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WORKING PAPER

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SP3 Agenda item 3: Aeronautical surveillance systems and Airborne Collision Avoidance systems

ASWG8 Agenda Item 6: Mode S and Extended Squitter

Address and Spectrum Issues for Small UAS

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SUMMARY

This Working Paper has been prepared in response to Action Item ASWG/7-27, "TSG to investigate and report back on 24-bit aircraft address and 1090 MHz spectrum issues associated with small UAS."

ACTION ITEM AND WP TYPE

Response to Action Item ASWG/7-27

TSG WP Type: B. Draft CP Material or proposal for WG discussion and comment

1. **INTRODUCTION**

1.1 Various papers presented at ASWG/7 engendered discussions about some of the technical and practical limitations associated with large numbers of small UAS attempting to make use of current Mode S surveillance avionics. As an outcome of these discussions, the TSG was requested (via Action Item ASWG/7-27) to investigate and report back on 24-bit aircraft address and 1090 MHz spectrum issues associated with small UAS.

2. **Discussion**

2.1 Availability of 24-bit aircraft addresses for small UAS

2.1.1 The 24 bits allocated in Mode S for aircraft address allows a unique address to be allocated to 16,177,214 aircraft, aerodrome surface vehicles, obstacles or fixed Mode S target detection devices for surveillance and/or radar monitoring purposes. See ICAO Annex 10, Volume III, Chapter 9. ICAO has allocated much of the available addresses to the various ICAO contracting States. For example, the Russian Federation and the U.S. have each been allocated 1,048,576 addresses (the largest block allocated by ICAO).

2.1.2 Within the U.S. allocation, most of the available addresses (over 910,000) are allocated for civil aircraft use; the remainder are allocated for testing (just over 1,000) and for use by State aircraft (over 100,000). There are over 350,000 registered civil aircraft in the U.S. and over 10,000 State aircraft. If there were no growth in these fleets, then a maximum of 600,000 aircraft addresses would be available. As of 2 April 2018, there were over 154,000 registered small UAS in the U.S. – these small UAS are registered under Part 107 of the U.S. Code of Federal Regulations, section 14. Additionally, there are over 880,000 “hobbyist” small air vehicles registered in the U.S.

2.1.3 Projections of small UAS growth in the U.S. indicate that it is likely that there will be over a million such vehicles by 2025. The FAA has therefore concluded that there are insufficient ICAO addresses for all of the envisioned small UAS. Note that FAA does not issue ICAO addresses to small UAS registered under Part 107 of the U.S. Code of Federal Regulations, section 14. Also, the FAA does not issue ICAO addresses to “hobbyist” small air vehicles registered in the U.S. Only aircraft/vehicles registered via the FAA’s Civil Aircraft Registry are issued an ICAO address.

2.2 Spectrum issues associated with small UAS

2.2.1 At FAA’s request, MITRE Corporation's Center for Advanced Aviation System Development (CAASD) conducted analyses which led to an AIAA paper entitled, “ADS-B Surveillance System Performance with Small UAS at Low Altitudes.” An earlier study, published in 2016, explored the impact of very high densities of small UAS (sUAS) transmitting ADS-B using the Universal Access Transceiver (UAT). The AIAA paper reports on an analysis which examined a broader range of operating scenarios characterized by various sUAS traffic densities and transmission power levels. The AIAA paper considered the implications of varying sUAS traffic density and transmission power on air-to-air and air-to-ground uses of ADS-B. The AIAA paper was presented at the AIAA Science and Technology Forum and Exposition (SciTech) in January 2017 and is referenced below. Note that although this paper is cited below (for its analysis results), the FAA does not agree with many of the statements made in sections V (Key Findings) and VI (Conclusion and Future Work) of the paper. Table 5 of the AIAA paper shows the impact on FAA ground stations of various assumed levels of UAS traffic (in addition to the assumed manned aircraft within line of sight to the ground station). RF experts within the FAA believe that avionics manufacturers cannot accurately control RF transmit power below 1W, nor can FAA/FCC effectively regulate RF transmit power levels below 1W. Therefore, FAA focuses on the 1W results in the AIAA paper, which shows that even the minimum analysed density of 0.5 sUAS per square kilometre / 1.75 sUAS per square mile (1400 sUAS operating within 800 square miles) causes FAA ground stations to become blinded from seeing manned aircraft ADS-B reports.

2.2.2 NASA performed a separate analysis from the MITRE CAASD study referenced above, using an independent model developed by NASA. See reference below; this paper is also attached since it is not yet available online. One key finding, based on NASA's probability of detection threshold of 80% or better, was that a 1W ADS-B transmitter for sUAS on the Air-to-Ground link would not meet this threshold.

2.2.3 Note that the MITRE CAASD and NASA analyses are based on models and do not include the impact of real world interference that the FAA has observed on both 978 MHz and 1090 MHz frequencies at numerous ground station locations. Therefore, FAA expects that the MITRE CAASD and NASA analysis results are optimistic relative to what would be observed in implemented systems.

2.2.4 The 1090 MHz frequency is currently more congested than the 978 MHz frequency, since 1090 MHz is also used by ATCRBS and Mode S systems (TCAS, SSRs and multilateration systems). Therefore, any impacts on 1090 MHz from sUAS ADS-B transmissions on this frequency are expected to be significantly worse than those calculated for UAT on 978 MHz.

3. Conclusion

3.1 The 24-bit aircraft address scheme in ICAO Annex 10, Volume III, Chapter 9 was not designed for the high density of vehicles in an airspace that is foreseen for small UAS.

3.2 Even at RF transmit power levels which are equivalent to cell phones (1W), small UAS operating in a typical large urban area at airspace densities of one vehicle per two square kilometres and equipped with ADS-B Out would be expected to cripple any ICAO standard surveillance system operating on 978 MHz or 1090 MHz.

3.3 Therefore, the FAA believes that widespread ADS-B Out equipage (as defined in RTCA/EUROCAE MOPS and ICAO documents) by small UAS is not a feasible alternative.

4. Actions on the meeting

The meeting is invited to consider this information and provide it to other entities as appropriate.

REFERENCES

Michael Guterres, Stanley Jones, Greg Orrell, and Robert Strain. "ADS-B Surveillance System Performance With Small UAS at Low Altitudes", AIAA Information Systems-AIAA Infotech @ Aerospace, AIAA SciTech Forum, (AIAA 2017-1154)
https://doi.org/10.2514/6.2017-1154

Konstantin J. Matheou, Rafael D. Apaza, Alan N. Downey, Robert J. Kerczewski, and John Wang. "ADS-B Mixed sUAS and NAS System Capacity Analysis and DAA Performance", ICNS Conference Paper 2B3, 2018.
[[see attached]]

ADS-B MIXED SUAS AND NAS SYSTEM CAPACITY ANALYSIS AND DAA PERFORMANCE

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I. Abstract

Automatic Dependent Surveillance-Broadcast (ADS-B) technology was introduced more than twenty years ago to improve surveillance within the US National Airspace Space (NAS) as well as in many other countries. Via the NextGen initiative, implementation of ADS-B technology across the US is planned in stages between 2012 and 2025. ADS-B's automatic one second epoch packet transmission exploits on-board GPS-derived navigational information to provide position information, as well as other information including vehicle identification, ground speed, vertical rate and track angle. The purpose of this technology is to improve surveillance data accuracy and provide access to better situational awareness to enable operational benefits such as shorter routes, reduced flight time and fuel burn, and reduced traffic delays, and to allow air traffic controllers to manage aircraft with greater safety margins. Other than the limited amount of information bits per packet that can be sent, ADS-B's other hard-limit limitation is capacity. Small unmanned aircraft systems (sUAS) can utilize limited ADS-B transmission power, in general, thus allowing this technology to be considered for use within a combined NAS and sUAS environment, but the potential number and density of sUAS predicted for future deployment calls into question the ability of ADS-B systems to meet the resulting capacity requirement. Hence, studies to understand potential limitations of ADS-B to fulfill capacity requirements in various sUAS scenarios are of great interest. In this paper we, validate/improve on, previous work performed by the MITRE Corporation concerning sUAS power and capacity in a sUAS and General Aviation (GA) mixed environment. In addition, we implement its inherent media access control layer capacity limitations which was not shown in the MITRE paper. Finally, a simple detect and avoid (DAA) algorithm is implemented to display that ADS-B technology is a viable technology for a mixed NAS/sUAS environment even in proposed larger mixed density environments.

II. Introduction

ADS-B modelling and simulation work has been on-going at NASA's Glenn Research Center (GRC) for the past few years. The motivation to simulate ADS-B technology is due to its acceptance by the Federal Aviation Administration (FAA). Due to the emergence of smaller drones being sold throughout the US and the rapid evolution of drone technology, many safety, commercial, and recreational types of applications will drive the number of drones (aka sUASs) to populate the skies, such that the inclusion of ADS-B technology on future drones may be a logical safety-enhancing extension. Thus, work on two tasks are presented that show simulation results in a mixed sUAS capacity environment, and further extends the analysis to display initial DAA algorithmic results.

III. Inspiration and Approach

Thus, the first step is to understand ADS-B performance in a mixed, sUAS and NAS, capacity environment. This has been completed previously by Guterres, Jones, Orrell, and Strain [1]. In work supporting UAS Traffic Management (UTM) research, GRC leveraged the work in [1], validating the results with GRC's ADS-B simulation model. GRC's model includes theoretically proven channel includes theoretically proven channel model algorithms for UTM including: 1) AWGN, 2) link budget, 3) multipath propagation (Fresnel coefficient), and 4) 900-1090MHz band co-cannel interference, a somewhat different approach from [1]. In implementing individual channel models, the GRC model specific channel impairments to be analyzed, thus allowing better checks to the overall model.

The ADS-B waveform is a Time Division Multiple Access (TDMA) based communications modulation [2]. Due to this slotted modulation design, there is an inherent capacity limit at the MAC layer. For air-to-air (A2A) and air-to-ground (A2G) ADS-B communications, there are a total of 3,200 Message Start Opportunity slots (MSOs) [3]. Theoretically the most aerial vehicles (AVs) at one time that can communicate are 3,200. But due to the random way the MSO's are chosen once the link budget is closed, another added layer of throughput interference is inherently added – MSO collisions. This additional functional throughput MSO Collisions algorithm has been added to the GRC ADS-B model. Thus, a more true 'probability of decoding' framed information coming over the air using ADS-B technology can be predicted for high capacity ADS-B usage. This is a performance feature extends the analysis in [1].

From [1], three transceiver types are implemented: 1) ADS-B, 2) Mode S, and 3) Air Traffic Control Radar Beacon System (ATCRBS). All these 3 technology modes share the 900-1090MHz spectrum, thus the need for co-channel interference algorithm in the GRC model. Also, the GRC model allows for various 'radius ranges' and various heights per 'radius range' that can be altered. The model currently only allows an average constant air speed per AV per 'radius range'. All the above parameters can be altered including transmit power for sUASs. The GRC ADS-B model will be discussed in more detail in the next section.

IV. ADS-B Model Details

The 'ADS-B Capacity' model was coded for air-to-air (A2A) and air-to-ground (A2G) analyses. The simulation was modelled similarly to [1]. The airport is located in the center, bottom of the cylinder at the 3-dimensional point (0, 0, 0). The 3 dimensions are: 1) distance x, 2) distance y, and 3) altitude. The National Air Space (NAS) general aircraft (GAs) are simulated to have an average altitude of 20,000 ft. and all have an average speed of 300nm/hr. The sUASs, on the other hand, are all randomized in altitude ranging between 50 to 400 ft. The sUAS average speed was chosen to be 50nm/hr. for all sUASs. All sUASs and GA's initial distance x and distance y placement were randomized at the beginning of the simulation to be between 2-21 nm from the center radially. This range was chosen to allow the high density 5 $^{AVs}/_{km^2}$, medium density 3 $^{AVs}/_{km^2}$, and low density 1 $^{AV}/_{km^2}$. Finally, all AV's are incoming/enroute towards the airport radially in a straight line fashion.

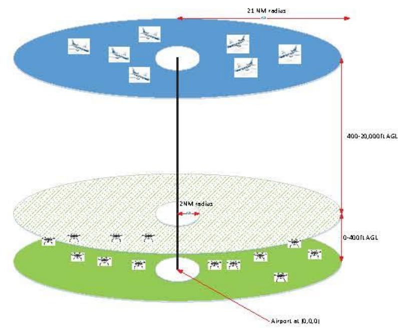


Figure 1- NAS/sUAS Airspace Simulation Approach

It is important to define the types of flying objects referred to in this paper. AV's are the most generalized type of flying objects that include GA and sUASs. GA is the type of aircraft that flies in the NAS, while sUAS are also referred to as drones that is not part of NAS.

In table 3 from [1], there are 16 density scenarios listed. For this paper, scenarios 1 through 12 have been simulated. For traffic density, the AV mix between lower flying sUASs and NAS type flying planes (GA) for all simulations are: 95% sUAS, 5% GA, where the types of radar technology for the 5% GA planes are split as follows: 3% ADS-B, 1% Mode S, and 1% ATCRBS. This mix again was chosen due the approach in [1].

Table 1-MITRE 12 Scenarios

	Transmit Power (W)				Traffic Density (AVs/km^2)		
	1.00	0.10	0.05	0.01	5	3	1
Scen 1	X				X		
Scen 2		X			X		
Scen 3			X		X		
Scen 4				X	X		
Scen 5	X					X	
Scen 6		X				X	
Scen 7			X			X	
Scen 8				X		X	
Scen 9	X						X
Scen 10		X					X
Scen 11			X				X
Scen 12				X			X

The basis of this paper's analysis is to understand how the power of sUAS in various high density scenarios affects communications performance in two ways: 1) probability in closing the communications link and 2) capturing a MSO and completing the MAC layer process to fully send framed information data to the receiver. Once the signal strength is good enough to enter the ADS-B receiver and there is an available MSO slot in a high ADS-B density scenario, the incoming framed information of the ADS-B signal can be used to begin 'smart' algorithm, one type of which is referred as Detect and Avoid (DAA).

The DAA approach was inspired by [2]. To understand capacity limitations is important, but an initial type of DAA algorithmic analysis should be done to better understand full UTM processing capacity and system performance of ADS-B technology.

V. DAA Model Details

Once the framed information passes through the MAC layer (network layer 2), the incoming bit-framed information can be processed. Detect and avoid (DAA) algorithms are processed at higher levels of the network stack. But due to channel impairments, AV ADS-B transceiver capacity, and inherent waveform capacity limitations due to TDMA modulation, the probability of the incoming frame being processed every second epoch will be less than 1.0. As shown in the results sections, the probability of a frame getting through the first time per certain capacity situations can vary from 0.20 to 0.95. Thus, an analysis using a DAA algorithm may increase the probability to 'track' other adjacent AVs utilizing ADS-B technology. But as always, there is a compromise in other performance parameters that may be lessened. For example, when the detection of a nearby ADS-B transceiver takes longer due to DAA processing, the situation may be too late and a crash may occur.

The DAA approach and design parameter definitions were inherited from [4]. The following DAA design parameter definitions are provided:

1) *Measurement Received* – means that the link budget of the ADS-B receiver was met and there were no MSO collisions. Thus, the received framed measurement information is then assumed to have been decoded.
2) Set Number – the count of *Measurement Received* times. Set number minimum is 2.
3) *Track* - when a number of *Set Number* times is counted within a *Maximum Size Set.*
4) *Maximum Set Size* – maximum number of measurements that can be missed between two received measurements and allow them to still form a track.
5) *Kill Track* – the number of times missed MSO slot before stopping to track an AV.

For example, when *Max Set Size* = 6, this means a maximum count of 4 MSO slots can be missed between 2 MSO caught slots before a *Track* is created. When Kill Track =1 means that the first missed *Measurement Received,* the *Track* will cease to exist and the whole process needs to start over. Using this DAA algorithmic terminology, an analysis of this is done within the next section.

VI. Channel Model Details

There are 4 algorithmic channel models being implemented within this model: 1) AWGN, 2) Link Budget, 3) Multipath Interference, and 4) Co-channel Interference.

Any communications system is normally baselined using an Average White Gaussian Noise channel. The energy per symbol over noise (S) is used as a parameter within the Link Budget model as shown below equation. For reference, the ADS-B modulation waveform is 8-DPSK. Thus, a total of 3 bits per symbols are sent over the air. Equation 1 sums up the link budget model where, either the minimum symbol power needs to be met, or the maximum transmitter distance can be found within an AWGN channel [3].

$$R_{max} = \left(\frac{P_t G_t^2 \sigma \lambda^2}{(4\pi^3) S_{min}}\right)^{1/4} \qquad eq.\ 1$$

Table 2 is a link budget table example that shows parameters and real values for a link budget. In this particular case an ADS-B transmitter power Pt=20dB with a certain grazing angle within a smooth surface multipath environment should be able to close the link within 90 nm (blue and red highlighted values are linear, not dB).

Multipath interference model has been duplicated from [1] and [2] using the below equation.

$$M(E,A) = 20log\left[C_o(E)exp\left(-2\left(\frac{2\pi}{\lambda}\right)^2 s^2 sin^2(E)\right)\right] + g_T(E,A) + g_R(E,A) \qquad eq.\ 2$$

Figure 2 is the reproduced Fresnel coefficient value, C, for a smooth surface (worst case) multipath scenario which is the one used in [1].

Table 2-Link Budget Example

			Comments
NUMERATOR	Pt(dB)	20.0	Power of transmitter in dB
	Pt	100.0	value
	Gt	1	Gain of tramsitter antenna
	Sigma	0.5	Surface area of target (ADS-B level 3)
	wavelength	0.3	wavelength of carrier wave
	Gr	1	Gain of receiver antenna
	tau	1.00E-06	pulse timeframe in seconds
	F Ratio	0.72	dependent of Grazing angle
DENOMINATOR	k	1.38E-23	Boltzman's constant
	Ts	967	System temperature of transceiver
	D0(1)(dB)	13	Detectability factor in dB
	D0(1)	19.95	Detectibility factor in linear value
	Lalpha(dB)	-5.14	Multipath in dB - Depends on Grazing Angle
	Lalpha ratio	0.31	Multipath linear value
	Lt(dB)	1	Line Transmission Loss
	Lt Ratio	1.26	Line Transmission loss linear value
	Rm=	90.0	Maximum needed range in NM (For Level 3)

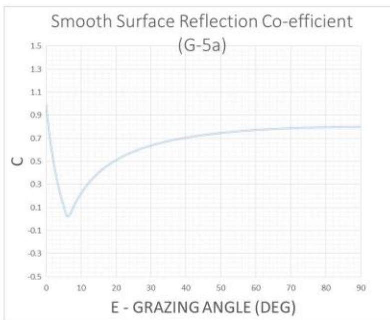


Figure 2 – Fresnel Coefficient Plot for Smooth Surface

ADS-B and the other 2 legacy technologies used currently in the NAS, Mode S, and ATCRBS, utilize the same 980-1090MHz spectrum. [1] implemented a Co-Channel interference model, where the equivalent was implemented with the GRC model. The algorithm output is shown Figure 3.

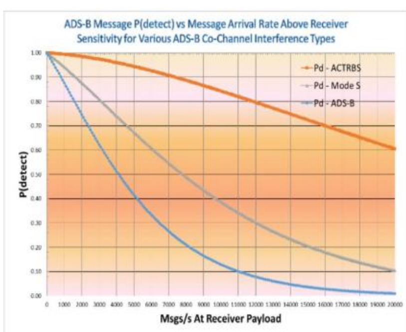


Figure 3 – ADS-B P(detect) vs Message Arrival Rate for Various Co-Channel Interference Types

VII. Results and Analysis

The following sections will present the simulation output and will be contrasted and compared to previous work and then will follow with additional information not presented in previous findings. The UAT system is modelled as an AWGN communication system where additional channel algorithm impairments are used to acquire the probabilistic values for both A2A and A2G implementations. The sections are split by A2A and A2G findings.

A. A2A Analysis

A2A analysis considers the communications between AVs only. In general, there are more multipath affects due to the AV's altitude, speed, and grazing angle. Likewise, depending on AV speed and distance away from each other, the transmission link between AVs may or may not close. The purpose of these simulations is to understand capacity limitations for future mixed sUAS and NAS GA environments. The percentages chosen were to compare to the MITRE previous results. The authors believe these percentages to be different than the ones used, but were kept the same for comparison reasons. Again, the mixed AV environment is a 95% sUAS using ADS-B UAT, to 3% GA ADS-B UAT, to 1% GA Mode S UAT, to 1% GA ATCRBS. A total of 20,000 AVs for High Density, 12,000 medium Density, and 4,000 AVs for Low Density.

1. High Density Detailed Analysis

It was determined a high density environment of $5\ {}^{AVs}/_{km^2}$ to be implemented with the defined percentage breakdown. sUAS 'communications link' distance was varied while sUAS transmitted power was kept the same for all sUASs. As the distance is varied, the receiving end antenna receiver captures a certain Es/No symbol power (S) level which either closes the link or the link stays open, thus never communicating with the adjacent AV's receiver.

A parameter than was deliberately chosen to be different than [1] was the transmitter power of the GA. The GA ADS-B transmitter power was at 100W, as opposed to 25W that was in [1]. The simulation performance output results in Table 3 show the worst case performance between: 1) 'Close Link Budget' which includes co-channel interference, AWGN, and multipath and 2) all channel impairments adding the MSO collisions which is referred to as 'Probability of Decoding'. The values from [1] are in bold.

Table 3 - A2A Worst Case Probabilities

	A2A			
	High Density			
Scenario	1	2	3	4
Worst Case Prob of Decoding	0.28	0.50	0.58	0.68
Worst Case Prob of Link Closing	0.65	0.65	0.65	0.80
From Mitre Table	**<0.25**	**0.1**	**0.3**	**0.78**
sUAS Distance MAX	3.5	2.0	1.5	1.0
	BLOS	BLOS	LOS	LOS

We are assuming that the MITRE paper analysis only went as far to 'Probability of Closing Link'. When we add MSO collisions, the probabilities seem to match a little better, but not exactly correlated. It is the opinion of the authors that due to running actual channel algorithms, thus capturing many nuances, our results are more accurate. They also distinguish between the two types of probabilistic performance, 'Probability of Decoding' and 'Probability Closing Link'.

Figure 4 shows the simulation results of the 1.0W baseline high density performance output of the GRC simulation. The x axis shows the 'head-on' distance between sUAS and another sUAS or GA. The power of the sUAS transmitter stays constant, but the 'head-on distance' increases. As the distance increases, the probability of a sUAS 'closing the link' starts reducing. This is the <u>black line</u> labelled 'sUAS ABOVE Receiver Operating Point'. Notice the more power, the longer 'Head-On Distance' the sUAS can communicate – see Table 3.

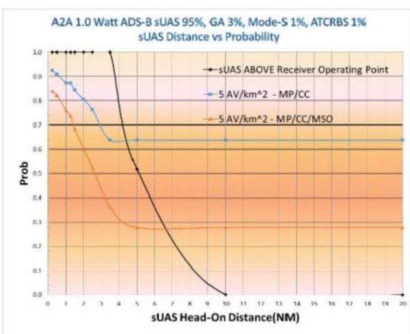


Figure 4 - A2A High Density 1.0W sUAS Transmit Power – Scenario 1

The <u>blue line</u> called 'MP/CC' represents the probability of closing the link when co-channel and multipath channel impairments are added. Finally, the additional MAC layer capacity performance (MSO collisions), once the link is closed after co-channel and multipath, is added. This is the <u>red line</u> called MP/CC/MSO which is the worst case probability of getting an ADS-B frame to the higher network layer levels of the receiver called 'Probability of Decoding'. It is important to note that once the sUAS's head-on distance is too long where the black link budget line is 5-10% or higher, the probability lines/curves retain their last value. This is because there are no more sUASs to cause more impairments than the last probability value measured.

Figure 5-Figure 7are the remaining High Density scenario plots that map worst case values in Table 3.

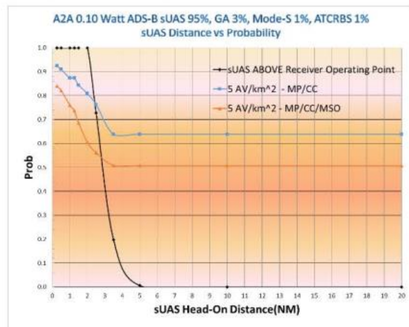


Figure 5 - A2A High Density 0.1W sUAS Transmit Power – Scenario 2

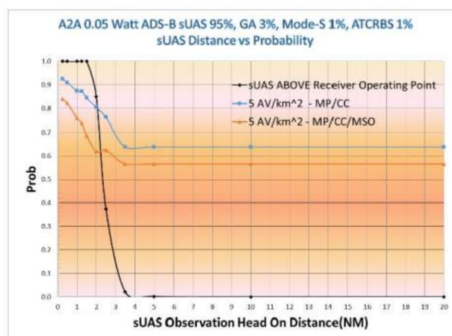


Figure 6 - A2A High Density 0.05W sUAS Transmit Power – Scenario 3

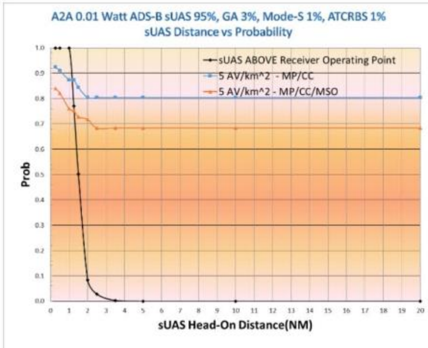
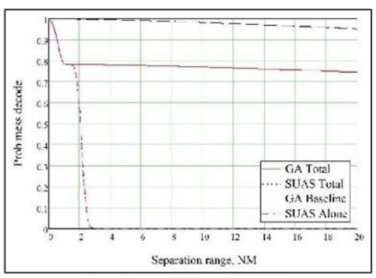


Figure 7 - A2A High Density 0.01W sUAS Transmit Power – Scenario 4

Figure 8 is Scenario 4 from [1]. When you compare the 0.78 'Probability message decode' to the GRC blue line which we assume is equivalent in meaning, they are very similar – 0.78 vs 0.80, but this does not include MSO collisions. When you add the additional MSO collisions probability, the actual 'Probability of Decoding' really is at a worst-case of 0.68 for a high density sUAS environment using 0.01W of transmitter power.



Shared-use UAT performance

Figure 8 – MITRE's A2A High Density 0.01W sUAS Transmit Power – Scenario 4

The GRC ADS-B model is a Monte-Carlo simulation that uses various channel algorithm models to estimate an Es/No value to close the link. This EsNo value is then compared to the ADS-B receiver operating point of 8dB Es/No, which per the standard, is sufficient to meet a BER of 1e-5 [2]. Figure 9 shows the tracking of the Es/No values that show best case and worst case Es/No receiver values. This plot is for Scenario 4.

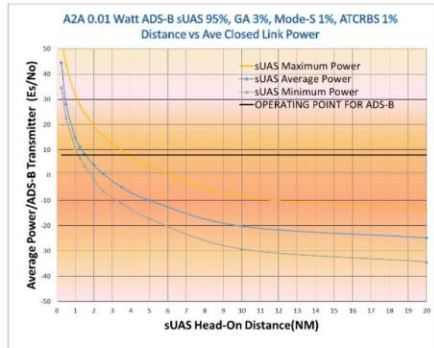


Figure 9 – Scenario 4 Average, Minimum, and Maximum Es/No Levels per sUAS Head-On Distance

Figure 9 shows, on average, any head-on distance between sUAS and any other type of ADS-B AV that is less than ~1.5nm will close the link. To be conservative as what is reflected in the table, the minimum curve is used, thus 1.0 nm will guarantee the 'closing of the link' 100% of the time. Of course, we will need to see what the ADS-B MSO collision probability is at this point to ensure that the frame will go through the MAC layer.

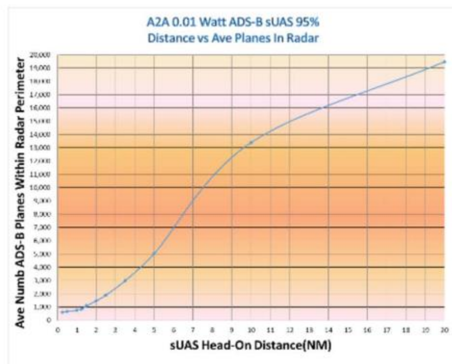


Figure 10 – Scenario 4 Average Number of ADS-B AVs Within Radar Range per sUAS Head-On Distance

Figure 10 shows how many average number of ADS-B AVs, which includes all sUASs and GAs, which are within each sUAS closing link perimeter.

2. Medium and Low Density Analysis

The remaining medium and low density analyses are shown in Table 4. Notice that the GRC simulations results are much more optimistic than those of [1] for 'Probability of Link Closing'.

Table 4 - A2A Worst Case Probabilities for Medium and Low Densities

	A2A							
	Medium sUAS Traffic				Low sUAS Traffic			
Scenario	5	6	7	8	9	10	11	12
Worst Case Prob of Decoding	0.48	0.70	0.79	0.84	0.55	0.66	0.72	0.95
Worst Case Prob of Link Closing	0.68	0.80	0.88	0.91	0.68	0.75	0.78	0.98
From Mitre Table	<0.25	0.27	0.48	>0.78	0.25	0.68	0.8	>0.8
sUAS Distance MAX	3.5	2.0	1.5	1.0	3.5	2.0	1.5	1.0
	BLOS	BLOS	LOS	LOS	BLOS	BLOS	LOS	LOS

B. A2G Analysis

The A2G analysis is very similar to the A2A analysis except, the ground station is considered to be always at low altitude, thus the multipath interference will be more constant. See Tables 5and 6.

Table 5 - A2G Worst Case Probabilities for High Density

	A2G			
	High sUAS Traffic			
Scenario	1	2	3	4
Worst Case Prob of Decoding	0.14	0.28	0.40	0.51
Worst Case Prob of Link Closing	0.18	0.33	0.52	0.60
From Mitre Table	<.25	<.35	<.1	0.38
sUAS Distance MAX	3.5	2.0	1.5	1.0
	BLOS	BLOS	LOS	LOS

Table 6 - A2G Worst Case Probabilities for Medium and Low Densities

	A2G							
	Medium sUAS Traffic				Low sUAS Traffic			
Scenario	5	6	7	8	9	10	11	12
Worst Case Prob of Decoding	0.30	0.48	0.60	0.74	0.72	0.78	0.81	0.89
Worst Case Prob of Link Closing	0.38	0.58	0.72	0.82	0.85	0.89	0.91	0.92
From Mitre Table	<.25	<.35	0.1	0.58	0.25	0.35	0.5	0.82
sUAS Distance MAX	3.5	2.0	1.5	1.0	3.5	2.0	1.5	1.0
	BLOS	BLOS	LOS	LOS	BLOS	BLOS	LOS	LOS

Again, the GRC simulation has a more optimistic worst case probabilities of closing the link.

C. DAA Analysis

The following analysis is for DAA algorithm utilizing ADS-B technology. The statistics that are being derived for the Probability to *From a Track* – A2G only. The definitions of the DAA parameters were defined in the above section. The P(Form a Track) cannot be captured as a closed form equation, thus simulations are run to capture this DAA statistic.

The first DAA simulation varies the total number of AVs between 100 and 3,000 only utilizing ADS-B technology and is run for a total of 180 seconds, where each ADS-B transmitter will send out its automatic message every second. The 4 defined ADS-B power levels are equally split per ADS-B level categories of 3, 2, 1, and sUAS. Thus, if there a total of 1,000 AVs, 250 AVs are dedicated to ADS-B power level 3 which is 250W. This mix of sUAS to NAS-type GA aerial vehicles, in this task simulation, are 75% GAs to 25% sUASs all equally randomized across a 100NM radius. This is to contrast the previous approach. Due to the larger radar perimeter regions of GA transmitter power levels, most GAs will communicate with the ground station, but not all sUASs will due to their limited ~1nm radar perimeter. Again, all AVs are enroute radially to the center where the airport/ground station is placed. For clarity, an example of 1000 AVs parameters are shown in Table 7. Since there are larger powered transmitters in the region, the total number of AVs being detected by the ground station will be close to the total from the beginning of the simulation. Once the simulation begins and the simulation comes close to the 180th second since all AVs are enroute and radially flying towards the center of the plot, it would be probable that all AVs are being detected by the ground station.

Table 7 - A2G DAA Simulation Input Parameters

ADS-B Level	Power(dB)	Amount Randomly Placed Within 100-5NM Radius	AGL(ft)	Speed (NM/hr)
3	24	250	20000	300
2	20	250	20000	300
1	14	250	20000	300
sUAS	-20	250	50-500	50

Table 8 shows the results of the P(Form a Track) as we adjust both, increasing AVs and increasing *MaxSetSize*. For example, when MaxSetSize=1, this means that it only takes one Received Message to form a track. We can double-check the situation when AVs=1000 and MaxSizeSet=1 the following way. Since all planes have ADS-B technology, we can refer to the 'co-channel interference' plot and the 'first time MSO collision' plot to validate the P(Form). From looking at the co-channel interference plot first, ~13% of the AVs do not make it through. Thus, there remain 870 AVs that have to compete for MSOs. The '% of First Time MSO Receiver Collisions' for 870 AVs is ~12%. Finally, even though 1,000 AVs are randomly placed within the 100nm radius, not all AVs will be captured by the ground station, especially since the power of the sUASs is only 0.01W. So, when taking that small percentage off the total, the P(Form) matches the simulation's computed output of ~77%. Unfortunately, this double check cannot be done for MaxSetSize>1 due to more intense combinational computations. Thus, the reason for a simulation, since a reasonable closed form approach cannot be created.

The simulation results in Table 8 show that as we increase the MaxSetSize variable, the P(Form) always increases. However, by increasing the MaxSetSize value, the DAA algorithm eventually will not be able to detect the incoming AV as quickly, since we are spending more time to ensure that the probability of forming a track is increased. These are design decisions that will eventually need to be tested and implemented in real flight cases. The purpose of these simulation results is to display the estimated performance of DAA algorithms as we adjust certain parameters.

Table 8 - A2G DAA P(Form) – AVs vs MaxSetSize

MaxSetSize	1	2	3	4	5
ADS-B AVs	P(Form)	P(Form)	P(Form)	P(Form)	P(Form)
100	97%	100%	100%	100%	100%
200	94%	100%	100%	100%	100%
300	92%	99%	100%	100%	100%
400	90%	99%	100%	100%	100%
500	87%	98%	100%	100%	100%
1000	77%	95%	99%	100%	100%
1500	68%	89%	96%	100%	100%
2000	60%	84%	93%	98%	99%
3000	47%	54%	70%	81%	89%
4000	38%			38%	38%
5000	31%				

The 'Probability of First Time MSO Receiver Collisions' plot is shown in Figure 11 to display the difference between the estimated closed form equivalent [4] versus the GRC simulation output.

Now we analyze the P(Losing Track). We incorporate the initial step of forming a track, but now we add another DAA parameter called 'Kill Track' where depending on its value will alter the probability of retaining the track. For this analysis, 1,000 ADS-B AVs, all enroute, utilizing the same above simulation parameters. The 1,000 AV amount was chosen because when the DAA parameter MaxSetSize>1, a P(From) of 95%will occur. The simulation was run for 180 seconds where an MSO is created per ADS-B per second.

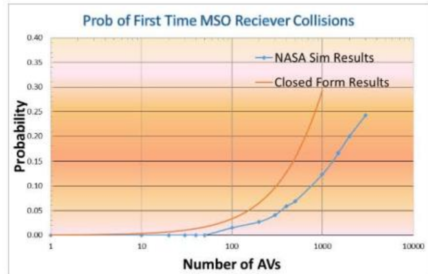


Figure 11 – Probability of First Time MSO Receiver Collisions

Table 9 - A2G DAA P(Losing Track)

MaxSetSize	measKillTrack	Prob_losing_Track
2	1	9.4%
3	1	8.8%
4	1	8.1%
5	1	0.0%
MaxSetSize	measKillTrack	Prob_losing_Track
2	2	5.1%
3	2	4.9%
4	2	4.7%
5	2	4.5%
MaxSetSize	measKillTrack	Prob_losing_Track
2	3	3.5%
3	3	3.4%
4	3	3.3%
5	3	3.2%
MaxSetSize	measKillTrack	Prob_losing_Track
2	4	2.6%
3	4	2.5%
4	4	2.5%
5	4	2.4%
MaxSetSize	measKillTrack	Prob_losing_Track
2	5	2.1%
2	6	1.7%
2	7	1.4%
2	8	1.2%
2	9	1.1%
MaxSetSize	measKillTrack	Prob_losing_Track
3	5	2.0%
3	6	1.7%
3	7	1.4%
3	8	1.2%
3	9	1.1%

As shown in Table 9, increasing the MaxSetSize from 2 to higher values does not affect the 'Probability of Losing Track'. It is very small difference, but it probability needs to be run longer to get the equivalent statistical value. We do notice by altering the 'Kill Track' parameter to higher values does affect the Probability of Losing Track.

The next DAA simulation will increase AV capacity. By looking at the previous data, the DAA parameter to close the Track will be held constant at MaxSetSize=2. The DAA parameter 'Kill Track' will be varied to an extreme. Due to higher capacity, simulation time has been reduced to one minute which may affect the statistical soundness.

Table 10 - A2G DAA P(Losing Track) with Increased Capacity

ADS-B AVs	MaxSetSize	measKillTrack	TimeRun(min)	Prob_losing_Track
1500	2	2	3	7.2%
1500	2	3	3	5.1%
1500	2	4	3	3.9%
1500	2	20	3	0.6%
ADS-B AVs	MaxSetSize	measKillTrack	TimeRun(min)	Prob_losing_Track
2000	2	2	3	9.0%
2000	2	5	1	3.0%
2000	2	6	1	3.1%
2000	2	8	1	2.1%
2000	2	20	1	0.1%
ADS-B AVs	MaxSetSize	measKillTrack	TimeRun(min)	Prob_losing_Track
3000	2	2	1	10.7%
3000	2	6	1	4.4%
3000	2	20	1	1.1%

For the highest capacity of AVs run of 3,000, the most feasible parameter setup not to lose tracking is measKillTrack=20, as shown in Table 10. But MaxSetSize must be increased to >5 to get to P(Form)>%90. But again, waiting 20 seconds and depending on speed of each AV, the DAA parameter may be too large for overall safety. A more itemized and critical analysis needs to be done to understand the best sweet spot per capacity amount.

VIII. Key Findings

There are two main tasks that were presented in this paper. The initial task was to simulate scenarios found in [1] concerning capacity in a mixed sUAS and GA environment and to compare results between the two implementations. Added to the first task was further inherent TDMA capacity performance called MSO collisions. Once the mixed sUAS capacity environment was analyzed up to the MAC layer environment, the second task was to begin DAA analysis using a simple algorithm found in [4].

A. Task 1 Key Findings

- The GRC simulation results – 'Worst Case Probability Closing Link' - do not match with the [1], are much more optimistic for all 3 density cases for both A2A and A2G results
- An 80% 'Probability to Decode' lower limit has been set by the author to identify worst case performance
- When adding the MSO collisions to the capacity to the simulation, the 'Probability to Decode' is always lower in percentage than the 'Worst Case Probability Closing Link' for both A2A and A2G results
- 68% 'probability to decode' for the lowest power sUAS transmitter of 0.01W in a high density A2A environment is not acceptable
- 51% 'probability to decode' for the lowest power sUAS transmitter of 0.01W in a high density A2A environment is not acceptable
- 84% and 95% 'probability to decode' for medium and low density A2A environments using the low power 0.01W transmitter is a plausible performance findings
- For A2G, only the low density 'probability to decode' for sUAS transmitter power levels of 0.01W and 0.05W have plausible performance results
- For a mixed sUAS/GA mixed environment due to the low power transmitters are able to meet the 80% 'probability to decode' cutoff, all sUAS are assumed to be within the Line of Sight (LOS) range – 1NM or less – for both A2A and A2G environments

B. Task 2 Key Findings

- For P(Form)≥99% with a capacity of ~1,000 ADS-B for A2G link, the DAA parameter MaxSetSize≥3. Thus, it will take 3 seconds to detect an ADS-B nearby transmitter
- For P(Losing the Track)≤1% with a capacity of ~1,000 ADS-B for A2G link, the DAA parameter KillTrack≥10. Thus, it will take 10 seconds for the ADS-B receiver to drop the nearby ADS-B AV

IX. Conclusion and Future Work

This paper presented ADS-B modelling that is being done at GRC. The model is constantly being improved from a computational efficiency, to validating its algorithmic results to ensure the probabilities being produced will hopefully closely mimic future real-world high capacity mixed environment scenarios.

As suggested in [1], for others to confirm their results, it is suggested to confirm this paper's results either in a similar algorithmic fashion or in a more efficient, less computational, closed form approach where higher capacity simulations can be found in a quicker timeframe. Now that this work has been published, it would be preferred to collaborate with interested parties to better various to identify the best results.

Due to the algorithmic approach that was taken with the GRC ADS-B capacity model, the results given are with confidence and are more optimistic than the results in [1].

For the DAA algorithmic probability analysis, more work needs to be done to better understand the performance. But at this time, the paper identifies parameter starting points for future real-time on-board DAA processing.

For future work:

1) Incorporate actual NAS and sUAS flight paths and speeds instead of using computer generated AV related data for speed, altitude, and flight path

2) Simulate various sUAS vs GA capacity mixes for A2A DAA simulations

3) Expand the simulation to accept ADS-B frames and extract information to run DAA algorithms with actual ADS-B data

4) Perform DAA A2A analysis similar to the DAA A2G analysis in this paper

5) Perform DAA analysis of speed, altitude, and angle using the ADS-B framed information to understand other DAA concepts as described in the DAA paper

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