OPEN-SOURCE OFDM WAVEFORM FOR RESEARCH AND EDUCATION ON EMERGING UNMANNED AERIAL COMMUNICATIONS SYSTEMS

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03/26/2015

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)
- US National Transportation Center expects around 200,000 UAVs for non-military purposes [1]
- L-DACS1 preferred over L-DACS2 due to efficiency of orthogonal frequency
- division multiplexing (OFDM) [2]

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

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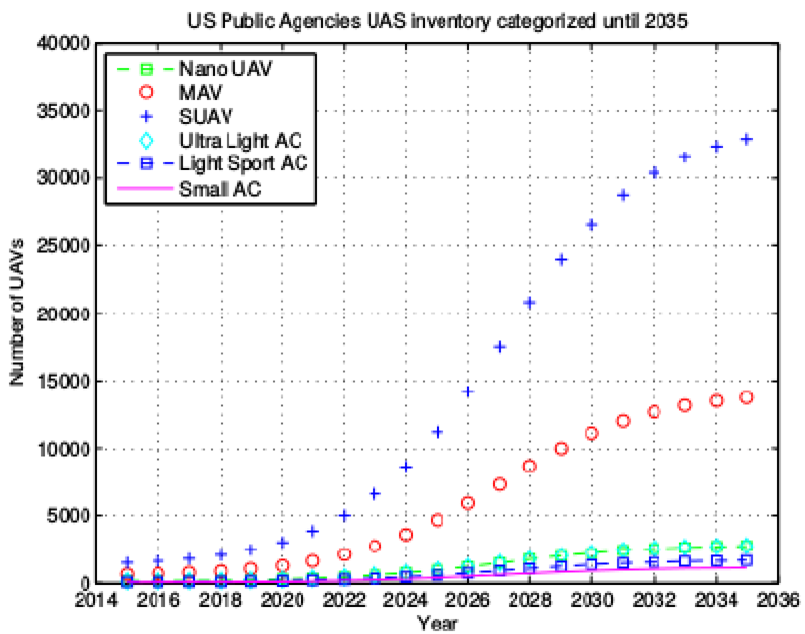
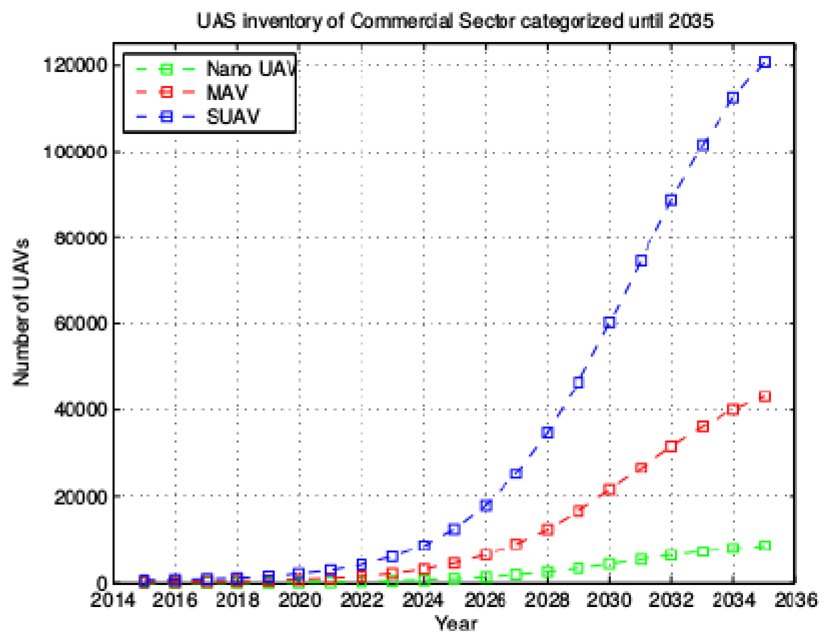
Projected Absolute UAV Quantities



(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

Introduction cont'd

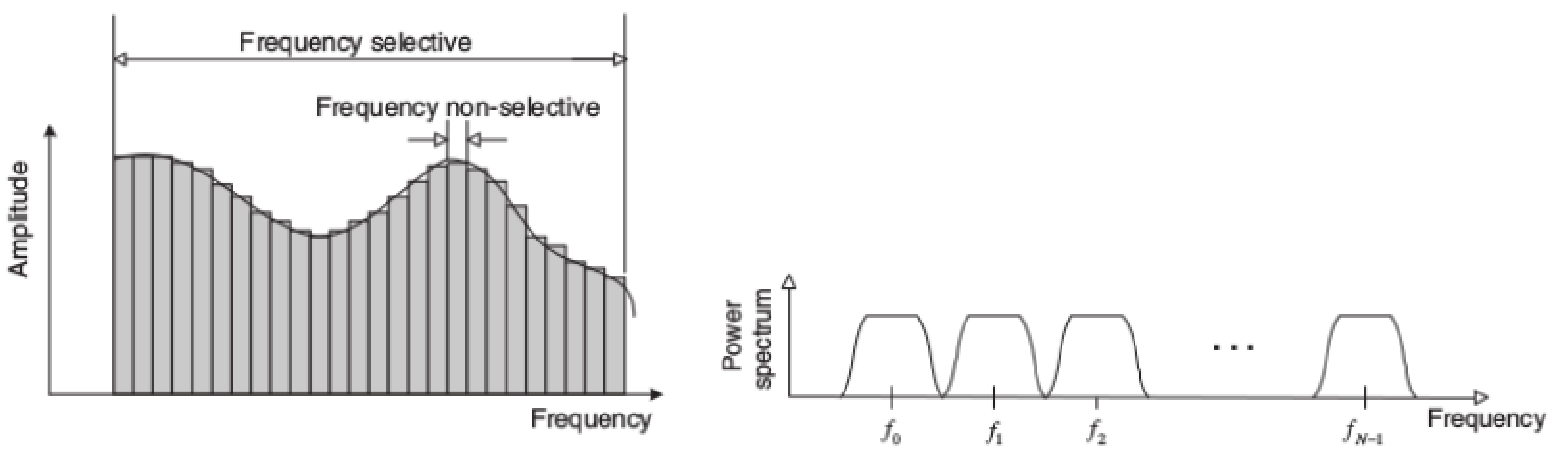
- Increase of spectral efficiency is of high importance to accommodate with 34 MHz of bandwidth
- Implementation and study of OFDM-based waveform has to be considered for future UAV waveforms

OFDM Fundamentals

- OFDM Implementation at TX side by N-point IFFT

$$x_s(k) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[s,k] e^{j2\pi f_k n T_s} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[s,k] e^{j2\pi kn/N}$$

- **Guard Interval** (Cyclic Prefix) in time-domain to prevent ISI and **guard band** for limiting ACI



(a) Channel (b) Multi-Carrier Signal

Implemented Waveform

- Open-source waveform implemented by Wireless@VT
- Waveform utilizes OFDM-FDD and ARQ with ACKs and NACKs
- Adjustable Parameters:
  - Modulation and Coding Schemes
  - ARQ Timeout Time
  - FFT Size
  - CP Length
  - UL/DL frequency
  - Bandwidth
  - Etc.
- Free download from [10]

Wideband Air-to-Ground Channel Model

- Research in this area is still very limited
- Channel Impulse Response as Delay-Tap Model:

$$h(t,\tau) = \sum_{p=0}^{L(t)-1} \left[z_p(t)\alpha_p(t) \underbrace{e^{j2\pi f_{D,p}(t)(t-\tau_p(t))}}_{\text{Doppler Effect}} \underbrace{e^{-j2\pi f_c(t)\tau_p(t)}}_{\text{Phase Shift}} \delta(\tau - \tau_p(t)) \right]$$

- Main Results of Literature Review:

$$\hat{B}_c = \frac{1}{5\sigma_t}$$

$$\hat{T}_c = \sqrt{\frac{9}{16\pi f_{D,\max}^2}} \approx \frac{0.423}{f_{D,\max}}$$

Reference	$L(t)$ min	$L(t)$ max	σ_t [μs] average	σ_t [μs] max	**Doppler Spectrum** [kHz]	$\hat{B}_{c,min}$ [kHz]	$\hat{T}_c$ [μs]	**Comments**
[3]	3		0.074	–	–	–	–	–
[4]	1 (mainly LoS)		0.0384	0.398	$[-5;5]$	≈ 500	≈ 85	v=±293 m/s,B=20 MHz STD(σ_t) ≈0.021 μs
[5]	2 or 3	7	–	0.480	–	≈420	–	Max RMS for Channel 2 (GCS Height: 2.10 m) and altitude 370 m
[6]	≈8		0.098[1]	0.485	–	≈410	–	Use of elevation angles θ: 7.5, 15, 22.5, 30°
[7]	1		–	–	$[-3.6;4.1]$	–	≈105	Time Delay MPC for en-route not considered.
[8]	≈3		–	0.050	–	4000	–	For Oxnard C-band measurement case

- Results in [6] best suit Air-to-Ground Channel for Micro and Small UAVs

Obtain Power-Delay-Profile based on [6]

- Average Number of Signal Components per Delay Bin from [6]

Delay Range [ns]	Average Number of Signal Components per Delay Bin	Delay Range [ns]	Average Number of Signal Components per Delay Bin
0–97	2.98	778–875	0.167
97–195	1.53	875–973	0.180
195–292	1.19	973–1,070	0.107
292–389	0.620	1,070–1,167	0.0664
389–486	0.404	1,167–1,264	0.0389
486–584	0.253	1,264–1,362	0.0228
584–681	0.163	1,362–1,459	0.00265
681–778	0.167	1,459–1,556	0.00139

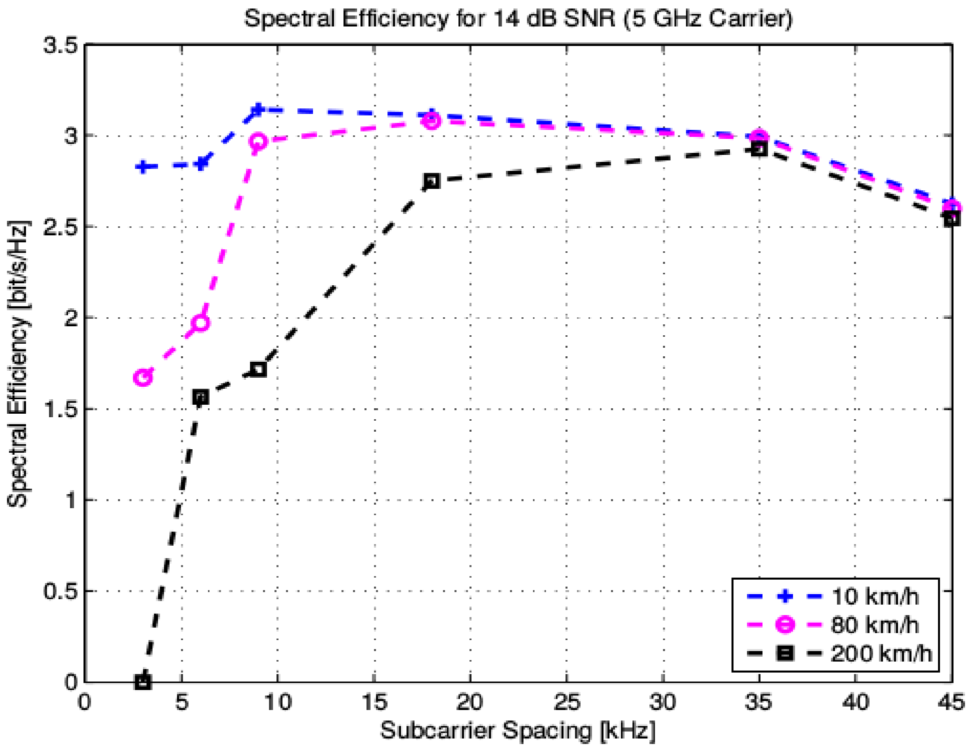
- Resulting PDP Profile:

$$P_{dB} = [0\ \ -8.7\ \ -9.6\ \ -11.3\ \ -13.4\ \ -15.2\ \ -17.0\ \ -20.2]$$

$$\tau = [0\ 33\ 70\ 115\ 175\ 262\ 405\ 682]\ \mathrm{ns}$$

Obtain Subcarrier Spacing

- Minimum UAV RX SNR= 14 dB (incl. 2 dB implementation loss and 6 dB aviation safety margin)
- Solve Problem [9]:



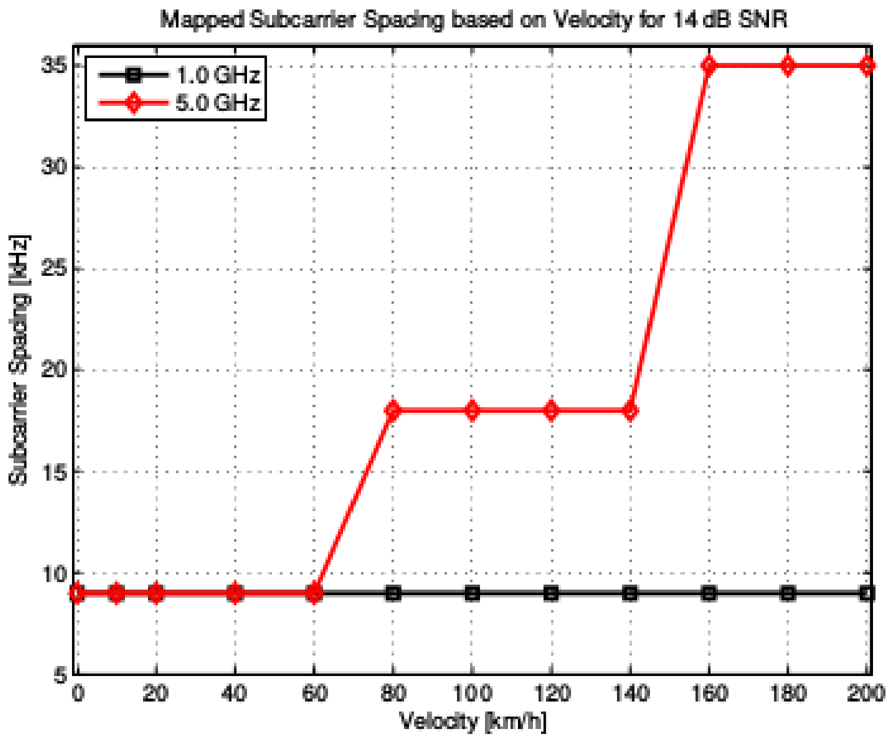
$$\Delta f^* = \underset{\Delta f_j}{\operatorname{argmax}} \frac{1}{\mathrm{BW}\left(\frac{1}{\Delta f_j} + N_{CP}T_s\right)} \sum_{k \in A_{\mathrm{eff}}^j} b_L(k, \Delta f_j)(1 - \mathrm{BER}_{\mathrm{AWGN}}(k, \Delta f_j))$$

$$\Delta f_j < \hat{B}_c,$$

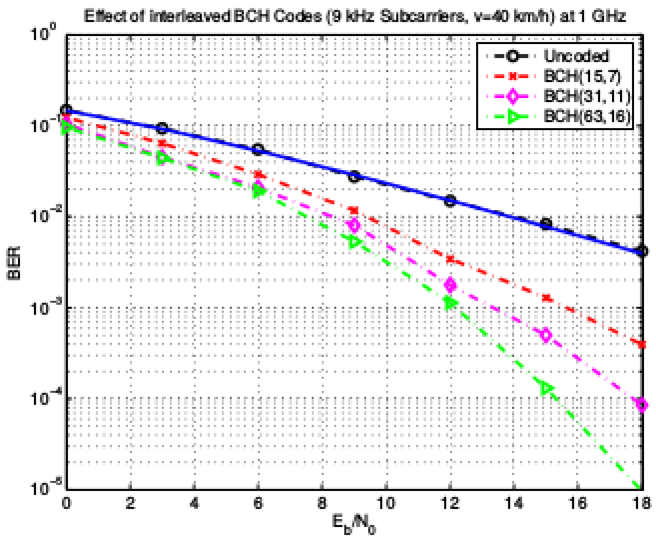
$$\frac{1}{\Delta f_j} + N_{CP}T_s < \hat{T}_c,$$

Subcarrier Spacing for different velocities

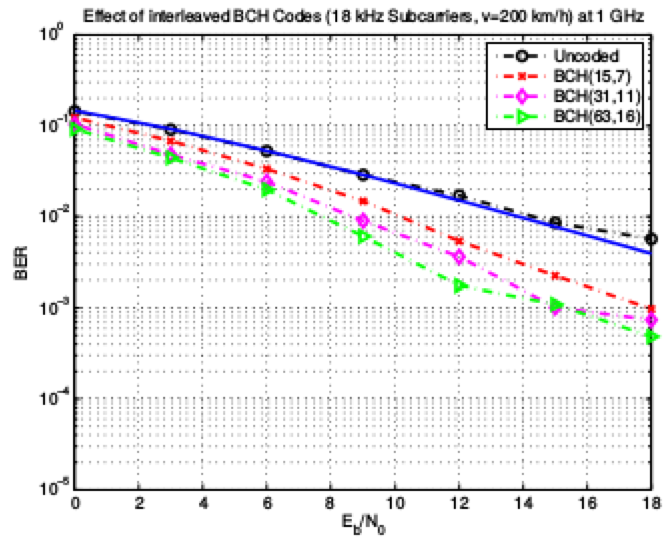
- Maximum Velocity
  - MAV < 40 km/h
  - SUAV < 120 km/h
  - Light Sport AC < 200 km/h
- Subcarrier Spacing requires adjustment if carrier frequency changes



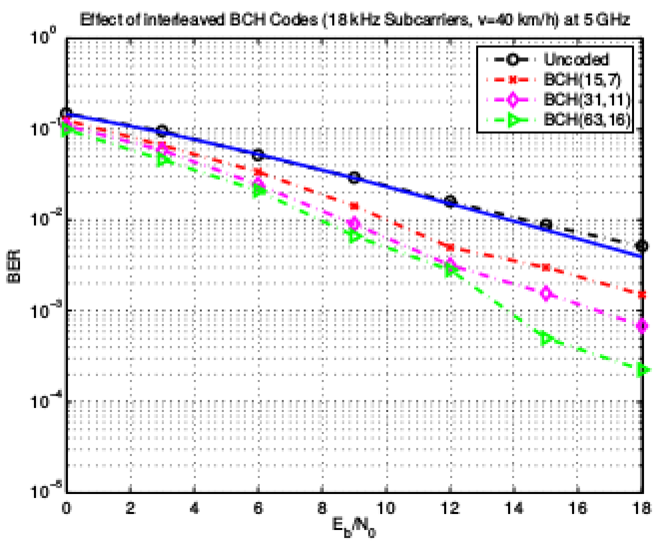
BER Performance of SISO 5 MHz OFDM with BCH FEC Coding



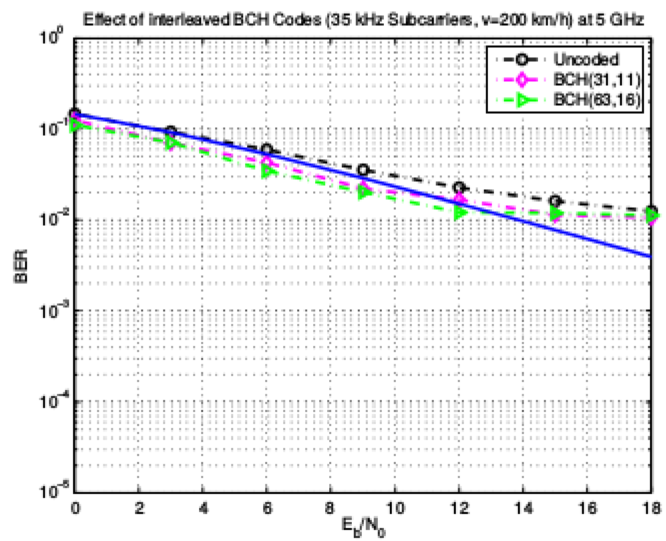
(a) $\Delta f = 9$ kHz, $v = 40$ km/h



(b) $\Delta f = 18$ kHz, $v = 200$ km/h



(c) $\Delta f = 18$ kHz, $v = 40$ km/h



(d) $\Delta f = 35$ kHz, $v = 200$ km/h

- At v=200 km/h, FEC coding less effective
- Use of Diversity Techniques at higher speeds required

Conclusion

- OFDM advantages:
  - Good Spectral Efficiency
  - Efficient transceiver implementations
  - Channel-Specific adaptation
  - MIMO-ready
- OFDM disadvantages:
  - Block Processing introduces delays
  - Frequency and Time Synchronization is a challenge
  - High PAPR
- Performance for MAV and SUAV acceptable, but at high speeds link degradation

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Backup Slides

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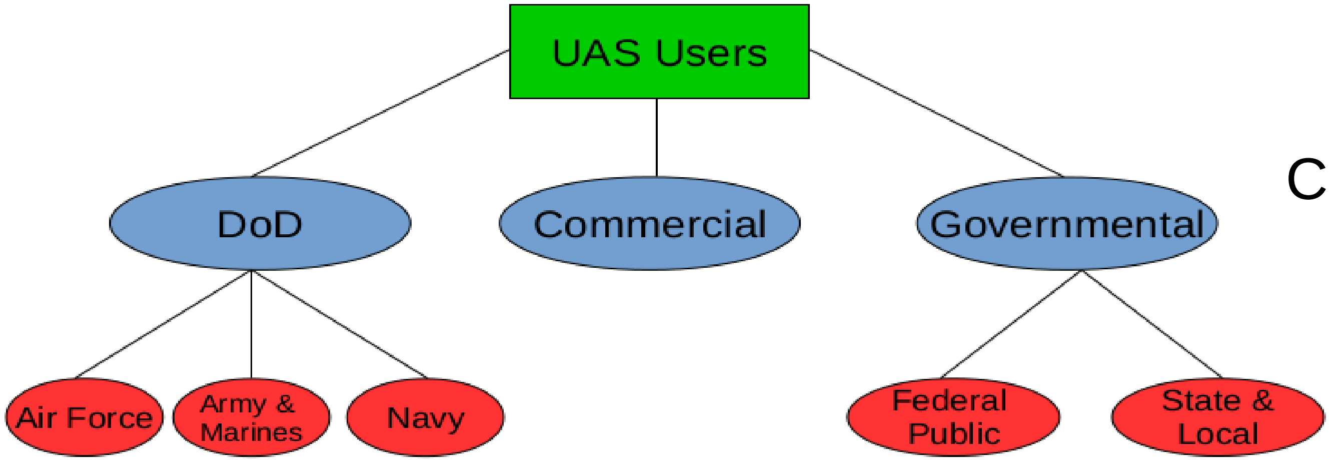
Projected and Current Applications



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	

Wideband Air-to-Ground Measurement Configurations

Reference	**Frequency** [MHz]	**Antenna** (Elevation Beamwidth)				**(Antenna) Height** [m]		**Ground Environment**
		Aircraft		Ground Station		Aircraft	Ground Station	
		Omni.	Direc.	Omni.	Direc.			
[55]	1,510.5 1,460.5 2,344.5 2,360.5	√	×	×	6° 6° 3° 6°	1,525/ 3,050 AMSL	2.5 (Antenna) + 700 AMSL 4.5 (Antenna) + 700 AMSL	Mountainous Desert
[44]	5,120	√	×	√	×	5,000/ 8,000/ 11,000 AMSL	18 (Antenna) + 750 AMSL	Sonthofen (Germany)
[49]	5,700	√	×	×	2 25° Antennas	370/970/ 1,830	2.10 + ? 7.65 + ?	Sea Surface
[51]	2,050	√	×	4-Array	×	$450 \leq h \leq 950$ AGL	GL	College Campus
[18]	5,135	√	×	×	Dish (d=2.4 m)	Taxiing, Take-off, En-route	Airbus Saint- Martin site	Saint-Martin (Airbus)
[48]	960-977 5,000-5,100	×	Cosine	×	2 x 81° Antennas 2 x 35° Antennas	$h_{\max} = 12,500$	3.5-18.3 + ?	Cleveland & Oxnard

Effect of RX Diversity using Maximal Ratio Combining

- > 6 dB gain at 0.01 BER
- Implementation of MRC in OFDM simple