Communicating with Unmanned Aerial Swarms using Automatic Dependent Surveillance Transponders

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***Abstract*— Suitably equipped air traffic can be tracked by decoding its Automatic Dependent Surveillance (ADS) Broadcast (ADS-B) signal. ADS is defined by initiatives in the U.S. through the NextGen program and in Europe through the SESAR program. ADS-B surveillance service in the U.S. comprises of the 1090 Extended Squitter (1090ES) that operates on 1090 MHz and the Universal Access Transceiver that operates on 978 MHz (978UAT). While 1090ES is used commercially and worldwide, UAT is a regional system used extensively in the U.S. for aircraft operating below 18000 ft. Since the ADS-B message contains aircraft state and intent information, ADS-B is a potential method for communication, navigation and surveillance of unmanned aerial systems (UAS) operating in low altitude. This paper describes and demonstrates a simulation tool developed to model ADS-B communication from UAS as a function of UAS and manned aircraft traffic, power of transmission, range between aircraft and operators, ping rate, maximum latency of aircraft state communication and required reliability of state information. Communication success is degraded with distance and due to collision with other ADS-B packets emitted by nearby aircraft in Mode S, A and TCAS, while broadcasting or communicating to different ground stations (False Replies Unsynchronized In Time or FRUIT). The model and its results on surveillance sensitivity to key parameters, are expected to inform the NASA UAS Traffic Management research, about the benefits and limitations of ADS-B utilization for high density UAS operations.**

Keywords—Unmanned Aerial Vehicles, Automatic Dependent Surveillance - Broadcast (ADS-B), Communication, Surveillance

I. Introduction

Automatic Dependent Surveillance[1] transponders allow the surveillance of airplane states using a communicative on-board unit, instead of relying solely on traditional radar-based surveillance systems. It is currently functional under the Broadcast (ADS-B) and the Contract (ADS-C) protocols. The ADS-B signal is emitted from the aircraft's Mode-S or C, transponder to provide surveillance data. The *surveillance* data includes aircraft position, velocity, as determined from a Global Navigation Satellite System, and additional elements of navigational intent and meteorological data. The aircraft information is *automatically* transmitted periodically without flight crew or operator input. The transmission is *dependent* on proper operation of on-board equipment that determines state and availability of a sending system. ADS-B applications broadcast the data to anyone listening, traditionally other suitably equipped aircraft or ground stations, which allows Air Traffic Control to automatically and periodically access data for use and re-broadcast (called ADS-R). Space-based ADS-B receivers have demonstrated the ability to relay messages received from manned aircraft in remote locations, to ground stations[2], [3].

The Federal Aviation Administration (FAA) forecasts seven million small unmanned aircraft systems (UAS) [4] to be operational by 2020, of which 2.6 million will be commercial. NASA postulates the demand for low-altitude UAS to rise for a variety of applications including infrastructure monitoring, precision agriculture, search and rescue, and delivery of goods. The NASA UAS Traffic Management (UTM) project is a systemic research approach to prototype technologies for a traffic management system that could develop airspace integration requirements for enabling safe, efficient low-altitude operations. Research results will be transferred to the FAA for further testing. ADS-B transponders are being considered a potential method of UAS surveillance and recent studies have shown the major impact of co-channel interference from UAS on General Aviation (GA), especially for high density operations[5],[6]. This paper presents a model for computing probability of successful ADS-B message reception, given transponder power, receiver sensitivity, ADS-B protocol parameters, UAS and GA traffic densities and squawk power, allowed latency, repeat frequency, range between transponders and ground station distribution. Results are expected to inform the bounds for UAS operations within national airspace.

II. Communication Modeling Methodology

The 1090-ES ADS-B Reception model, developed by NASA Langley Research Center for manned aviation, as presented in [7], has been used as a starting point for our UAS communication model because its results have been validated against reception parameters from a 1999 flight test data. Our model uses different parameters and standards for UAS flight, models probabilistic impact of repeated messaging and investigates trade-offs between many operational scenarios.

A. Validated Model for Manned Aviation Communication

ADS-B reception probability is modeled as a discrete convolution of Poisson random variables for the 1090 MHz channel[7]. This channel is also used by aircraft to respond to the Traffic Collision Avoidance Systems using Mode S or C transponders and secondary surveillance radars (SSR) of the Air

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Traffic Control Radar Beacon System using Mode A and C transponders. The model allows for up to five ATCRBS and one Mode S FRUIT overlaps, as specified in RTCA document DO-260A. ADS-B single message reception probability (p) is:

$$p = [d(0)P(0;m_A)P(0;m_S)] + \left[\sum_{x=1}^{5} d_A(x)P(x;m_A)\right]P(0;m_S) + [d_S(1)P(1;m_S)]P(0;m_A) + \left[\sum_{x=1}^{5} d_A(x)P(x;m_A)\right][d_S(1)P(1;m_S)] \quad (1)$$

P(x;m) is the Poisson probability of x given m FRUIT overlaps, m is the mean FRUIT Mode A/C or S overlaps (computed as function of number of aircraft within receiving distance and number of interrogators with appropriate beams) and *d(x)* is the single message decode probability with *x* FRUIT overlaps. The model cleanly separates *d(x)* as a function of transponder power, range and sensitivity and *P(x;m)* as a function of other/secondary air traffic in the area and their power ('noise').

B. *Adapted Model for Unmanned Aviation Communication*

The single message decode probabilities in Eq. (1) are computed using minimum receiver sensitivity and success criteria for block tests, set by DO-260A for Class A3 ADS-B on UAS. Mean FRUITs use SSR density data from [7] since only manned aircraft will be interrogated. State reports are set at 2Hz for 1090ES and 1Hz for 978UAT. The probability of successful reception increases with the repeated pings (y in number) and is given by binomial probability (P) as:

$$P = 1 - (1-p)^y \quad (2)$$

We use the traffic densities in [5] as representative examples of high traffic. We assume a 2D model and density because the height of the cylindrical volume in [5] is very small compared to the diameter. If the availability of ADS-R is assumed, traffic can be up to double of that shown, for those aircraft that have signed up for ADS-R, TIS-B and FIS-B client services.

III. UAS Communication Results

The results from varying the key parameters show that only <1W transponders on UAS will allow reliable communication using ADS-B, given the assumed traffic. They set upper bounds for allowed traffic, given power and reliability. Nautical miles (NM) are standard units in the FAA. Integrating ADS-B into the UTM also requires that receivers be available within reception range. While online crowdsourced data show ~600 ground receivers in the continental U.S., our tests indicate the need for more, to support high density, beyond line of sight operations.

A. *Instantaneous and Binomial Probability of Reception*

For a uniform density of UAS and GA in an area, squawking at 10W and 25W respectively, the probability of an ADS-B receiver decoding any packet from another ADS-B transmitter depends more steeply on the traffic density than the transmitter power - Figure 1. Secondary traffic's power ('noise') is varied independent of primary transmitter power in this section for representative purposes. While range increases with transmit power, positive probability of message decode is possible only up to 1.74 UAS per sq. NM if they transmit at 10W. The number of message repeats required to transmit with 1σ,2σ, 3σ reliability increases with traffic and range, for any transmit power, to make up for lowering instantaneous probability - Figure 2. Sensitivity to GA is negligible due to its relatively low traffic.

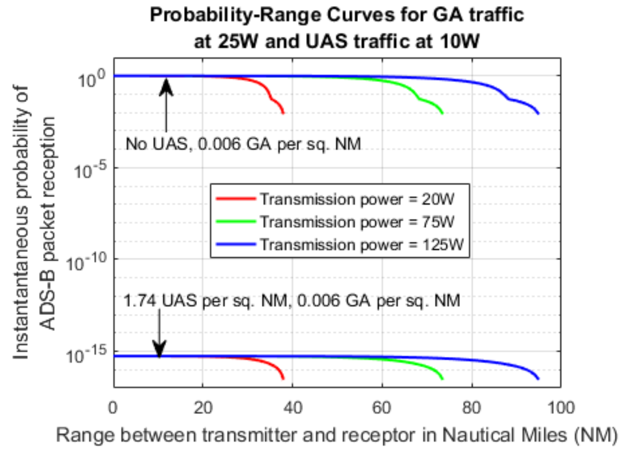

Figure 1: Packet decode probability with increasing power, traffic

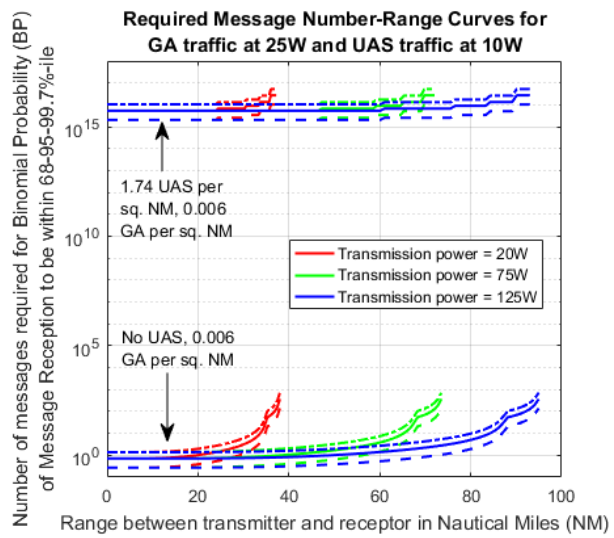

Figure 2: Number of messages required such that the cumulative packet decode probability is 68% (dashed line)-95% (solid line)-99.7% (dot-dashed line), with increasing power and traffic

B. *GA Decode Sensitivity to UAS Traffic and Power*

The NASA-FAA Research Transition Team has set a tentative upper limit of 10 seconds of no update on the primary communication link, after which UAS operators are required to activate their secondary or execute procedures to mitigate loss of link. In this section, we assume successful transmission if the state is communicated at 2σ reliability within 20 messages (2Hz). An ADS-B transponder with power 125W (or 25W) on a manned aircraft/GA has a maximum transmission range of 96NM (or 42NM) when there are no squawking UAS in the area - Figure 3. Increasing UAS traffic and power reduces the effective range drastically, more so if the GA transmit power is lower. Since the FAA has mandated all aircraft flying in most controlled airspace to be ADS-B 1090ES equipped by 2020, allowing dense UAS traffic on this frequency poses a risk to the full effectiveness of that mandate. The theoretical upper limit of UAS traffic density such that GA ADS-B messages can be decoded decreases with GA and UAS power because the GA and UAS traffic noise increases - Figure 4. This limit is almost insensitive to transmit power, if it is increased independently from traffic 'noise' power.

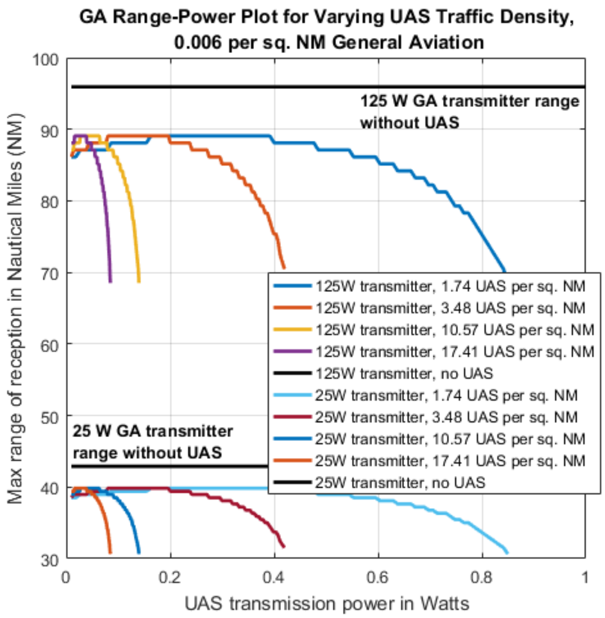

Figure 3: Allowable range between GA ADS-B transmitter and receiver to ensure 95% probability of state update within 10 seconds

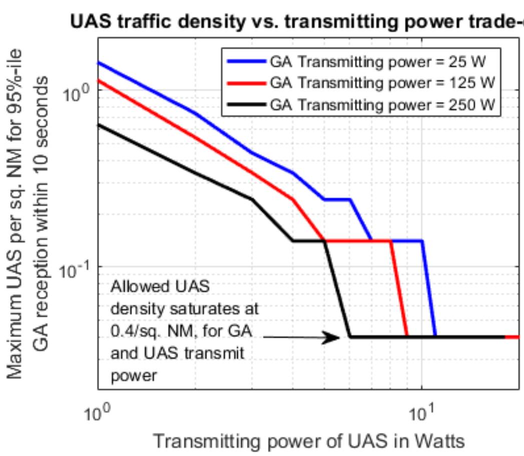

Figure 4: Allowable UAS traffic per GA transmitter power, assuming GA traffic has the same power and variable UAS traffic power

C. *UAS Decode Sensitivity to all Traffic and Power*

Message collision interference from dense UAS traffic was found to be of concern for UAS communication as well, therefore will affect traffic allowed on 978UAT. The maximum range between any pair of ADS-B transmitter and receiver on UAS such that there exists 95% probability of decoding each other's state within 10 seconds, increases with UAS transmit power and, after an inflexion point, drops off drastically due to message interference - Figure 5. This inflection occurs at shorter ranges for denser traffic. For example, at 17.41 UAS per sq. NM, there is no gain in range for transmit power more than 0.06W and no reliable reception more than 0.085W. For the least dense case of 1.74 UAS per sq. NM, a maximum range of 5.8 NM is possible at transmit power 0.68W and decode reliability drops to less than 95% at power 0.14W. If GA traffic is removed from this simulation, the maximum range and thus transmit limit is only slightly higher, e.g. 6.2NM at 0.73W. The model helps set a theoretical upper limit to UAS transmit power given expected traffic, and vice versa.

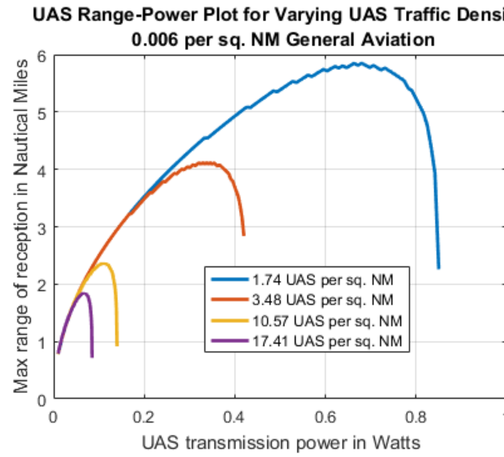

Figure 5: Allowable range between UAS ADS-B transmitter and receiver to ensure 95% probability of state update within 10 seconds

IV. Discussion

Our results show that UAS ADS-B can be used for vehicle-to-vehicle/ground surveillance only at very low power and short distances, given the traffic numbers assumed, beyond which it will adversely affect manned aviation surveillance and itself.

The results presented are a function of ADS-B protocol and UAS operational examples. If the protocol for ADS-B were to allow more frequent updates, variable message lengths or exclusive GA/UAS traffic, or if sense-and-avoid operations were to allow more latency time for state updates, or any other traffic changes, they could relax the power and density limits presented. Our model allows for easy change of parameter values to test the impact of such protocol, power, traffic or operational changes on the integration of ADS-B or similar technologies with UAS.

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