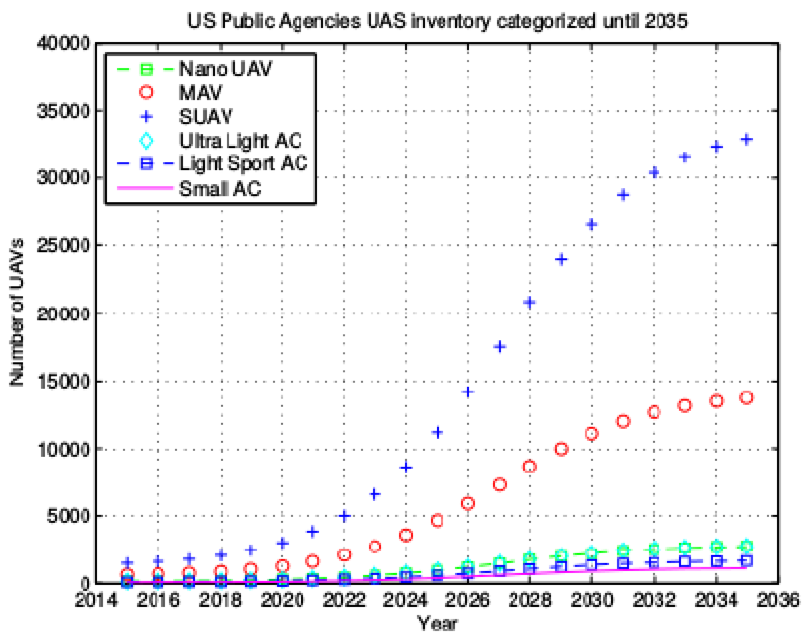
- Spectrum sharing solely based on sensing is not suitable for the UAS context
- Sensing as support of DSA
- Knowledge about neighboring UAVs (location, pre-determined route, phase of flight, etc.) needs to be available to make accurate decisions about opportunistic spectrum access
- A-priori knowledge of spectrum availability may also apply
- Location-based sensing allows the spectrum to “move”

References

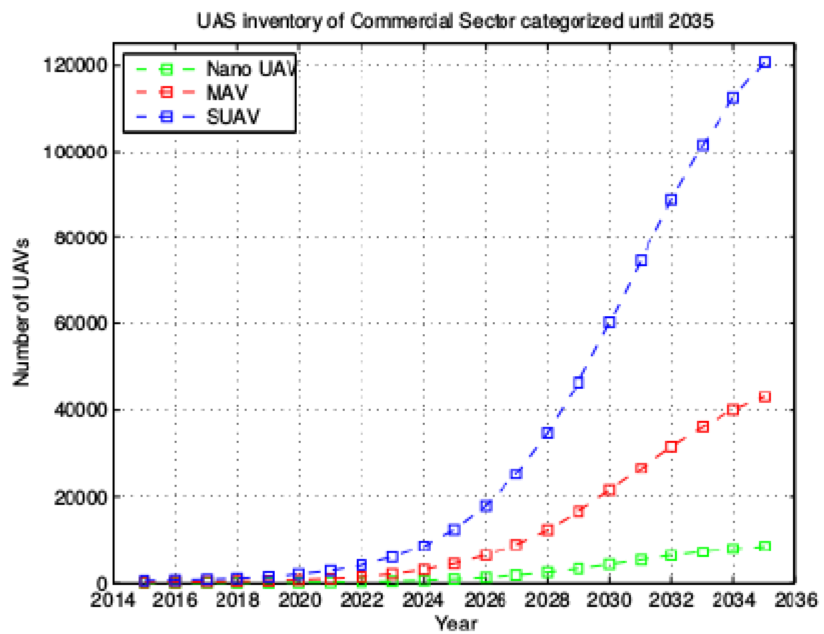
- [1] R. Austin, Unmanned Aircraft Systems: UAVs Design, Development and Deployment. Wiley, May 2010.
- [2] John A. Volpe National Transportation Systems Center, “Unmanned Aircraft System (UAS) Service Demand 2015 – 2035,” U.S. Department of Transportation, Tech. Rep. DOT-VNTSC-DoD-13-01, September 2013.
- [3] R. S. Stansbury, M. A. Vyas, and T. A. Wilson, “A Survey of UAS Technologies for Command, Control, and Communication (C3),” Journal of Intelligent and Robotic Systems, vol. 54, no. 1-3, pp. 61–78, 2009. [Online]. Available: http://dblp.uni-trier.de/db/journals/jirs/jirs54.html#StansburyVW09
- [4] ITU, “Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace,” International Telecommunication Union, Tech. Rep. M.2171, December 2009.
- [5] A. Al-Hourani, S. Kandeepan, and A. Jamalipour, “Modeling Air-to-Ground Path Loss for Low Altitude Platforms in Urban Environments”, Globecom 2014.
- [6] I. Abualhaol and M. M. Matalgah, “Throughput optimization of cooperative uavs using adaptive channel assignment,” in Wireless Communications and Networking Conference, 2006. WCNC2006. IEEE, vol. 4, April 2006, pp. 2279–2284.

Backup Slides

Projected Absolute UAV Quantities



(a) Projection of public agency UAV quantities (without DoD)



(b) Projection of commercial UAV quantities

- Predicted Quantity for all 3 Type of Users by Function $f(x) = p_1 + \dfrac{(p_2 - p_1)}{1 + 10^{p_4(p_3 - x)}}$

	p_1	p_2	p_3	p_4
Commmercial	487.95	$2.03 \cdot 10^5$	15.75	0.18
Federal Agencies	207.22	$1.02 \cdot 10^4$	9.73	0.18
State and Local Agencies	$1.87 \cdot 10^3$	$4.64 \cdot 10^4$	12.49	0.19

Link-Specific Data Rate Requirement

- CNPC Data Rate Requirement in bps [4]

<table>
<tr><th rowspan="3"></th><th rowspan="3">Flight Phase</th><th rowspan="3">Percentage Flight Phase</th><th colspan="4">Command & Control</th><th colspan="4">ATC Relay</th><th colspan="3">S&A</th></tr>
<tr><th colspan="2">Control</th><th colspan="2">NavAID</th><th colspan="2">ATC Voice</th><th colspan="2">ATC Data</th><th>Target Track</th><th>Airborne Weather</th><th>Spare Time Video</th></tr>
<tr><th>UL</th><th>DL</th><th>UL</th><th>DL</th><th>UL</th><th>DL</th><th>UL</th><th>DL</th><th>DL</th><th>DL</th><th>DL</th></tr>
<tr><td rowspan="5">Airport Surface and Low Altitude</td><td rowspan="2">Departure</td><td rowspan="2">42%</td><td>2,386</td><td>5,715</td><td>669</td><td>839</td><td>4,800</td><td>4,800</td><td>49</td><td>59</td><td rowspan="2">9,120</td><td rowspan="2">27,771</td><td rowspan="2">270,000</td></tr>
<tr><td colspan="4">=9,606</td><td colspan="4">UL: =4,849
DL: =4,859</td></tr>
<tr><td rowspan="2">Arrival</td><td rowspan="2">58%</td><td>4,606</td><td>7,615</td><td>669</td><td>1,140</td><td>4,800</td><td>4,800</td><td>16</td><td>32</td><td rowspan="2">9,120</td><td rowspan="2">27,771</td><td rowspan="2">270,000</td></tr>
<tr><td colspan="4">=14,030</td><td colspan="4">UL: =4,816
DL: =4,832</td></tr>
<tr><td colspan="2">Average</td><td colspan="4">$0.42 \cdot 9,606 + 0.58 \cdot 14,030$
=12,167</td><td colspan="4">UL, DL ≈ 4,855</td><td>9,120</td><td>27,771</td><td>270,000</td></tr>
<tr><td rowspan="2">Medium and High Altitude</td><td rowspan="2">En-route</td><td rowspan="2">100%</td><td>1,201</td><td>2,356</td><td>669</td><td>839</td><td>4,800</td><td>4,800</td><td>23</td><td>28</td><td>9,120</td><td>3,968</td><td>27,000</td></tr>
<tr><td colspan="4">=5,062</td><td colspan="4">UL: =4,823
DL: =4,828
UL, DL ≈ 4,855</td><td>9,120</td><td>3,968</td><td>27,000</td></tr>
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Cell Types

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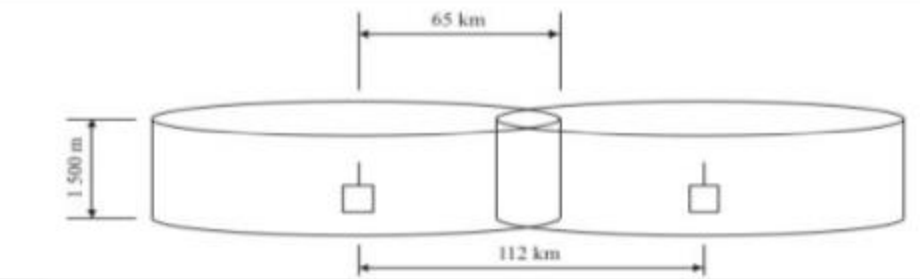
<tr><th>Cell Name</th><th>Configuration</th></tr>
<tr><td>A</td><td>
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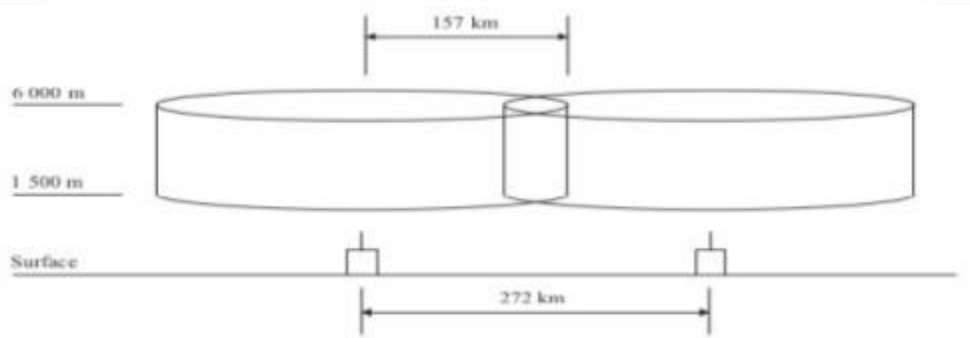
<tr><td>B</td><td>
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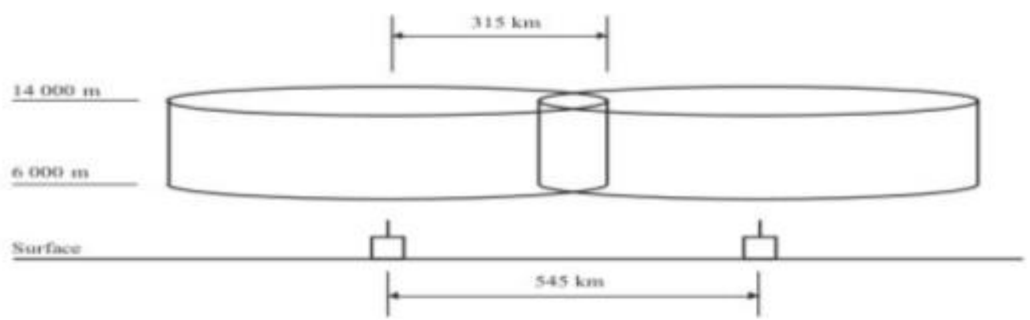
<tr><td>C</td><td>
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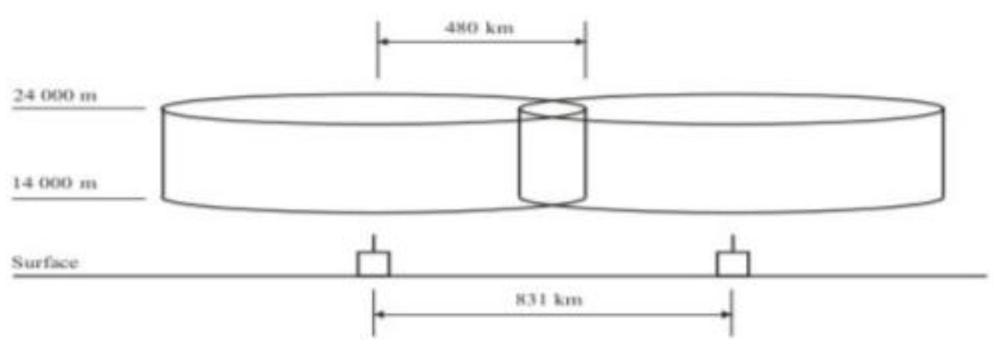
<tr><td>D</td><td>
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LAP ATG Propagation