Unmanned Aircraft System Control and ATC Communications Bandwidth Requirements Task

Summary Task Briefing

Steve Henriksen
(703) 668-6195
stephen.henriksen@itt.com

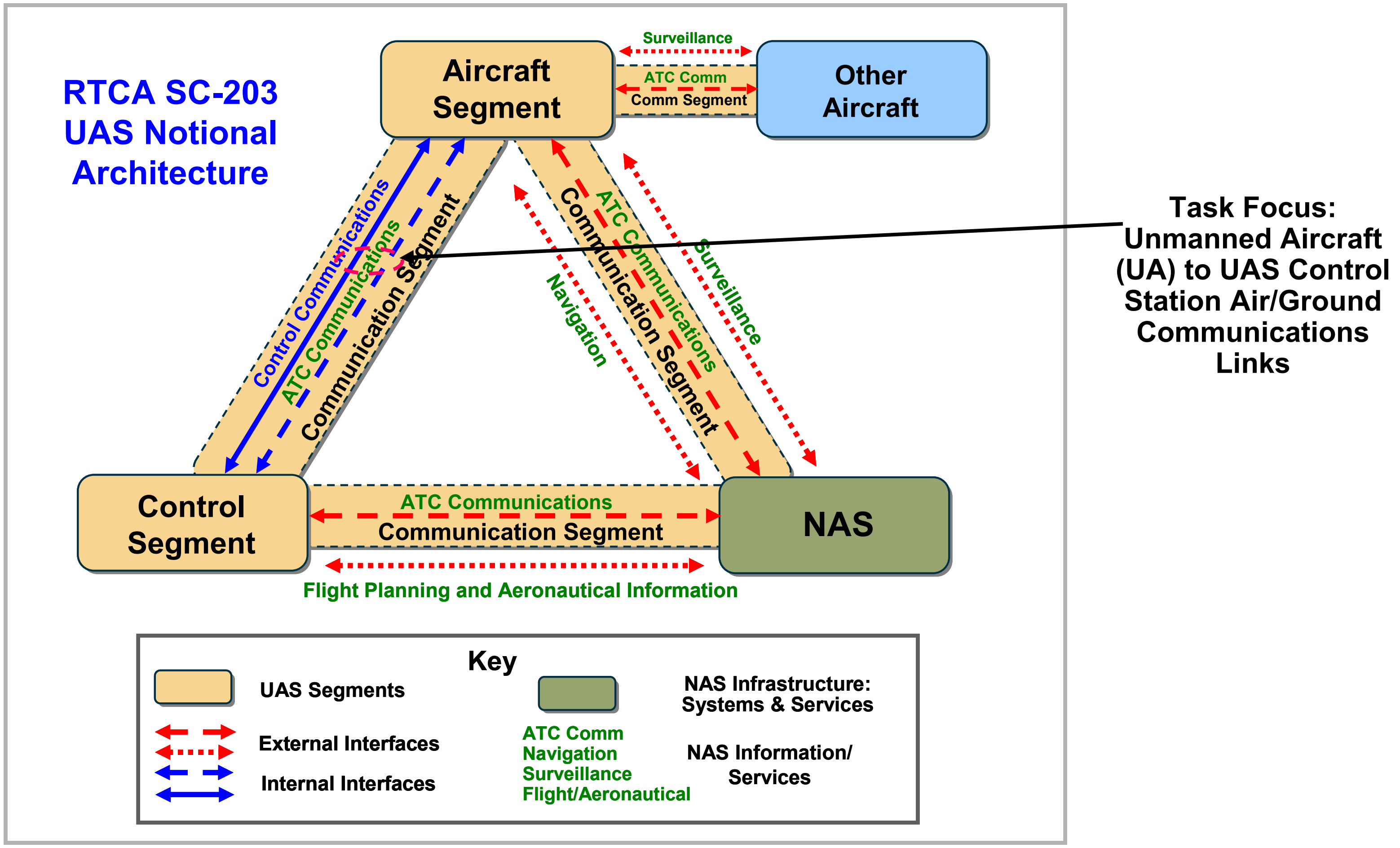
February 28, 2007

Task Background

- NASA GRC Access 5 Project team (2004-2006) defined functional communication requirements for unmanned aircraft systems (UAS)
- FAA/NASA/Eurocontrol Future Communications Study (FCS) (2004 – present) is identifying requirements and technologies for the future radio system
  - The Communications Operating Concept and Requirements (COCR) for the Future Radio System, which drives the technology evaluations, acknowledges the potential future impact of UAS, and implicitly includes UAS in its capacity analyses
- RTCA SC-203 (UAS) Control and Communications Working Group is addressing UAS communications spectrum requirements
- ITU World Radio Conference (WRC) planning activities include the U.S seeking an agenda item for WRC-11 addressing UAS communications spectrum requirements

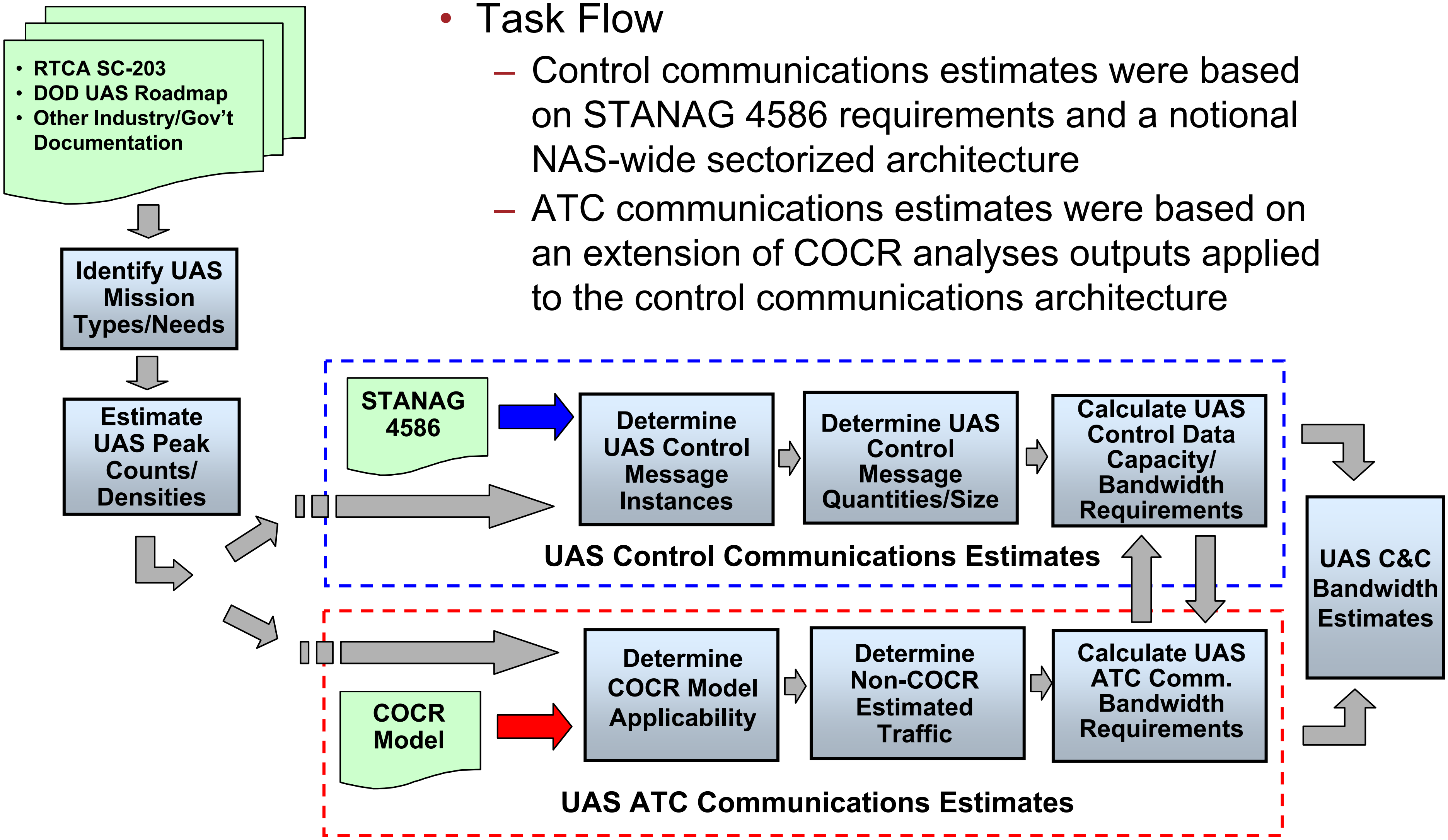
Task Purpose

- Estimate future UAS Control and ATC Communications (C&C) bandwidth requirements for safe, reliable, and routine operation in the NAS, to support U.S. WRC preparation activities



Task Workflow Diagram

- Task Flow
  - Control communications estimates were based on STANAG 4586 requirements and a notional NAS-wide sectorized architecture
  - ATC communications estimates were based on an extension of COCR analyses outputs applied to the control communications architecture

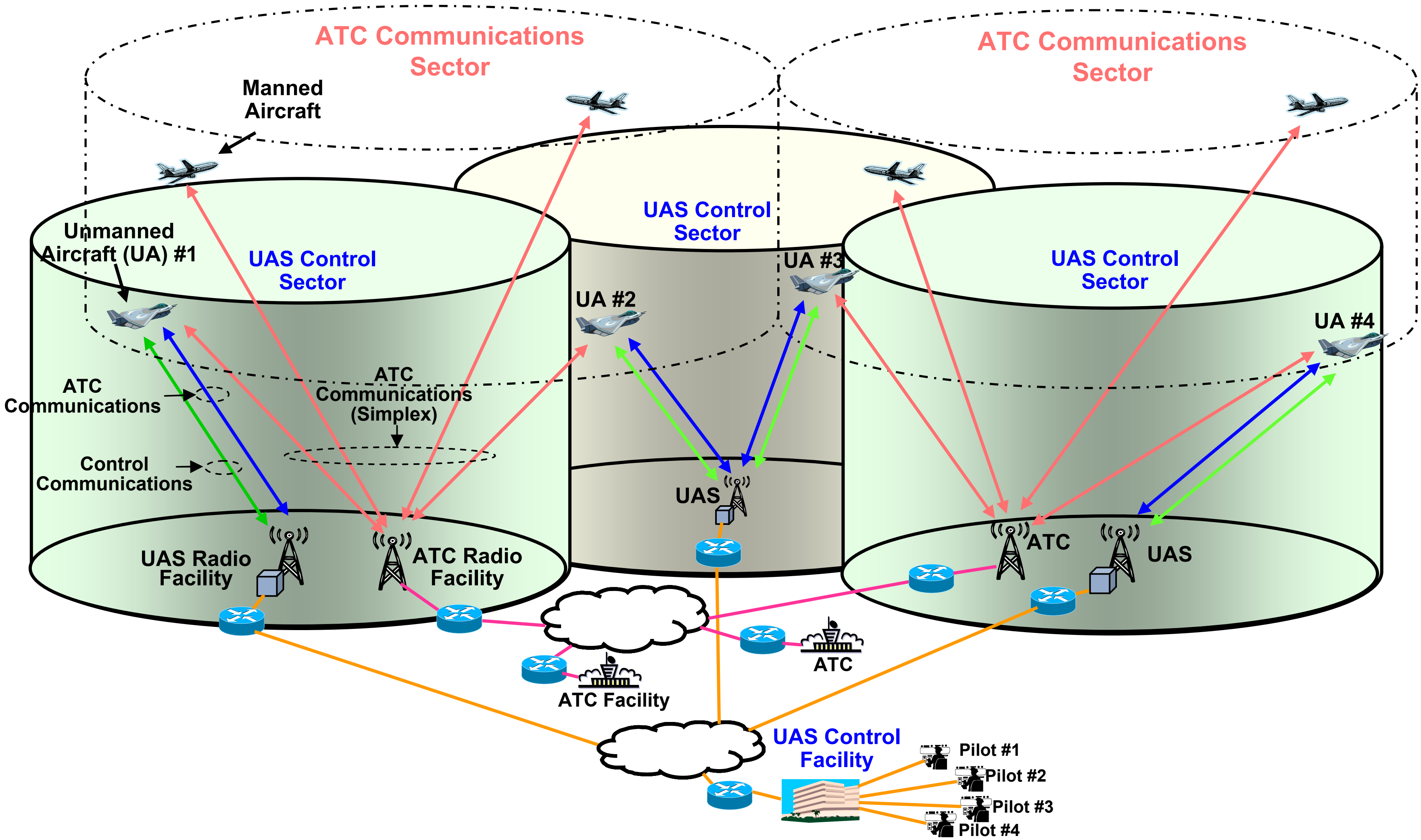


Study Modeling Assumptions

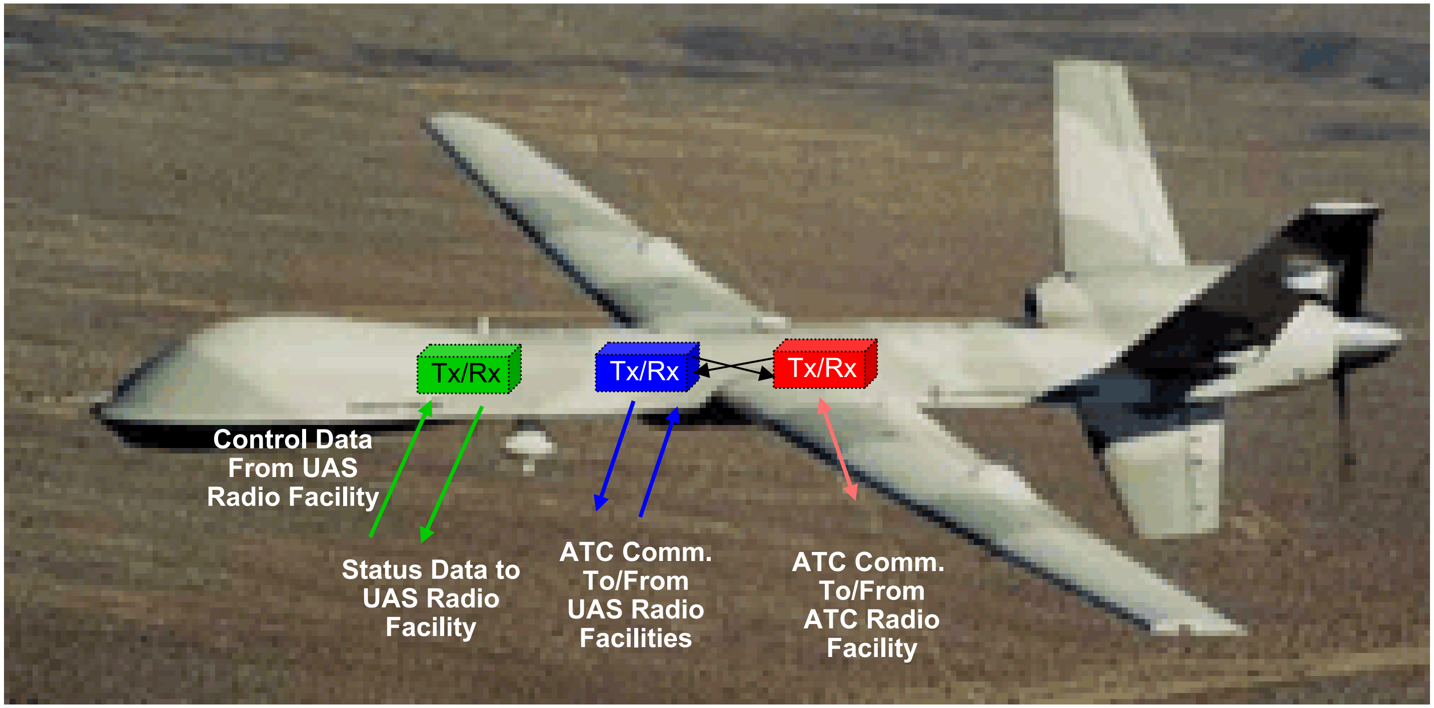
- UAS ATC communications services were assumed to be as defined in the COCR for air/ground services
  - Includes both data and voice services
- Study estimated C&C bandwidth requirements for new UAS radio facility to UA links only, assumed COCR ATC communications capacity requirements already accommodate ATC to UA links
- Study did not include UAS Sense and Avoid related communications links (e.g. radar, optical, video, etc.) or UAS payload related communications
- Study focused on long term bandwidth requirements for UAS approximately through 2030
- Potential aircraft or ground co-site interference issues were not considered

Communications Architecture Assumptions

- This task was based on the concept that both ATC communications and UAS commands will be provided via a sectorized Air/Ground Line of Sight (LOS) communications architecture



Communications Architecture Assumptions (cont.)



- Up to seven links
  - Existing ATC Radio facility to UA Link: Channel for ATC communications shared with all aircraft in sector (currently simplex VHF DSB-AM)
  - New UAS radio facility to UA Links:
    - Dedicated voice and data channels for ATC communications (uplink and downlink) – Up to four links
    - Dedicated channels for control communications (uplink and downlink) – Two links

UAS Specific Mission Types/Needs

- RTCA SC-203 UAS mission scenarios were examined to identify UAS specific needs that might impact UAS communications requirements
- Evaluation of these mission scenarios identified two main differences from traditional manned aircraft flight scenarios
  - Many proposed UAS missions include the need to “loiter” within particular airspace for periods from hours to months
  - Many UAS missions will not traverse airports or the TMA domains
- Aside from the potential operational impact this has on ATC controller procedures, from the traffic modeling perspective it implies potentially non-homogeneous flight durations and service instances for manned and unmanned aircraft
  - An assessment of the COCR traffic model led to the conclusion that this does not significantly impact the COCR ATS service capacity requirements, which include UAS traffic

UAS Aircraft Counts/Densities

- UAS bandwidth requirements are dependent on projected UAS traffic densities and thus estimates of the associated Peak Instantaneous Aircraft Counts (PIACs)
- While there is considerable information available on projected number of military UAS systems, there are few projected estimates for UAS operation in the NAS
- Review of available civil UAS projections for the period of interest provide rough order of magnitude guidance for estimating UAS PIACs:
  – A UAS PIAC range of 5% – 10% of manned aircraft per service volume was assumed for this study

UAS Aircraft Counts/Densities (cont.)

- COCR and Eurocontrol FCS test service volumes were used to determine the projected range of UA PIAC and UA densities

Service Volume	Total PIAC	Volume (nmi^2)	Total Aircraft/nmi^2	UA Density: Aircraft/nmi^2	
				5%	10%
COCR - NAS Airport HD Phase 1	200				
COCR - NAS Airport LD Phase 1	12				
COCR - NAS Airport HD Phase 2	290				
COCR - NAS Airport LD Phase 2	19				
COCR - NAS TMA LD Phase 1	14	3,039	0.0046	0.0002	0.0005
COCR - NAS TMA HD Phase 1	16	2,831	0.0057	0.0003	0.0006
COCR - NAS En Route LD Phase 1	24	20,782	0.0012	0.0001	0.0001
COCR - NAS En Route HD Phase 1	24	5,119	0.0047	0.0002	0.0005
COCR - NAS TMA LD Phase 2	39	9,240	0.0042	0.0002	0.0004
COCR - NAS TMA HD Phase 2	44	7,691	0.0057	0.0003	0.0006
COCR - NAS En Route LD Phase 2	59	33,388	0.0018	0.0001	0.0002
COCR - NAS En Route HD Phase 2	45	10,132	0.0044	0.0002	0.0004
COCR - NAS En Route Super Sector	95	31,996	0.0030	0.0001	0.0003
Eurocontrol - TV1 Airport Total	290				
Eurocontrol - TV1a Airport Surface	264				
Eurocontrol - TV1 Airport in Flight	26	259	0.1004	0.0050	0.0100
Eurocontrol - TV2.1 - TMA Small	44	7,691	0.0057	0.0003	0.0006
Eurocontrol - TV2.2 - TMA Large	53	18,056	0.0029	0.0001	0.0003
Eurocontrol - TV3.1 - ENR Small	28	10,132	0.0028	0.0001	0.0003
Eurocontrol - TV3.2 - ENR Medium	62	33,739	0.0018	0.0001	0.0002
Eurocontrol - TV3.3 - ENR Large	204	134,957	0.0015	0.0001	0.0002
Eurocontrol - TV3.4 - ENR Super Large	522	539,829	0.0010	0.00005	0.0001

UAS Message/Service Instances

- UAS ATC communications service statistics and resulting capacity requirements were assumed to be identical to the manned aircraft ATS service statistics defined in the COCR

PHASE 2		APT SV Dep	APT SV Arr	TMA SV Dep	TMA SV Arr	ENR SV	ORP SV	AOA
Separate ATS	UL	6.9	1.8	5.6	3.8	5.7	5.7	6.7
	DL	6.2	1.9	6.8	1.6	6.7	8.5	12.5
	UL&DL	6.9	1.9	6.9	3.8	6.7	8.5	12.5

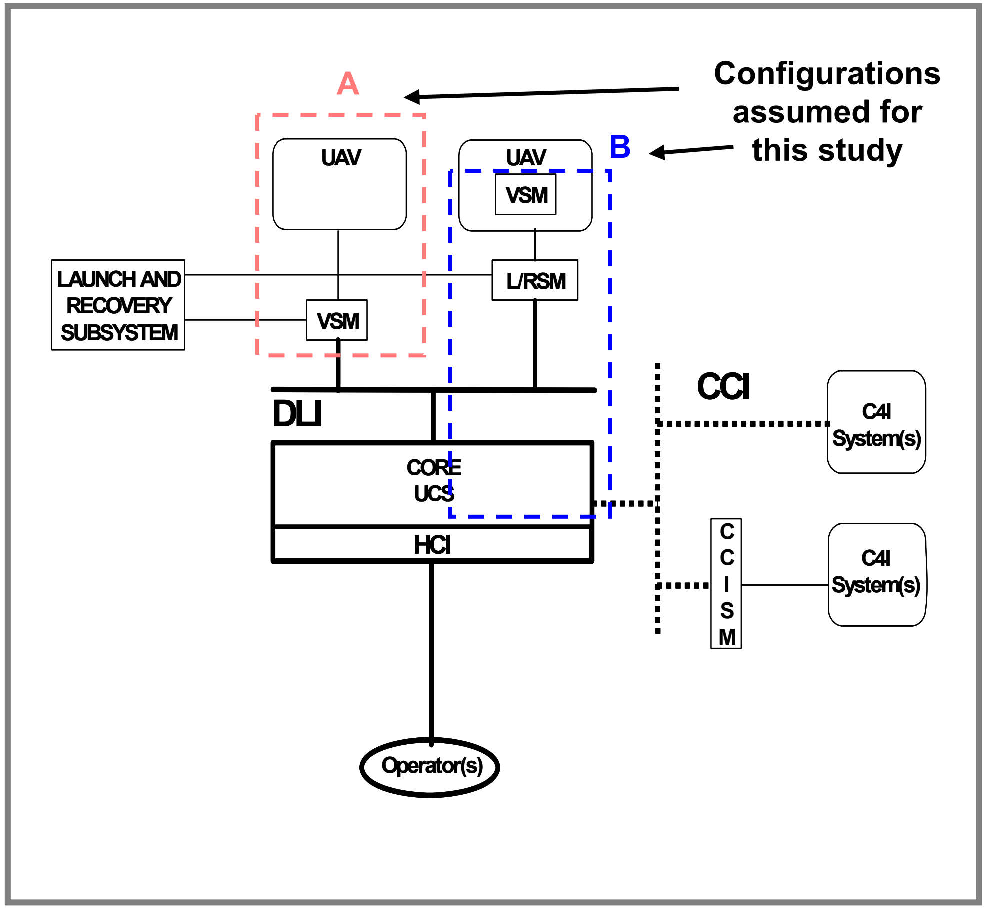
COCR V1.0 Air/Ground Data Capacity Requirements (kbps) for Each Aircraft using a Separate 'Channel' excluding the A-EXEC service – Phase 2 (Note: Includes "overheads associated with the network, integrity and security".)

- UAS message instances for Control communications messages were based on implementation of STANAG 4586* compliant Data Link Interface (DLI) messages
  - STANAG 4586 is accepted as a generic standard for UAS message types and formats

* STANAG 4586, *Standard Interfaces of UAV Control System (UCS) for NATO UAV Interoperability*, Edition 2, March 2005

UAS Architecture Task Assumption

- DLI command/status messages flow between the VSM and the Core UCS (CUCS)
- STANAG 4586 accommodates the VSM residing either on the ground or within the aircraft (UAV)
- For this study, both configurations were considered
  - "A" assumes a non-networked, native or proprietary type RF link with some security overhead assumed
  - "B" implies an RF link that includes overhead for standards-based security and transport/network layer protocols



UAS Control Message Quantities/Sizes

- Per STANAG 4586, unmanned aircraft control and status messages fall into three general categories
  - Initialization, configuration, and mission upload messages exchanged preflight
    - Configuration messages also can be exchanged infrequently during flight as necessary if the operating mode or configuration of the aircraft is changed
  - Control messages sent to control the aircraft and its engines
    - The frequency of these messages is highly related to the level of autonomy characterizing the aircraft
  - Status messages sent (pushed) by the aircraft
    - These report dynamic changes in aircraft movements, direction, orientation, engine operation, etc.
    - These messages can be sent very frequently
      - Typical update rates are 1 to 10 times per second for critical parameters according to UAS manufacturers
      - **These updates rates are the major drivers in determination of aggregate aircraft to ground data rate, and hence bandwidth**

UAS Control Message Quantities/Sizes (2)

- As recommended by STANAG 4586, messages for Configuration B included the following overhead
  - STANAG 4586 wrapper overhead: 34 bytes
  - Network/Transport layer overhead
    - Space Communications Protocol Specification (SCPS) Transport Protocol (SCPS-TP) with UDP messages: 8 byte header
    - IPv6: 40 byte header
  - Security overhead
    - SCPS Security Protocol (SCPS-SP) with 14 byte overhead
      - 2 byte header
      - 12 byte (96 bit) length Integrity Check Value (ICV)
      - Key management overhead was not included
  - Messages for Configuration A were assumed to include 10% security overhead, and not include DLI wrapper, or transport/ network layer overhead

UAS Control Configuration Messages (Configuration B)

CUCS Originated

Message	STANAG 4586 Msg #	# of msg sent	Msg length	Msg length w/DLI wrapper	Msg length with Network /Transport Layer Overhead (bytes)[1]	Msg length with Security Overhead (bytes)[2]	Total DLI bytes
Field Configuration Request: Excludes payload related message types, except 300	**1200**	97	35	69	117	131	12707
Configuration Complete	**1203**	1	28	62	110	124	124
CUCS Configures User Interface							
Data Link Assignment Request	**404**	1	25	59	107	121	121
Data Link Set Up Message	**400**	1	33	67	115	129	129
Pedestal Configuration Message	**402**	1	40	74	122	136	136
Data Link Control Command	**401**	1	25	59	107	121	121
Pedestal Control Command	**403**	1	46	80	128	142	142
Specified Vehicle ID Connection Request							
CUCS Authorization Request CUCS requests control over a specific Vehicle/ Vehicle type.	**1**	1	31	65	113	127	127
CUCS Configuration and Command Messages: CUCS controls the AV/payload at specified LOI							
Display Unit Request	**1201**	1	25	59	107	121	121
CUCS Resource Report	**1202**	1	34	68	116	130	130
Vehicle Configuration Command	**40**	1	20	54	102	116	116
Vehicle Operating Mode Command	**42**	1	17	51	99	113	113
Loiter Configuration	**41**	1	42	76	124	138	138
Vehicle Steering Command	**43**	1	66	100	148	162	162
Air Vehicle Lights	**44**	1	18	52	100	114	114
Relative Route/Waypoint Absolute Reference Message	**47**	1	61	95	143	157	157
Configuration Complete	**1203**	1	28	62	110	124	124

VSM originated

Message	STANAG 4586 Msg #	# of msg sent	Msg length	Msg length w/DLI wrapper	Msg length with Network /Transport Layer Overhead (bytes)[1]	Msg length with Security Overhead (bytes)[2]	Total DLI bytes
Field Configuration Integer Response	**1300**	7	146	180	228	242	1694
Field Configuration Double Response Excludes payload related message types	**1301**	51	202	236	284	298	15198
Field Configuration Enumerated Response Excludes payload related message types	**1302**	6	128	162	210	224	1344
Field Configuration Command Excludes payload related message types	**1303**	28	32	66	114	128	3584
Vehicle Configuration	**100**	1	53	87	135	149	149
Vehicle ID	**20**	1	73	107	155	169	169
Data Link Configuration/Assignment Message	**500**	1	28	62	110	124	124
Payload Configuration (Needed for vehicle control; assumes 2 payloads)	**300**	2	28	62	110	124	248
Configuration Complete	**1203**	1	28	62	110	124	124
Data Link Configuration/Assignment Message	**500**	1	28	62	110	124	124
Data Link Control Command Status	**502**	1	24	58	106	120	120
Data Link Status Report	**501**	1	38	72	120	134	134
Pedestal Status Report	**503**	1	58	92	140	154	154
VSM Authorization Response VSM grants CUCS control over specified vehicle/ Vehicle Type	**21**	1	31	65	113	127	127
VSM Status Messages/Configuration updates.							
Vehicle Operating Mode Report	**106**	1	17	51	99	113	113
Configuration Complete	**1203**	1	28	62	110	124	124

Number of bytes associated with initial connection and configuration

Total bytes From Control Station 14,782

Total bytes From Aircraft 23,530

- Characterized by a two way message exchange as the aircraft's operating parameters are initially configured
- Total amount of data exchanged is modest
  - Less than 15K bytes sent to the UA
  - Less than 25K bytes sent to the control station
- Several hundred bytes are also exchanged during each handoff from one UAS radio control station to another (not shown in table)

UAS Control Mission Upload Messages (Configuration B)

CUCS (Control Station) Originated

Functions		STANAG 4586 Msg #	# of msg sent	Msg length	Msg length w/DLI wrapper	Msg length with Network /Transport Layer Overhead (bytes)[1]	Msg length with Security Overhead (bytes)[2]	Total DLI bytes
Point-to-Point Mission								
Mission related	Messages #800 - 900 ref. Vol 1: STANAG 4586 Implementation Guideline 3.4.3.2.6 Mission Messages This sequence assumes ground VSM with message 800 to convert and transmit to AV in native format							
Mission Plan Upload Msg 802-806 sequence for each waypoint	AV Position Waypoint	**802**	10	60	94	142	156	1560
	AV Loiter waypoint	**803**	0	38	72	120	134	0
	Payload Action waypoint	**804**	0	58	92	140	154	0
	Airframe action waypoint	**805**	5	20	54	102	116	580
	Vehicle specific waypoint	**806**	5	39	73	121	135	675
	Assumed # waypoints	10						
	AV Route	**801**	1	39	73	121	135	135
	Mission Upload Command	**800**	10	39	73	121	135	1350

Total bytes From Control Station 4165

VSM (Aircraft) Originated

	STANAG 4586 Msg #	# of msg sent	Msg length	Msg length w/DLI wrapper	Msg length with Network /Transport Layer Overhead (bytes)[1]	Msg length with Security Overhead (bytes)[2]	Total DLI bytes
Mission Upload/Download Status	**900**	2	18	52	100	114	228
Assumed # updates	2						

Total bytes From Aircraft 228

- This also requires relatively few bytes exchanged
- Above example is for a loitering type mission

UAS Command and Status Message Capacities

CUCS (Ground) Originated

	STANAG 4586 Msg #	Aperiodic: # of msg sent per Phase of Flight	Periodic: Message Rate #/sec	Msg length (bytes)	Msg length w/DLI wrapper (bytes)	Msg length with Network /Transport Layer Overhead (bytes)[1]	Msg length with Security Overhead (bytes)[2]	Aperiodic: Total Bytes per Phase of Flight	Periodic: Bits/sec	Periodic Bit/Sec w/o Transport/ Network Overhead
Vehicle Steering Command	43		0.2	66	100	148	162	0	259.2	116.2
Engine Command	45		0.1	21	55	103	117	0	93.6	18.5
Subsystem Status Request	1000		5	20	54	102	116	0	4640	880.0
Subsystem Status Detail Request	1001	1		20	54	102	116	116	0	0.0
								116		

Aggregate Data Rate From Control Station (bps): **B** 4,993 Networked; **A** 1,015 Non-Networked

VSM (Aircraft) Originated

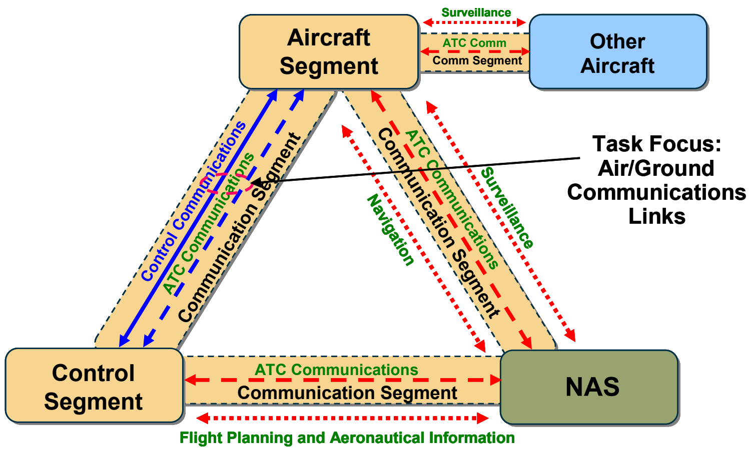
	STANAG 4586 Msg #	Aperiodic: # of msg sent per Phase of Flight	Periodic: Message Rate #/sec	Msg length (bytes)	Msg length w/DLI wrapper (bytes)	Msg length with Network /Transport Layer Overhead (bytes)[1]	Msg length with Security Overhead (bytes)[2]	Aperiodic: Total Bytes per Phase of Flight	Periodic: Bits/sec	Periodic Bit/Sec w/o transport/network overhead
Inertial States	101		2	84	118	166	180	0	2880	1478.4
Air and Ground Relative States	102		2	64	98	146	160	0	2560	1126.4
Body-Relative Sensed States	103		10	40	74	122	136	0	10880	3520.0
Vehicle Operating States	104		2	145	179	227	241	0	3856	2552.0
Engine Operating States	105		5	36	70	118	132	0	5280	1584.0
Vehicle Light States	107		1	36	70	118	132	0	1056	316.8
Data Link Status Report	501		1	38	72	120	134	0	1072	334.4
Pedestal Status Report	503		0.2	58	92	140	154	0	246.4	102.1
Subsystem Status Report	1101		1	22	56	104	118	0	944	193.6
Subsystem Status Alert Message	1100	1		107	141	189	203	203	0	0.0
								203		

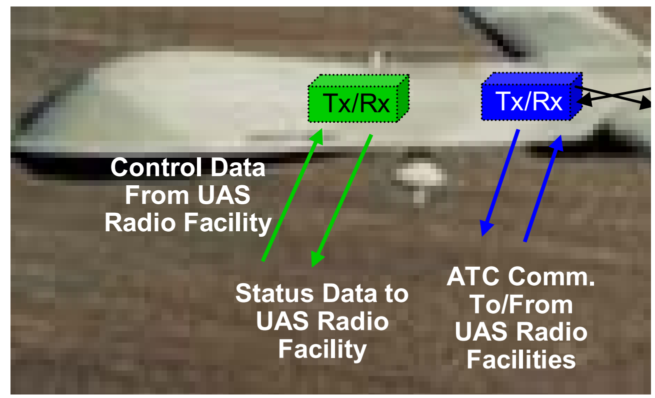
Aggregate Data Rate From Aircraft (bps): **B** 28,774 Networked; **A** 11,208 Non-Networked

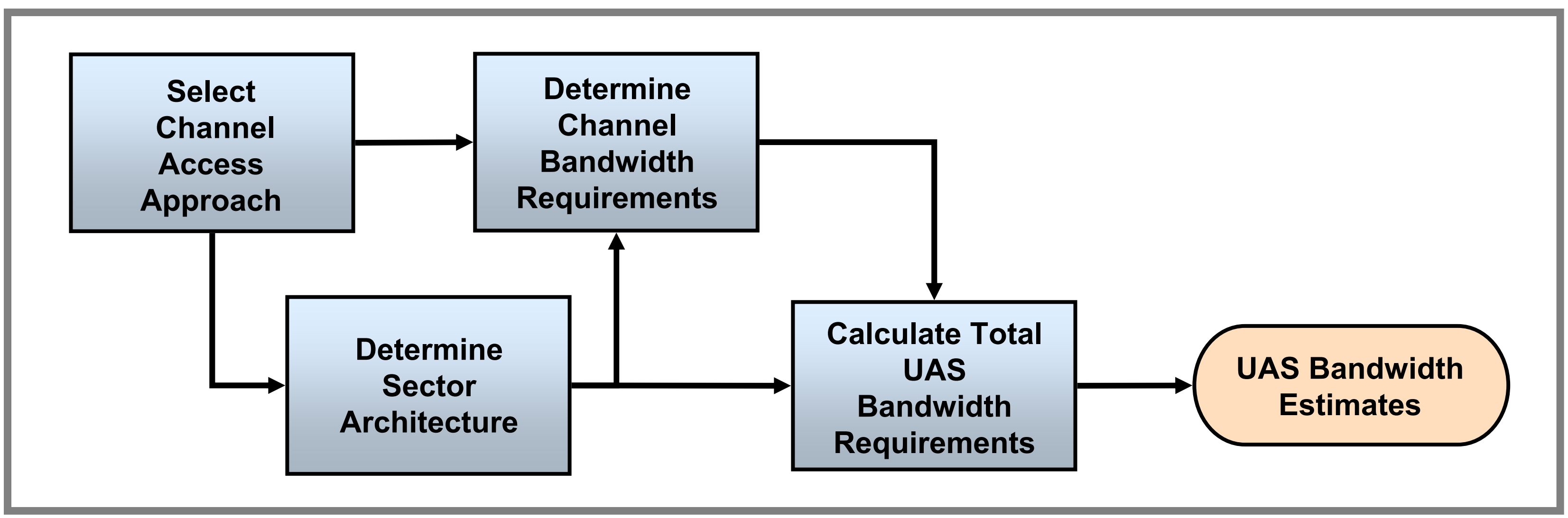
- These include the major driver of UAS link capacities: aircraft status and telemetry messages
  - Aggregated status/telemetry message data rate is tens of thousand of bits per second – almost 28 kbps is estimated above (Configuration B)
  - Control message traffic is aperiodic and varies according to aircraft autonomy
    - A average aggregate data rate was estimated to be around 5000 bps (Config. B)

Estimating UAS C&C Bandwidth Requirements

- A parallel process was used to estimate Control and ATC Communications bandwidth requirements for the links of interest







Channel Access Approach

- UAS Control Communications
  - Message capacity estimates driven by nominally constant rate command messages uplinked to the UA and status/telemetry messages downlinked from the UA point to the need for dedicated full duplex channels for each ground station to UA link
    - Dedicated channels are needed because contention based protocols could not efficiently provide sufficient Quality of Service in terms of latency and availability
  - Dedicated bandwidth could be provided by FDMA, TDMA, or CDMA; each has its advantages and disadvantages

Access Type	Complexity	UA Power/ Bandwidth Demands	Flexibility
FDMA	Low	Low	Good
TDMA	Medium	High	Fair
CDMA	High	High	Fair to Good

  - An FDMA system consisting of one set of asymmetrical dedicated full duplex channels per Ground Station to UA link was assumed to be best for bandwidth estimation purposes
    - Asymmetrical channels because the downlink (status/telemetry) capacity requirements are greater than the uplink (command) capacity requirements

Channel Access Approach (2)

- ATC Communications
  - The UA to UAS Control facility link is analogous to the hard wired circuit that connects a manned aircraft pilot with his aircraft radio
    - On a manned aircraft this is a dedicated high availability, low latency "link"
  - In the UAS case this link could be provided either by a shared link or a dedicated link, each with its own advantages and disadvantages

Access	Advantages	Disadvantages
Dedicated	• Minimum latency • Predictable availability • Simpler • Possible to use non-aviation standard technologies (e.g. P25)	• Bandwidth intensive • No current ICAO standard
Shared	• Minimum potential bandwidth impact • Possible use of existing ICAO standard (e.g. VDL M3)	• More complex • Availability issue - channel contention for two links rather than for one link • Existing standards like VDL-M3 might not work without modifications, which would have to be standardized

  - An FDMA system consisting of two dedicated duplex channel pairs per Ground Station to UA link (voice and data) was assumed for bandwidth estimation purposes
    - For implementation, voice and data traffic could be multiplexed, resulting in one duplex ATC Communications uplink and downlink channel pair

Channel Bandwidth Requirements

- UAS C&C Communications
  - Communications link budgets are typically used to perform power-bandwidth tradeoffs for links and were developed in this study to determine appropriate channel bandwidths
  - Key link budget parameters included the following
    - Range between the UA and the UAS Ground Station – determined by sector architecture
    - Required received E_b/N_0 performance – dependent on modulation type and Forward Error Correction (FEC) coding (if any)
    - Frequency band – aeronautical bands were considered
    - Receive system noise temperature – dependent on external noise, line losses, and front end (receiver or low noise amplifier) noise figure
    - Antenna gains – based on aeronautical standards

Channel Bandwidth Requirements (2)

- Selected UAS Control Communications Link Parameters
  - UAS Control Communications Modulation types
    - Existing UAS often use aeronautical telemetry standard constant envelope* modulations such as Narrow Band FM, some type of Continuous Phase Modulation (CPM), or other interoperable modulation types for line of sight control/status/telemetry links, including
      - Variants of shaped offset QPSK (SOQPSK)
      - Variants of Feher patented QPSK (FQPSK)
    - The Consultative Committee for Space Data Systems (CCSDS) has standardized similar bandwidth efficient modulations for space telemetry applications, which include, in addition to the two modulations just listed:
      - Gaussian Minimum Shift Keying (GMSK) – a type of CPM
      - Filtered OQPSK modulations (aside from SOQPSK), such as Square Root Raised Cosine (SRRC) OQPSK
      - 4D-8PSK-Trellis coded modulation (TCM)

* Constant envelope modulations provide good performance with nonlinear amplifiers used in transmitters

Channel Bandwidth Requirements (3)

- UAS Control Communications Modulation types (cont.)
  - The telemetry standard modulations are fairly bandwidth efficient and, when employed with suitable FEC coding, provide excellent E_b/N_0 performance

Modulation Type	Two Sided -60 dB Bandwidth [14]	Occupied Bandwidth
Unfiltered BPSK[15]	635 R_s	20.56 R_s
Baseband Filtered OQPSK/PM		
Butterworth 6^{th} order	2.70 R_s	0.88 R_s
SRRC (α=0.5)	2.68 R_s	0.88 R_s
Bessel 6^{th} order	3.69 R_s	0.93 R_s
Baseband Filtered OQPSK I/Q		
Butterworth 6^{th} order	4.06 R_s	0.86 R_s
SRRC α=0.5	4.24 R_s	0.88 R_s
Bessel 6^{th} order	4.95 R_s	1.34 R_s
Precoded GMSK $BT_s = 0.25$	2.14 R_s	0.86 R_s
SOQPSK		
Version A	1.94 R_s	0.77 R_s
Version B	2.06 R_s	0.83 R_s
FQPSK-B	2.18 R_s	0.78 R_s

Occupied Bandwidth Recommended Efficient Modulations after Spectral Regrowth due to Saturated SSPA. Please note that R_s is the coded symbol rate, i.e. after the FEC encoder, not the channel symbol rate after the modulator.

Modulation Type	Receiver Type	E_b/N_o for 10^{-6} BER	CCSDS Yellow Book Reference
Unfiltered BPSK (reference only)	Integrate and Dump	2.55 dB	1-06, 1-14
Baseband Filtered OQPSK/PM			
Butterworth 6th Order	Integrate and Dump	3.09 dB	N/A
SRRC α=0.5		3.16 dB	
Baseband Filtered OQPSK I/Q			
Butterworth 3rd order	Integrate and Dump	2.91 dB	1-06, 1-14
Butterworth 6th order		3.04 dB	
SRRC α=0.5		3.06 dB	
Pulse-Shaped SRRC α=0.5	Matched Filter	2.77 dB	
Shaped Offset QPSK			
Version A	Integrate and Dump	3.74 dB	N/A
Version B		3.46 dB	
Precoded GMSK BT_s=0.25	Quasi-Matched Filter + 3 tap equalizer	2.73 dB	1-06, 1-14
FQPSK-B	Quasi-Matched Filter + 3 tap equalizer	2.88 dB	1-14

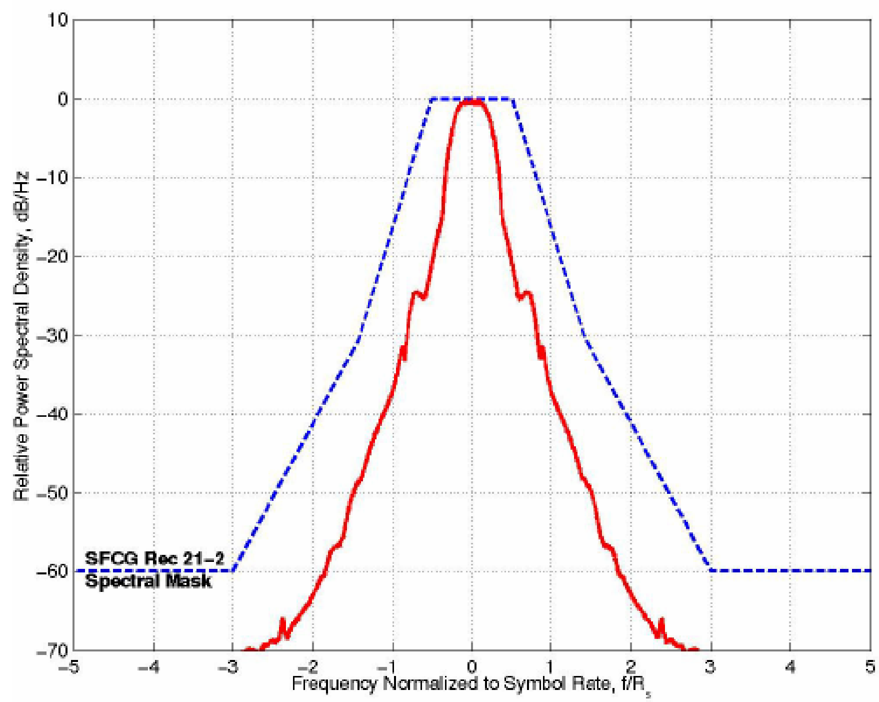
Simulated BER of selected bandwidth-efficient modulations using the CCSDS standard rate ½, k=7 convolutional inner code concatenated with a (255,223) Reed-Solomon outer code.

[Both tables are from CCSDS 413.0-G-1, *Bandwidth Efficient Modulations, Summary of Definition, Implementation, and Performance*, April 2003, Appendix B]

Channel Bandwidth Requirements (4)

- UAS Control Communications Modulation type(s) (cont.)
  - SRRC (α= 0.5) OQPSK was selected as the modulation used in the link budgets, as it combines good E_b/N_0 performance with good interference susceptibility performance
  - Link budget parameters
    - Spectral efficiency at 99% bandwidth (Occupied Bandwidth) = $0.88R_s$
    - Required BER = 10^{-6}

Link FEC Coding	Theoretical E_b/N_0 (dB)
Uncoded	11.5
3/4 Conv. FEC Only	6.5
CC RS+3/4 Conv. FEC	4.5
1/2 Conv. FEC Only	5.0
CC RS+1/2 Conv. FEC	3.0



Simulated Spectrum of Nyquist Pulse-Shaped SRRC (α=0.5) OQPSK at Output of Saturated SSPA

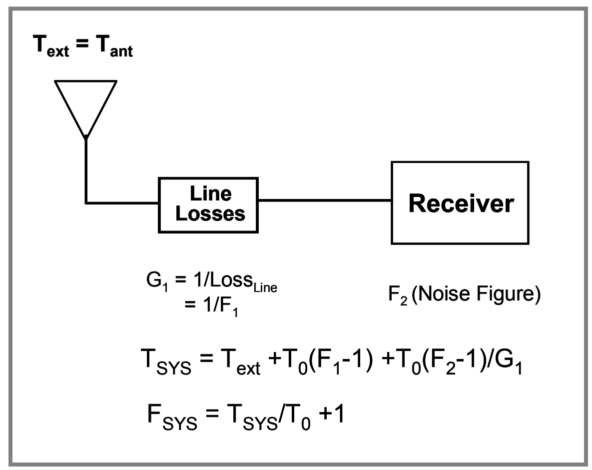
Note: R_s is the coded symbol rate, i.e. after the FEC encoder, not the channel symbol rate after the modulator.

[Figure is from: CCSDS 413.0-G-1, Bandwidth Efficient Modulations, Summary of Definition, Implementation, and Performance, April 2003]

Channel Bandwidth Requirements (5)

- Selected UAS Control Communications Link Parameters
  - Frequency Band
    - UAS control communications link budgets were based on an implementation in the aeronautical "L-Band," that is 960 – 1215 MHz
      - This yields a 2 dB range in free space path loss across this band
      - 1088 MHz (center of band) was used in the link budgets for path loss
  - System Noise Temperature
    - Used line loss values consistent with typical aeronautical application link budgets
    - System noise temperature was dependent on 100K external noise, line losses, and receiver noise figure

Calculating System Noise Temperature and Noise Figure



- Antenna Gains
  - Assumed 6 dBi gain for the ground system antenna consistent with typical aeronautical application link budgets
  - Assumed 0 dBi gain for the UA antenna consistent with UAT MOPS values

Channel Bandwidth Requirements (6)

- UAS ATC Communications Link Parameters
  - ATC voice was assumed to be 4800 bps vocoded data, and the same modulation and FEC coding parameters used for the Control communications links were applied
    - Duplex (separate uplink and downlink) channels were assumed
      - This may be necessitated by the end-to-end latency issues with vocoded speech and the burden of two "hops"
  - Because the COCR stated that the ATC per aircraft data capacity requirements include "overheads associated with the network, integrity and security," the same Filtered OQPSK modulation was used as for the other links, but no FEC link coding was assumed to be applied
    - Duplex (separate uplink and downlink) channels were assumed

PHASE 2		APT SV Dep	APT SV Arr	TMA SV Dep	TMA SV Arr	ENR SV	ORP SV	AOA
Separate ATS	UL	6.9	1.8	5.6	3.8	5.7	5.7	6.7
	DL	6.2	1.9	6.8	1.6	6.7	8.5	12.5
	UL&DL	6.9	1.9	6.9	3.8	6.7	8.5	12.5

COCR V1.0 Air/Ground Data Capacity Requirements (kbps) for Each Aircraft using a Separate 'Channel'

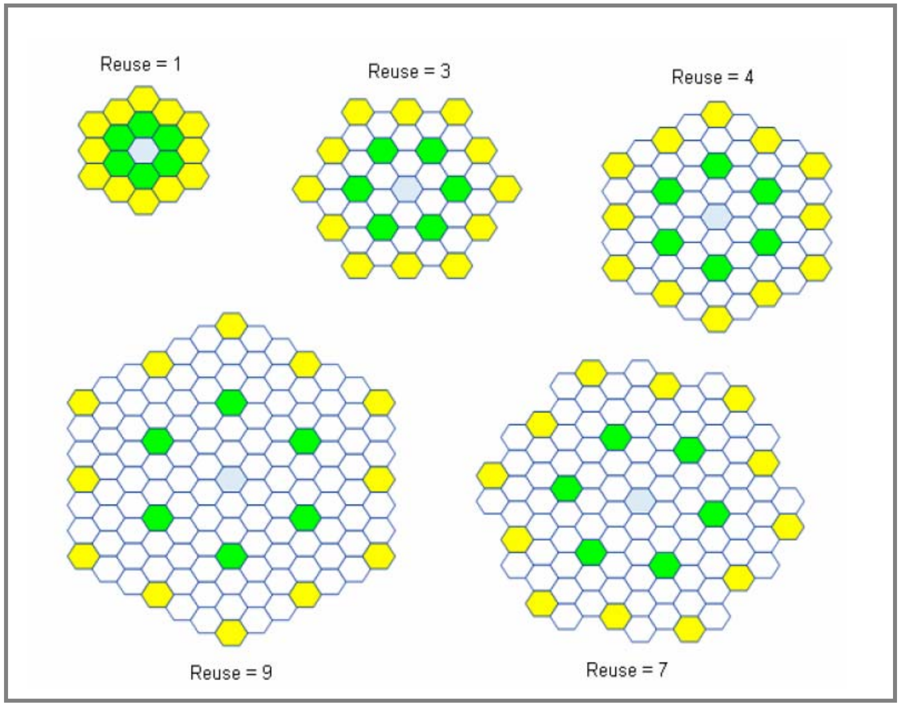
Sector Architecture

- Consistent with standard telecommunications practice, the sector architecture was defined using hexagonal tiling
- Each hexagonal sector provides a given number of separate channels to serve the expected maximum number of users in that sector
- All available frequencies are allocated and re-used in repeating clusters of sectors of size *N*

N (re-use parameter) can only take on values according to the following relation:

$$N = i^2 + ij + j^2$$

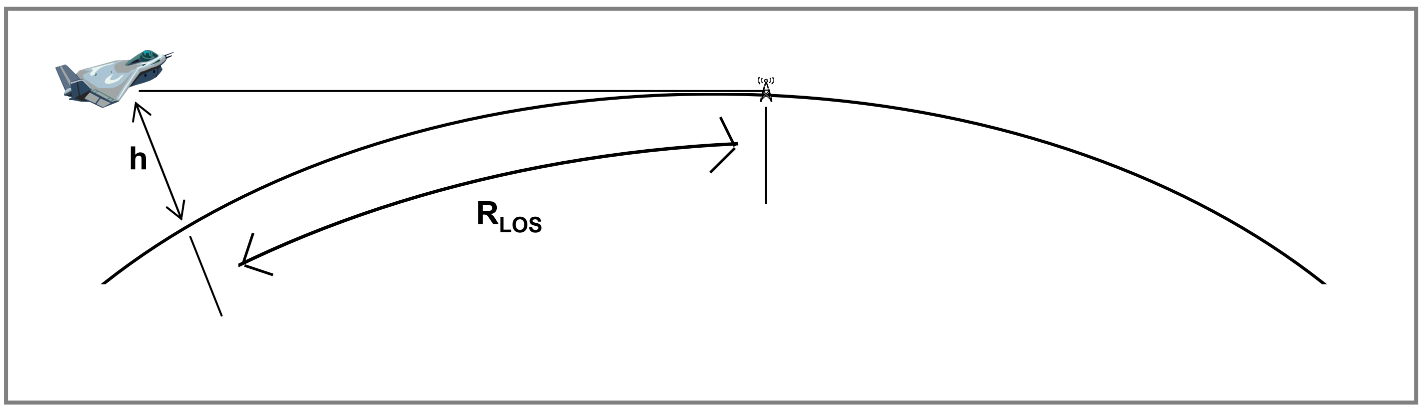
where i and j are nonnegative integers



From: *VDL Mode 2 & 3 Frequency Demand for Air Traffic Service Data Communications*, *Data Communications System (DCS)*, FAA Air Traffic Organization – Washington / Communications, c2006 [undated], p. 28.

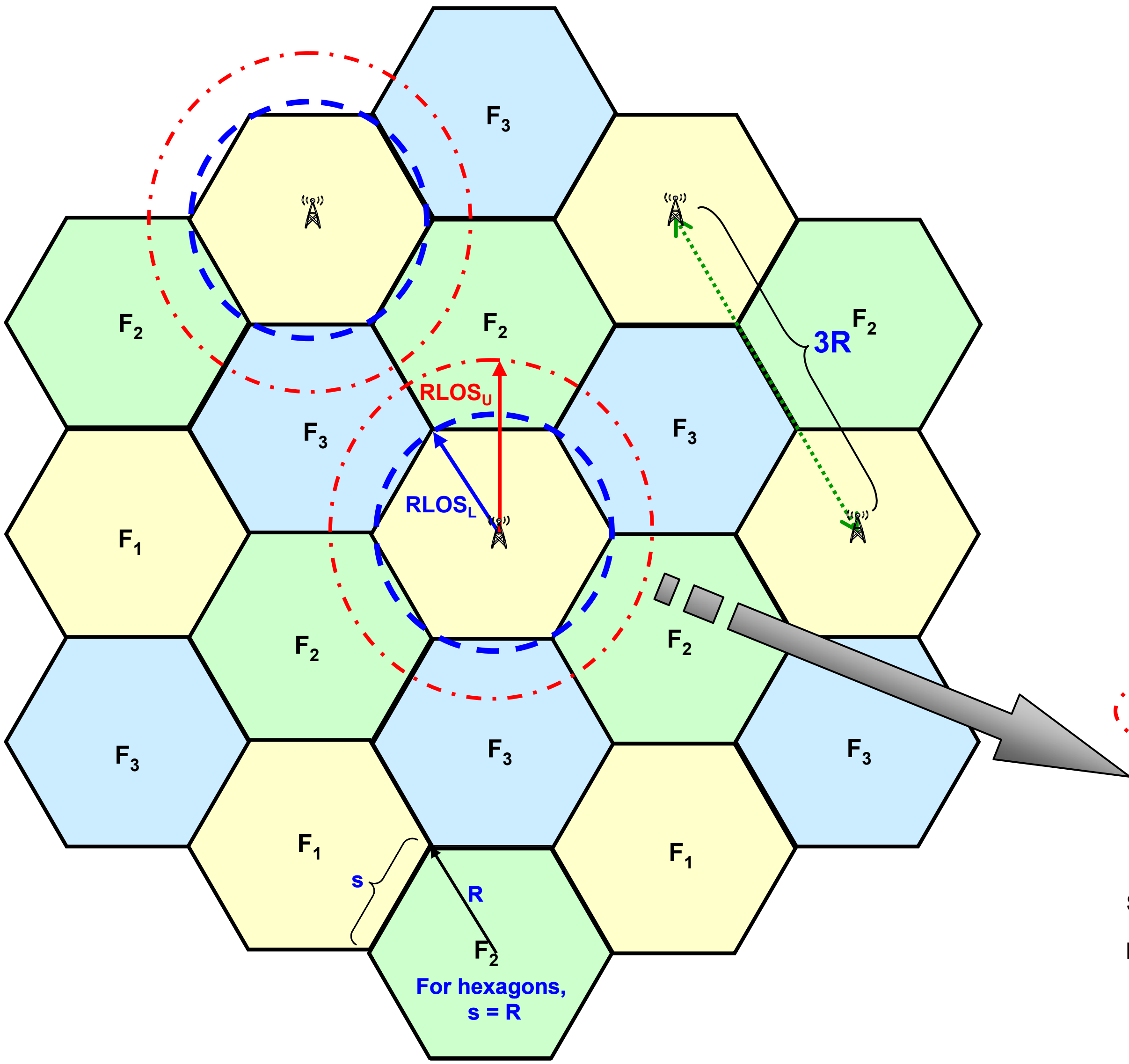
Sector Architecture (2)

- For the cell size and distances typically considered for cellular telecommunications co-channel interference is not usually limited by the curvature of the earth; however for air/ground communications this is not the case
- For aircraft communicating with a ground station, radio line of sight = R_{LOS} (nmi) = $1.23\sqrt{h}$, where h is in feet (4/3 earth effective radius assumption)

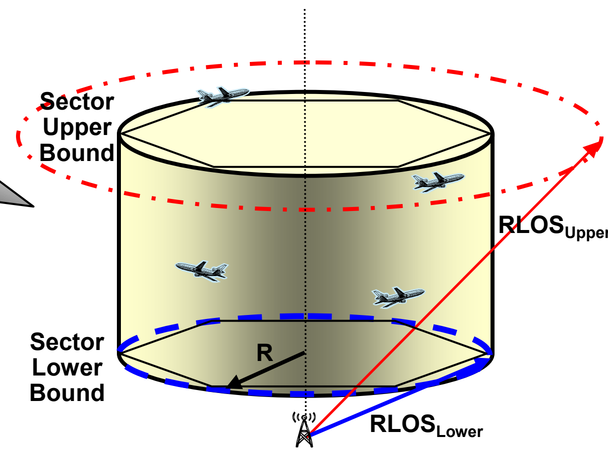


- For h = 60000 feet, R_{LOS} is 301 nmi.

Sector Architecture Example: Cluster Size N = 3



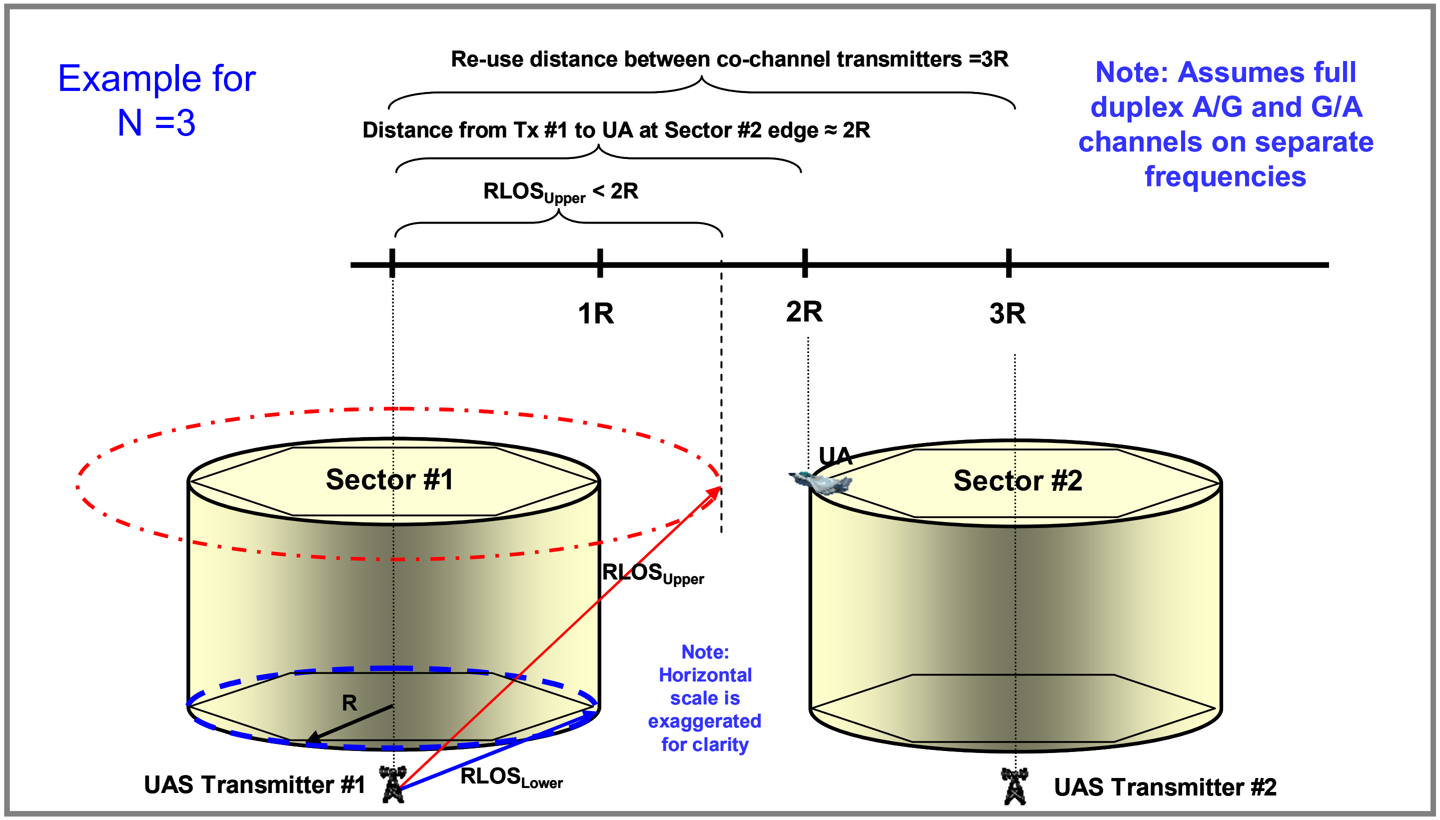
F1, F2, and F3 are the three distinct sets of frequencies allocated to the sectors repeated across the pattern



Sector radius
$R \approx RLOS_L$

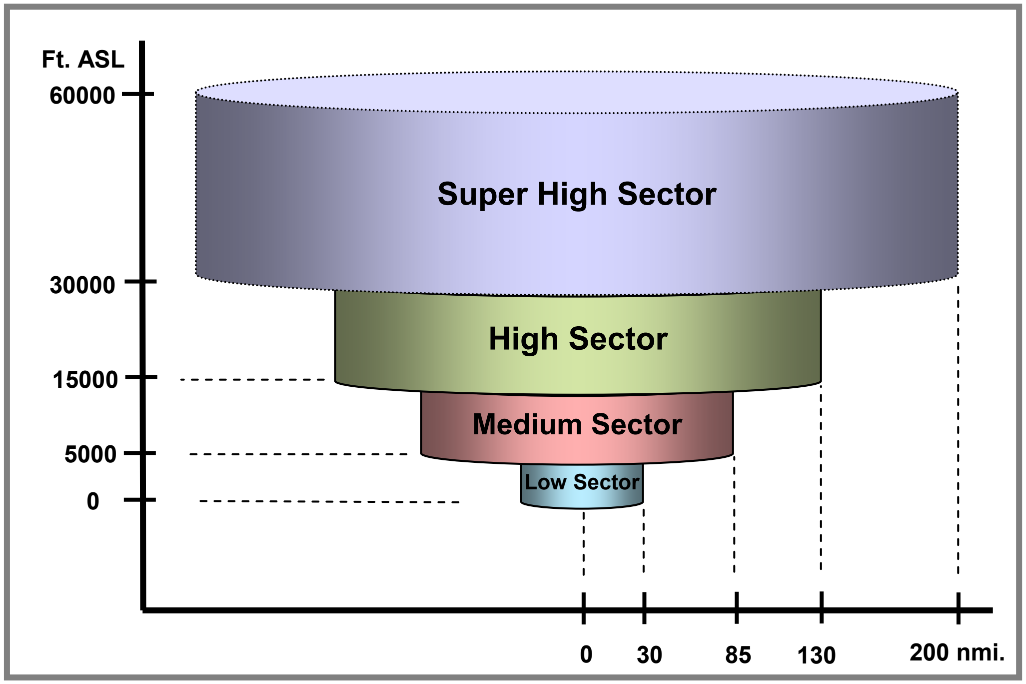
Sector Architecture Constraints

- To assure coverage $R < RLOS_{Lower}$, where
  - R is the sector radius
  - $RLOS_{Lower}$ is the radio line of sight (RLOS) of the lower boundary of the sector
    - For sectors with lower boundary of ground level, this condition is satisfied through typical ground station antenna heights and take-off/landing aircraft altitudes; at 1000 ft, R_{LOS} = 39 miles
- To avoid co-channel interference (for duplex channels) $RLOS_{Upper} < (Q – 1)$, where
  - $RLOS_{Upper}$ is the radio line of sight of the upper boundary of the sector
  - Q is the co-channel re-use distance = SQRT (3N), where N is the cluster size



Multi-level Sector Architecture

- An initial sector architecture was defined to roughly parallel the layered approach used for air traffic control
- It features N = 3 re-use for the top three levels, and N = 7 for the bottom level
- This approach would require sub-banding of frequencies for each sector layer to avoid co-channel interference between layers
- Separate sub-bands for uplinks and downlinks also would provide co-channel interference protection



Cylindrical sectors	Super High Sector	High Sector	Medium Sector ("TMA")	Low Sector ("Airport")
Sector radius (nmi)	200	130	85	30
Sector top (ft)	60000	30000	15000	5000
Sector bottom (ft)	30000	15000	5000	0
Sector height (nmi)	4.9	2.5	1.6	0.8
Circular Sector area (nmi^2)	125,664	53,093	22,698	2,827
Hexagonal Sector Area (nmi^2)	103,923	43,908	18,771	2,338
Hexagonal Sector volume (nmi^3)	513,107	108,394	30,893	1,924
Ratio: Circular/Hexagonal Area	1.21			
Radio line of sight at top (nmi)	301	213	151	87
Radio line of sight at bottom (nmi)	213	151	87	0
$RLOS_{top}/RLOS_{bottom}$	1.41	1.41	1.73	
$RLOS_{top}$/Sector radius	1.51	1.64	1.77	2.90
Cluster Size N	3	3	3	7
Reuse distance -1	2.00	2.00	2.00	3.58

Multi-layered Sector Architecture (2)

- Cylindrical sector tiling using hexagonal tiling provides approximately 20% overlap of sectors

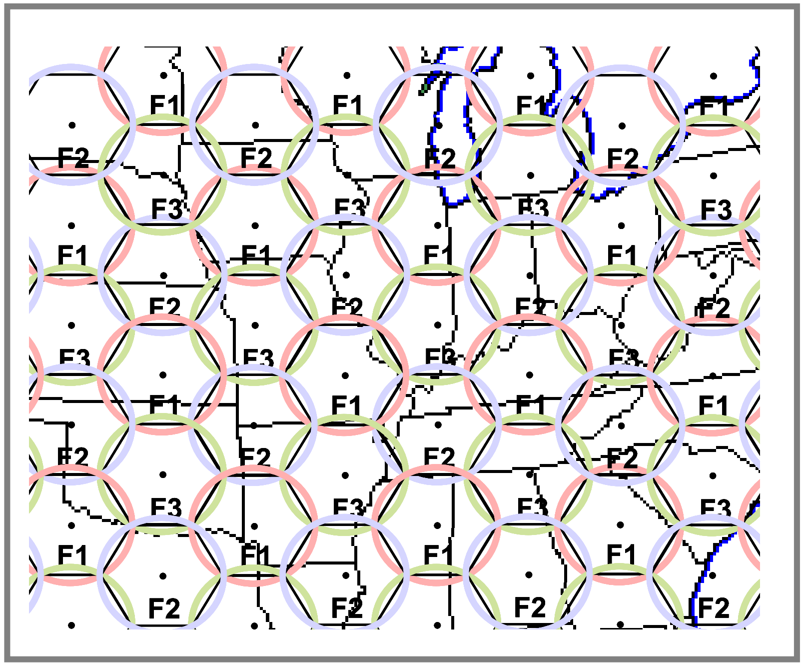


Illustration of Medium Sector Coverage Over the CONUS (R = 85 nmi)

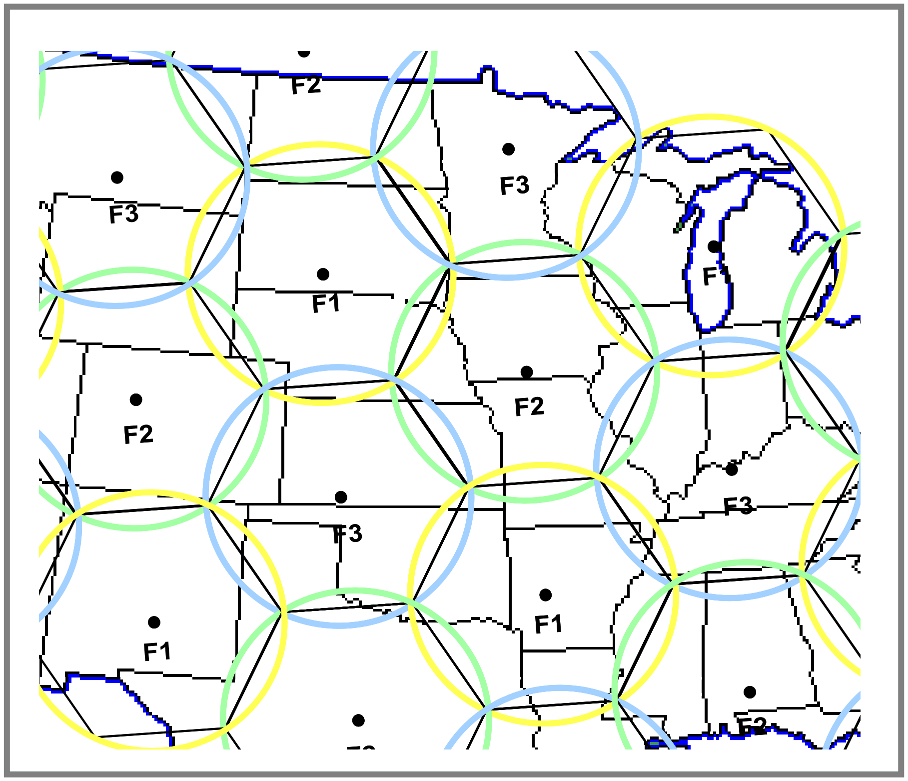
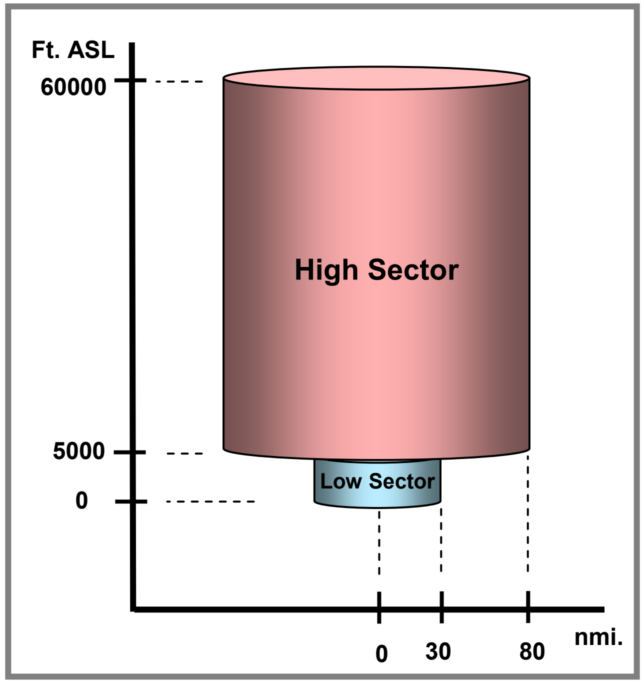


Illustration of Super High Sector Coverage Over the CONUS (R = 200 nmi)

Preferred Sector Architecture

- A simpler alternative sector architecture was defined to avoid multiple layers and the need for significant sub-banding
- It features N = 9 re-use for the High Sector level, and N = 7 for the Low Sector level
- Separate sub-bands for uplinks and downlinks would be desirable to provide co-channel interference protection



Cylindrical Sectors	High Sector	Low Sector
Sector radius (nmi)	80	30
Sector top (ft)	60000	5000
Sector bottom (ft)	5000	0
Sector height (nmi)	9.1	0.8
Circular Sector area (nmi^2)	20,106	2,827
Hexagonal Sector Area (nmi^2)	16,628	2,338
Hexagonal Sector volume (nmi^3)	150,511	1,924
Ratio: Circular/Hexagonal Area	1.21	
Radio line of sight at top (nmi)	301	87
Radio line of sight at bottom (nmi)	87	0
$RLOS_{top}/RLOS_{bottom}$	3.46	
$RLOS_{top}$/Sector radius	3.77	2.90
Cluster Size N	9	7
Reuse distance -1	4.20	3.58

Link Budgets

- Link budgets were performed for both sector architectures to derive acceptable bandwidth and power parameters
  - The simpler architecture provided better link performance

- All link budgets were based on the following assumptions:
  - Required BER = 10^{-6}
  - At least 10 dB required link margin

Link Budget Parameter	High Sector 5000 - 60000 ft	Low Sector 0 - 5000 ft	Airport Surface
Air-to-Ground Slant Range (nmi)	80	30	5
Transmit Power (dBm)	41.8	41.8	41.8
Transmit Line losses (dB)	-3	-3	-3
Transmit Antenna Gain (dBi)	0	0	0
Transmit EIRP (dBm)	38.8	38.8	38.8
Free Space Path Loss (dB)	136.6	128.1	112.5
Receive Antenna Gain (dBi)	6	6	6
Receive Line Losses (dB)	-2	-2	-2
Received Power (dBm)	-93.8	-85.3	-69.8
Receiver Noise Figure (dB)	8	8	8
External Noise Figure (dB)	1.3	1.3	1.3
System Noise Figure (dB)	10.1	10.1	10.1
Noise Floor - kT_0B (dBm)	-126.4	-126.4	-126.4
Receiver Noise Power (dBm)	-116.2	-116.2	-116.2
Theoretical E_b/N_0 (dB)	3.0	3.0	3.0
Theoretical C/N (dB)	3.6	3.6	3.6
Implementation Losses (dB)	2	2	2
Required C/N (dB)	5.6	5.6	5.6
Received C/N (dB)	22.4	30.9	46.5
Margin (dB)	16.8	25.3	40.9

Example: SRRC (α=0.5) OQPSK with concatenated RS (255, 233) and rate ½, k=7 convolutional FEC coding

Calculating Total UAS C&C Communications Bandwidth

- COCR and Eurocontrol FCS test service volumes similar in size to the notional architecture sector volumes were used to provide suitable total PIAC densities to determine total channel counts

Service Volume	Total PIAC	Volume (nmi^2)	Total Aircraft/nmi^2	UA Density: Aircraft/nmi^2	
				5%	10%
COCR - NAS Airport HD Phase 1	200				
COCR - NAS Airport LD Phase 1	12				
COCR - NAS Airport HD Phase 2	290				
COCR - NAS Airport LD Phase 2	19				
COCR - NAS TMA LD Phase 1	14	3,039	0.0046	0.0002	0.0005
COCR - NAS TMA HD Phase 1	16	2,831	0.0057	0.0003	0.0006
COCR - NAS En Route LD Phase 1	24	20,782	0.0012	0.0001	0.0001
COCR - NAS En Route HD Phase 1	24	5,119	0.0047	0.0002	0.0005
COCR - NAS TMA LD Phase 2	39	9,240	0.0042	0.0002	0.0004
COCR - NAS TMA HD Phase 2	44	7,691	0.0057	0.0003	0.0006
COCR - NAS En Route LD Phase 2	59	33,388	0.0018	0.0001	0.0002
COCR - NAS En Route HD Phase 2	45	10,132	0.0044	0.0002	0.0004
COCR - NAS En Route Super Sector	95	31,996	0.0030	0.0001	0.0003
Eurocontrol - TV1 Airport Total	290				
Eurocontrol - TV1a Airport Surface	264				
Eurocontrol - TV1 Airport in Flight	26	259	0.1004	0.0050	0.0100
Eurocontrol - TV2.1 - TMA Small	44	7,691	0.0057	0.0003	0.0006
Eurocontrol - TV2.2 - TMA Large	53	18,056	0.0029	0.0001	0.0003
Eurocontrol - TV3.1 - ENR Small	28	10,132	0.0028	0.0001	0.0003
Eurocontrol - TV3.2 - ENR Medium	62	33,739	0.0018	0.0001	0.0002
Eurocontrol - TV3.3 - ENR Large	204	134,957	0.0015	0.0001	0.0002
Eurocontrol - TV3.4 - ENR Super Large	522	539,829	0.0010	0.00005	0.0001

Calculated Total UAS C&C Communications Bandwidth

- Total calculated C&C communications bandwidth requirements were derived based on link budget results and computed UA aircraft densities

Sector Architecture Parameters	**High Sector**	**Low Sector**	**Airport Surface**	**Total**
Sector radius (nmi)	80	30		
Sector top (ft)	60000	5000		
Sector bottom (ft)	5000	0		
Sector height (nmi)	9.1	0.8		
Circular Sector area (nmi^2)	20,106	2,827		
Hexagonal Sector Area (nmi^2)	16,628	2,338		
Hexagonal Sector volume (nmi^3)	150,511	1,924		
Ratio: Circular/Hexagonal Area	1.21			
Radio line of sight at top (nmi)	301	87		
Radio line of sight at bottom (nmi)	87	0		
$RLOS_{top}/RLOS_{bottom}$	3.46	Note 1		
$RLOS_{top}$/Sector radius	3.77	2.90		
Cluster Size N	9	7	1	
Reuse distance -1	4.20	3.58		
Total Aircraft density (#UA per nmi^3)	0.00151	0.00565		
Percentage of UA in the NAS	10	10	10	
UAS Aircraft density (#UA per nmi^3)	0.000151	0.000565		
Computed Peak UA Count per Sector	23	1	26	
Control Link - Number of Downlink/Uplink Channels	207	7	26	240
Control Link - Downlink Channel Bandwidth (Hz)	58,000	58,000	58,000	58,000
Control Link - Uplink Channel Bandwidth (Hz)	10,100	10,100	10,100	10,100
Control Link - Total Downlink Bandwidth (Hz)	12,006,000	406,000	1,508,000	13,920,000
Control Link - Total Uplink Bandwidth (Hz)	2,090,700	70,700	262,600	2,424,000
Control Link - Total Uplink + Downlink BW (Hz)	**14,096,700**	**476,700**	**1,770,600**	**16,344,000**

Example: Total Required Control Communications Bandwidth Based on the Link Coding Parameters Used in the Example Link Budget

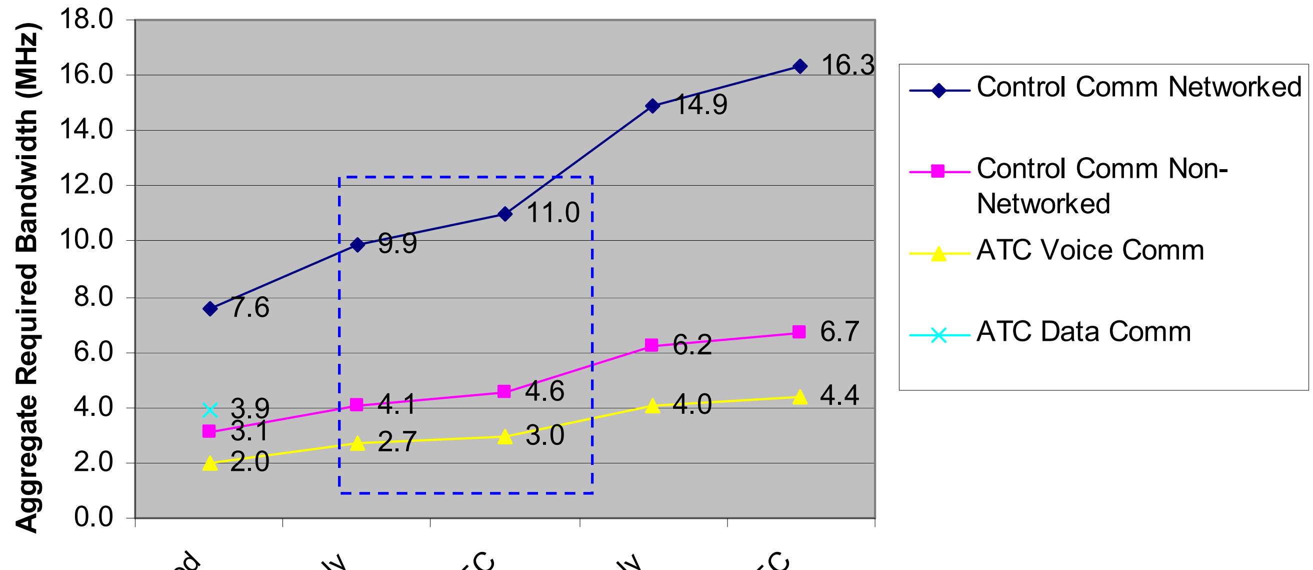
Required Bandwidth Sensitivity

- Total required Control Communications bandwidth requirements were most sensitive to certain parameters:
  - UA peak counts
    - UA assumed to be 10% of the total PIAC; a different value linearly scales the results
  - Data rate requirements of the UAS Command & Status/Telemetry messages
    - These were highly dependent on update rates
      - Conservative values were assumed to upper bound the aggregate rate, based on low to moderate autonomy UAS
    - Locating the VSM on the UA (Configuration B) resulted in significant network and transport layer protocol overhead on the A/G links
    - Configuration A assumption that the VSM is located on the ground and that the UAS employs native/proprietary (i.e. non networked) link protocols significantly reduces required bandwidth
  - Link FEC coding, necessary to increase link margin to accommodate excess path losses impacted required channel bandwidth
    - A range of link FEC coding alternatives were used to provide a range of total required bandwidth

Required Bandwidth Results

- The table below illustrates required total UAS C&C communications bandwidth estimates and their sensitivity to overhead and link FEC coding assumptions

Note: Box highlights best reasonable estimates



Link FEC Coding	Downlink Control Comm Link Margin (dB)
Uncoded	11.7
3/4 Conv. FEC Only	15.5
CC RS+3/4 Conv. FEC	17.1
1/2 Conv. FEC Only	15.2
CC RS+1/2 Conv. FEC	16.8

Concluding Remarks

- It was not possible to derive a single number to estimate total UAS C&C bandwidth requirements
  - A range was provided to provide bounds, based on stated configurations and assumptions
  - For this architecture, the findings based modest FEC coding, such as provided by the two rate ¾ cases seem to provide the most reasonable compromise between performance and bandwidth
    - In particular, the concatenated RS + ¾ rate convolution FEC coding provides significant excess path margin, plus additional protection against burst errors
- The notional architecture used to estimate total bandwidth requirements allowed for significant link margin because of the modest sector radii
  - Other architectures are possible and may be more efficient (the initial architecture resulted in poorer performance in almost every respect)
  - A detailed design was beyond the scope of this task
  - Co-site interference issues, not considered for this study, need to be explored
  - The potential impacts of sub-banding need to be addressed