2012 IEEE/ACM Third International Conference on Cyber-Physical Systems

Investigating Communication Infrastructure of Next Generation Air Traffic Management

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***Abstract*—Growing demand for use of the National Airspace System (NAS) has resulted in research and development programs to modernize the air traffic control system. The primary focus of the US FAA's Next Generation Air Transportation System (NextGen) plan is to transform the air transportation system into a more flexible, adaptive, and highly automated system capable of handling two to three times the current traffic. According to the NextGen plan, Automatic Dependent Surveillance - Broadcast (ADS-B) is designed to improve the safety, capacity, and efficiency of the NAS. ADS-B works by broadcasting flight information such as the flight number, position, speed and intent using satellite-based navigation systems, to other aircraft or air traffic control facilities. Our research interests focus on the interoperability of the ADS-B data link with existing surveillance systems and operational ability of ADS-B to assist the flight crew by meeting safety assurance. Because the NAS involves a multitude of interacting agents and technologies, the high complexity of integrated sensing and decision support for the air traffic control is the main challenge. We have developed a simulation environment which includes an air traffic model, existing surveillance systems, ADS-B systems, and wireless channel model. The critical issue of the interoperability and collaboration between existing systems and ADS-B is validated. Two parts of the interference issue are analysed: (1) interference from ADS-B to existing systems, and (2) interference from existing systems to the ADS-B. It is shown that ADS-B meets the performance requirements of both air-to-ground and air-to-air ranges. Furthermore, the effect of ground surveillance systems and aircraft density to the ADS-B performance along the flight path is analysed.**

***Index Terms*—Air Traffic Control, Surveillance System, Automatic Dependent Surveillance - Broadcast.**

I. Introduction

Future National Airspace System (NAS) capacity is one of the major challenges facing the Federal Aviation Administration (FAA) in the next decades. According to the Next Generation Air Transportation System (NextGen) plan, air traffic is expected to grow two to three times the current levels by 2025, and the current system is not expandable to those levels of traffic [1]. The air traffic system must be capable of handling this increased traffic, otherwise delays and flight cancellations will become more common. Furthermore, current radar systems are expensive to maintain, are subject to terrain blockage, and cannot provide coverage in areas where there is no line of sight. Since general aviation operators tend to fly at low altitude, they are often outside of radar coverage [2].

The air traffic control (ATC) system is networked to reap the benefits of shared information such as the flight number, position, and speed of aircraft. It is a prime example of a cyber-physical system in which computation for sensing, monitoring, control, and optimization are tightly coupled with the actions of the aircraft themselves

Automatic Dependent Surveillance - Broadcast (ADS-B) is designed to increase the safety, capacity, and efficiency of the NAS by enhancing information sharing between aircraft and ATC facilities [3]. A cornerstone of ADS-B is the increased reliance by using satellite-based navigation systems such as the Global Positioning System (GPS). With satellite navigational data, the position of an aircraft can be derived for each vehicle, and this information can be transmitted via a data link to any aircraft or ground stations to support the surveillance of aircraft. The use of onboard sensing to enable more dynamic and flexible aircraft operations will be an essential component to achieve a more robust and efficient air transportation system.

Since a radical change in the current radar-based surveillance system is not an option for the FAA, the system has to rely on both current equipment and ADS-B equipment harmoniously. As the density of ADS-B equipped aircraft grows, the increased interference levels could adversely affect the performance of existing surveillance systems. It is important to ensure that the signals transmitted by ADS-B avionics do not degrade the ability of existing ground surveillance systems, in particular, to manage their shared use of the 1030/1090 MHz frequencies. On the other hand, the interference effect of existing surveillance systems is also critical to guarantee the performance requirement of ADS-B systems.

One of the most important tasks of the air traffic controller is to prevent loss of separation between aircraft. The introduction of ADS-B systems into the NAS is hampered because the current surveillance requirements to support separation services assume surveillance provided by radar technology. Currently, it is not known whether ADS-B would meet the ATC requirements.

Two of our fundamental research interests are on the interoperability between existing surveillance systems and ADS-B systems and operational ability of ADS-B systems to assist the flight crew by meeting safety assurance and other application requirements in future terminal environments. The structure of the NAS is complex since it involves a multitude of interacting agents and technologies: aircraft monitoring, flow management, communication, and human-in-the-loop. The high complexity of integrated sensing and decision support for

978-0-7695-4695-7/12 $26.00 © 2012 IEEE
DOI 10.1109/ICCPS.2012.12

air traffic management is the main challenge. In particularly, a critical aspect is the need to accurately model the surveillance system and the coupled dynamic interactions among aircraft and air traffic controllers.

This paper focuses on the modelling and performance evaluation of ADS-B in the future terminal environment. The main contributions of the paper are the following: (1) a unified simulation environment considering the physical details of the air traffic model, flight path, and surveillance system, which are networked through wireless channels, (2) the validation of the interoperability between existing systems and ADS-B, (3) the evaluation of the operational ability of ADS-B by meeting separation assurance and other application requirements. Our simulation development includes the departure and arrival rates of the air traffic model, relative geometries of the flight path, surveillance systems including exiting radar systems and ADS-B, and 1030/1090 MHz channel model.

The remainder of this paper is organized as follows. In Section II, we give a brief overview of the air traffic surveillance system, where we describe the ground and airborne surveillance system. In Section III, we summarize existing work for ADS-B systems. Section IV describes the system model including the air traffic model, flight path, surveillance system, and wireless channel. In Section V, we present expected performance of ADS-B in several possible future scenarios. Finally, Section VI concludes the paper.

II. Overview of Air Traffic Surveillance System

In this section we give an overview of the key components of air traffic surveillance systems. The ATC system includes information gathering by a group of heterogeneous sensors. The air traffic surveillance system can be divided into two categories, ground and airborne surveillance system.

A. Ground Surveillance System

Ground radars scan through 360 degrees of azimuth and present target information to ATC facilities. Ground surveillance systems currently consist of two major systems, primary and secondary surveillance radars (SSR). The primary surveillance radar tracks aircraft by reflecting radio waves off aircraft, while SSR interrogates aircraft transponders which respond with aircraft information. The interrogation from SSR is transmitted to aircraft in the 1030 MHz band and the confirmation of reception is replied in the 1090 MHz band. Since the ADS-B operation shares the 1090 MHz channel with SSR replies, we focus on SSRs.

With the SSR system, each aircraft is equipped with a transponder which replies to interrogations from ground radars with unique data [4]. SSR is a dependent surveillance technology since a functional transponder is required on the aircraft to be observed by SSRs. The exact message, which is sent by the aircraft, depends on the SSR mode. There are three important SSR modes: Mode-A, C, S. Mode-A transponders reply with a 4 digit code, Mode-C transponders reply with a 4 digit code along with altitude, Mode-S transponders reply with a 4 digit code, altitude, identifier, along with data needed for collision avoidance functions. Normally only one code will be assigned for the entire flight.

The interrogator of Mode-A, C sends three pulses: P_1, P_2 and P_3. P_1 and P_3 can be seen as the most important signals since the interval between them determines the reply format. Mode-A is used, when the interval between the P_1 and P_3 pulses is 8μs. The transponder replies with the aircraft identification code 12 bits, which is defined by the ATC facility. When the interval between the P_1 and P_3 pulses is 21μs, Mode-C is used. The transponder of Mode-C replies with the aircraft flight level. The reply of both Mode-A, C takes 20.3μs. The SSR computes the angle-of-arrival of the signal and the delay between the transmission of the interrogation and the reception of the reply, allowing the SSR to determine the azimuth and the location of the aircraft.

Since all equipped aircraft in the antenna mainbeam respond to each interrogation of Mode-A, C, replies from aircraft with nearly identical ranges will overlap at the interrogator receiver. This phenomenon is called synchronous garble. This happens especially when a large number of aircraft are located in a small area. Synchronous garble is managed in the ground system by using a narrow antenna beam and by restricting each sensor to the absolute minimum range required for ATC purposes. Typical SSR halfpower azimuth beamwiths are about 4 degrees. Sliding-window technology achieves about 18 replies during the halfpower beam dwell or, due to the link budget margin, about 24 replies at the typical 6 dB beam dwell. Monopulse technology can operate with one fourth this rate.

The selective addressing of Mode-S provides a natural mechanism for a data link to support air traffic service applications [5]. Mode-S uses the same frequencies as Mode-A, C for interrogations and replies (1030 and 1090 MHz, respectively). Each aircraft is assigned a unique 24 bit address code which permits data link messages to be transferred along with surveillance interrogations and replies. The Mode-S interrogation consists of a two-pulse preamble plus a string of 56 or 112 data bits (including the 24 bit address) transmitted using binary differential phase shift keying (DPSK) at a 4 Mbps rate. The reply also comprises 56 or 112 bits including address, and is transmitted at 1 Mbps using binary pulse-position modulation (PPM). The use of monopulse, together with a more capable message structure that provides altitude and the Mode-S address in a single reply, makes it possible to perform routine surveillance with one transaction (i.e., interrogation/reply) per scan. The narrow beam ($2.4°$) is used by Mode-S sensors. Mode-S supports the reliable surveillance and communication by using the parity coding scheme.

The secondary radars can be further sub-divided into terminal and en-route radars. Terminal radars, have a faster update rate for terminal operations near airports, but cover a smaller geographic area. En-route radars have a slower update rate, yet cover a much larger geographic area.

B. Airborne Surveillance System

Both primary and secondary radars are very large structures that are expensive to deploy and need lots of maintenance.

Instead of relying on costly radar technology, the airborne surveillance system has the potential to reduce costs and give the FAA greater flexibility. The airborne surveillance system can provide immediate protection against collisions involving a significant and growing fraction of the aircraft population. Furthermore, some airborne surveillance systems receive data directly from transmitters, rather than passively scanning for input like radars, so that clutter is avoided. We describe two representative airborne surveillance systems: Traffic Alert and Collision Avoidance System (TCAS) and ADS-B.

1) Traffic Alert and Collision Avoidance System: The main functions of TCAS[1] are to identify a potential collision threat, communicate the detected threat to the pilot, and assist in the resolution of the threat by recommending an avoidance maneuver [6]. This is applied if ATC fails to maintain separation via clearances. The TCAS is a beacon-based airborne collision avoidance system that is able to operate in all airspace without reliance on ground equipment.

A TCAS installation can conceptually be divided into two subsystems, surveillance and control logic. TCAS works by one aircraft interrogating other aircraft transponders. This way, each TCAS equipped aircraft can locate nearby transponder equipped aircraft, and potential collisions can be detected. Surveillance of the air traffic environment is based on air-to-air interrogations broadcast once per second from antennae on the TCAS aircraft using the same frequency (1030 MHz). Transponders on nearby intruder aircraft receive these interrogations and send replies at 1090 MHz. Two types of transponders are currently in use: Mode-C transponders, which do not have unique addressing capability, and Mode-S transponders, which have a unique 24 bit identifier. To track Mode-C intruders, TCAS transmits "Mode-A, C-only all-call" interrogations once per second. All Mode-A, C equipped aircraft in a region around the TCAS aircraft reply. TCAS sends interrogators using a four-beam directional antenna with 90 degree beams. TCAS computes slant range on the basis of the round-trip time of the signal and estimates the bearing to the intruder by using a four-element directional antenna. In contrast, Mode-S equipped intruders are tracked with a selective interrogation once per second directed at that specific intruder by listening the squitter. Note that Mode-S transponders send out spontaneous signals known as 56-bit squitters. All aircraft with TCAS are equipped with Mode-S transponders. Selective interrogation reduces the likelihood of overlapping replies, and also reduces frequency congestion at 1030/1090 MHz. Without reliance on ground equipment, TCAS is capable of providing resolution advisories in the vertical dimension (climb, descend) in airspace.

2) Automatic Dependent Surveillance - Broadcast: ADS-B is a replacement (or supplement to) for traditional radar based surveillance of aircraft. ADS-B uses satellite-based navigation systems to determine an aircraft's precise location in space. The system then converts the position into a digital code, which is combined with other information such as the type of aircraft, flight number, speed, and intent. An ADS-B equipped aircraft broadcasts its information through an omnidirectional fashion, and any aircraft or ATC facility can receive this information. These broadcasts are not in response to interrogations, unlike existing transponder technology. ADS-B transmission occurs at much lower rate than SSR replies. Note that ADS-B cannot replace existing SSRs, until all aircraft are equipped with ADS-B equipment to broadcast state vector information. ADS-B will most likely be mandated in airspace where Mode-C transponders are currently required [2].

In the United States, ADS-B will employ two different data links: one uses the Mode-S Extended Squitter (Mode-S ES) [7], intended primarily for commercial aircraft flying at or above 18000 ft, and the second uses a UHF data link known as the Universal Access Transceiver (UAT) [8], designed for small general aviation aircraft. Since we are concerned on operators flying at high altitude, we focus on Mode-S ES. The European Union will also employ Mode-S ES [9].

The concept of Mode-S ES is to use the existing Mode-S signal format, including the wireless channel, data rate, modulation, preamble, and pulse shape [5]. The carrier frequency is 1090 MHz $+/-$ 1 MHz. The waveform is a PPM with a data rate of 1Mbps. There are two types of broadcast from an aircraft: the short squitter and the extended squitter. The short squitter has a length of 56 bits with its unique Mode-S address. Each Mode-S transponder broadcasts in an omnidirectional azimuth pattern once per second at the reply frequency of 1090 MHz. The extended squitter also transmits a 56 bit data field which contains additional information for the ADS-B i.e., the total frame length is 112 bit. A transmitted message includes a preamble so that a receiver can detect the beginning of the message and can synchronize on the data in the message. The preamble consists of 4 pulses and each message contains 24 parity bits, which can be used for error detection or correction.

According to the ADS-B Minimum Aviation System Performance Standard (MASPS) [3], the transmitter power levels for Mode-S ES are described in Table I. Receiver sensitivity is characterized by the Minimum Triggering Level (MTL). MTL is defined as the power level of a received signal for which correct reception is 90% reliable in the absence of interference. Standard values for receiver MTL are shown in Table I.

The Mode-S ES uses a random time multiple access technique due to the interference of existing systems. Whereas each type of message is transmitted in a pattern that is nominally periodic with a standard rate, the transmission times are deviated slightly using a pseudo random process. Specifically, a timing jitter uniformly distributed over a range of $+/-$ 100 ms is applied to each transmission. This jitter is much larger than the duration of each message, so that synchronous interference effects are avoided.

The squitter broadcast is extended to 112 bits to provide for the transmission of a 56 bit ADS message field, with all other fields remaining the same as in the shorter 56 bit format. Aircraft equipped with a Mode-S transponder and a

[1]We give a functional overview of TCAS II rather than TCAS I since TCAS II is intended to provide a comprehensive level of separation assurance while TCAS I provides proximity warning only without any recommendations of avoidance maneuvers.

GPS receiver determine their position once every second (1 Hz). This position information is inserted into the 56-bit ADS message field of the long squitter. The information of ADS-B such as the type of aircraft, flight number, position, speed, and intent, is updated several times a second and broadcast from the aircraft on a discrete frequency as an extended squitter. The basic position-velocity information is broadcast as follows. Position and velocity messages are transmitted at a rate of 2 messages per second. Note that this system uses separate broadcast messages to convey aircraft position and aircraft velocity information. Aircraft identity is transmitted once per 5 seconds. Because an aircraft's identifier is fixed for the duration of a flight, the identifier is provided in a separate format only once every 5 seconds.

III. Related Work

A number of different organizations estimate the performance of Mode-S ES by applying different tools. Analysis tools to validate the performance of Mode-S ES are as follows: real test measurement, simulation, and analytical models. We summarize the performance analysis efforts of ADS-B by different organizations.

Previous field measurements have presented the interrogation and reply rates by 1090 MHz receivers [10], [11]. MIT Lincoln Laboratory provides a quantitative assessment of the existing interference environment at 1090 MHz and the surveillance performance of Mode-S ES in the Los Angeles Basin [12]. A wide range of scenarios is captured to measure the airborne and ground-based reception of Mode-S ES emitted by aircraft. Air-to-air ranges of greater than 100 NM are routinely observed. FAA and EUROCONTROL take measurements of the overall 1090 interference rate from Dublin, Ireland, to Frankfurt, Germany [9]. Mode-A, C reply rates as high as 40000 per second above -90 dBm are measured. It is also shown that the interrogation rates outside of the terminal areas are relatively low.

The performance of Mode-S ES physical layer is evaluated by two simulation tools that have been developed by MIT Lincoln Laboratory [9]. The first tool is a pulse-level simulation, whose output gives the probability of correct reception of an extended squitter signal as a function of signal power. The second tool is a track-level simulation, whose input is the per-squitter reception probability from the pulse-level simulation, and whose output gives the performance over a time period such as 12 seconds. When applied to long-range air-to-air surveillance, this simulation can determine the maximum range at which 95% or more of the targets are being received sufficiently reliably to be in track as required by the ADS-B MASPS [3]. The co-channel interference from SSR and TCAS is not considered.

EUROCONTROL [13] uses the Constant Interrogation Rate (CIR) model originally developed by Helios Technology [14]. The CIR model assumes a constant interrogation versus altitude profile that is applicable to all aircraft in the scenario. The profile is selected so that CIR in the stressful environment scenario matches the trial measurements. A log of 1090 MHz transmissions is generated on the basis of this profile for each aircraft, taking into account its transmit power, cable losses, and antenna gain [15]. Monte Carlo techniques are used to determine the effective track update period distribution per target and per distance from the receiver.

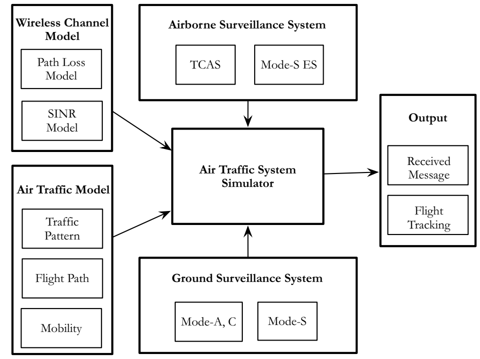


Fig. 1: Diagram of air traffic system simulation.

The analytic assessment of the expected capability of Mode-S ES in future operational environments involves cascaded use of a series of different models [16]. Received signal levels reflect the effects of both free space path loss and channel variations. The desired extended squitter message competes with co-channel interference defined by the air traffic distribution surrounding the receiver and co-channel transmit rates of these aircraft. Parametric fits to available bench data provide the decoder and receiver sensitivity models. Overall link performance is represented by the variation in probability of correct extended squitter message decode as a function of separation range for specified percentages of the traffic load.

The interference level from SSR depends not only on the flight altitude, but also on various parameters such as the flight path, air traffic scenarios, ground surveillance systems, and aircraft equipment. However, the interference models [13], [16] are hard to generalize because the parametric fit of the interference profile requires calibration by comparing with measurements for different scenarios. The real measurement is expensive and location specific. Furthermore, none of these studies considers realistic air traffic models and ground surveillance systems. Plan views of traffic distributions around high-activity areas are assumed to have Gaussian features in orthogonal directions [13], [16]. However, this assumption does not hold for general scenarios as we will discuss in Section IV. If more complex features (non-Gaussian) are modeled, the approaches [13], [16] become increasingly difficult to obtain an analytical solution. In addition, aircraft movement effects are not properly taken into account, e.g., the aircraft remain static in the duration of the simulation run. It is critical to consider realistic flight paths and ground surveillance systems because received signal levels reflect the effects of both path loss and variations due to air-to-ground and air-to-air antenna gain differences associated with relative aircraft orientation.

IV. System Model

Our system model simulates a flight through a modeled airspace and measures statistics on the results. The process

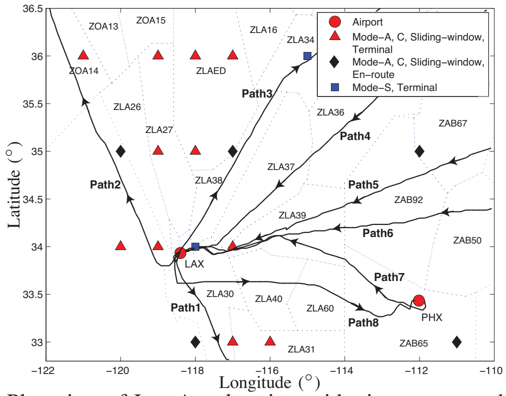


Fig. 2: Plan view of Los Angeles sites with airports, ground radars, and flight path. A number of ATC sectors are used for this study around the LA ARTCC (labeled above as ZLA30, etc.). The flight trajectories are taken from FACET [17].

and its inputs are illustrated in Figure 1. The traffic scenarios and operational environment represent a series of assumptions regarding the number and distribution of the participating aircraft and ground radars. Each analysis tool also incorporates a wireless model for the behavior of a Mode-S ES receiver in the presence of co-channel interference. For example, the traffic scenarios control the number of aircraft in a given volume of airspace, their altitudes and their equipage. The aircraft equipage is specified for each aircraft. This information includes whether the aircraft is transponder equipped and, if so, with what type of transponder. With regard to the operational environment, the SSR is provided for high density scenarios in order to model interference on 1030/1090 MHz. The simulation model consists of two main components: the air traffic model and the surveillance network model.

A. Air Traffic Model

The performance of "radar versus radar" and "radar versus ADS-B" depends greatly on the relative orientation of each. The relative geometries of the flight path is also critical for the ADS-B versus ADS-B performance of the two aircraft. Hence, it is essential to properly model the air traffic scenarios.

We mainly consider a portion of the Los Angeles Air Route Traffic Control Center (ARTCC), which contains a number of sectors as shown in Figure 2. Note that the LA Basin region in the year 2020 is considered as a standard [3]. These sectors surround the LA terminal control center, which controls the aircraft on their approaches into Long Beach, Riverside, and LA airports. Figure 2 presents the geographic information of airports, ground radars, and representative flight paths around the LA ARTCC. We consider the two major airports around the LA ARTCC, Los Angeles International Airport (LAX) and Phoenix Sky Harbor International Airport (PHX).

We focus on the arrival/departure rate of LAX. The Aviation System Performance Metrics (ASPM) provides information on selected airline and airport performance with different focuses and perspectives such as air traffic operations (arrivals and departures), airline schedules, operations and delays, weather information, and related statistics [18]. We extract arrival/departure rates of LAX from ASPM [18] and model

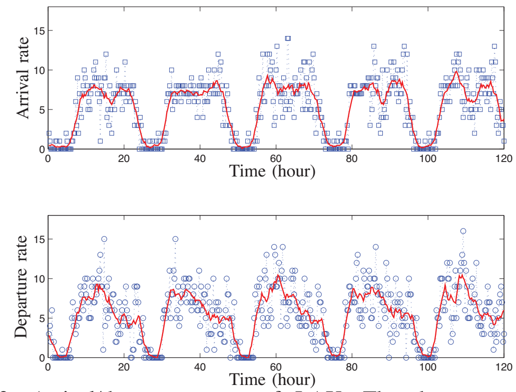


Fig. 3: Arrival/departure rates of LAX. The data comes from ASPM [18].

the important features of the traffic load. Figure 3 presents arrival/departure rates of LAX for five days. The data is updated every 15 min. The dots depict the number of arrivals/departures of the ASPM recorded points. The solid curve is the result using a sliding window. We observe the periodicity of arrival/departure rates with the interval of one day in LAX.

A flight plan is a set of waypoints (reference points defined precisely in the airspace), which the aircraft are expected to follow. Even though in low traffic density regions, aircraft might fly off these flight plans to benefit from faster routes, when this airspace becomes congested, aircraft will follow arrivals for up to 200 NM from the destination airport. The routes can be viewed as tracks which the aircraft follow closely with minor deviations until they reach the arrival airport. In the current system, the air traffic controllers build a mental model of this airspace: they know how much time an aircraft takes to fly from one point to another, and how much time an aircraft can lose using minor deviations of its flight plans in order to delay the arrival. An air traffic controller can thus regulate the flow by adjusting the flight plans of individual aircraft, according to procedures which have been established over time to meet the acceptance rates at airports.

We extract the trajectory of the actual flown aircraft of LAX from FACET [17]. The recorded trajectories are extracted as sequence of waypoints which are used as flight plans for our simulations. The position is given in latitude/longitude and altitude which we convert into Cartesian coordinates, an approximation valid for the portion of airspace of interest to us. Since our interest focuses on a number of sectors round the LA ARTCC, the actual flight plans are truncated, and we consider only points corresponding to sectors. The terminal area has relatively high traffic density, there exist prescribed routes corresponding to different approaches into airport runways. The paths 4, 5, 6, and 7 are merging into LAX. The paths 7 and 8 are dual airways: they have two lanes to separate aircraft between LAX and PHX.

B. Surveillance Network Model

Calculating the 1090 MHz interference environment is critical for determining Mode-S ES performance. Predicting the 1090 MHz environment is highly dependent not only on traffic growth, but also on the evolution of the ground radar infrastructure and aircraft equipage. The levels of 1090 MHz interference might be expected to increase proportionally to the increases in aircraft traffic levels. Such increased interference levels could also adversely affect the performance of air-to-ground and air-to-air surveillance performance. Furthermore, aircraft at different altitudes and locations over different scenarios will experience a different field of SSR and TCAS interrogation environments.

As use of the system grows, the existing system is expected to upgrade to reduce the interference, partly as a result of an on-going transition from Mode-A, C to Mode-S, partly as a result of upgrading some SSRs from the sliding-window technology to monopulse technology, and also partly as a result of the success of ADS-B providing a basis for discontinuing operation of some SSRs. Hence, we consider various types of equipment for both aircraft and ground radars. The aircraft is declared to be Mode-A, C, S transponder, TCAS, ADS-B equipped capable or nonequipped. The term ADS-B equipage is used to indicate that the aircraft has the capability to both transmit and receive the required information.

Ground radars are placed in realistic locations to properly model an airspace. The simulation includes 18 ground radars: 11 Mode-A, C terminal stations, 5 Mode-A, C en-route stations, and 2 Mode-S terminal stations. Currently, all Mode-A, C radars use the sliding-window technology. The monopulse technology will replace the current sliding-window technology as a part of the NextGen plan [1]. Hence, the Mode-A, C radars are modeled as either sliding-window or monopulse radars with different sweep periods for the simulation. Terminal ATC operation requires a 4.8 second update for aircraft out to 60 NM and en-route sensors currently provide a 12 second update rate to a range of 200 NM. Note that both terminal and en-route antennas provide the data-link service at 1030 and 1090 MHz. The default values of radar parameters are presented in Section II-A, Tables I and II.

Based on the effective number and characteristics of these basic interrogation sources, and the distribution and type of responding aircraft, the model develops the expected distribution of co-channel interference competing with reception of the desired extended squitter message. A detailed representation of this process requires simulation of each interrogation and each reply over the whole distribution of potential interrogators and responding aircraft. The simulation model keeps track of aircraft, estimates ranges and timing between communicating (or interfering) pairs of aircraft, and generates the received signal and interference power levels for the aircraft and radar.

The wireless channel model computes the signal levels at the receiver of all ADS-B messages and replies transmitted by other aircraft and interrogators of SSRs. It also includes the path loss and variations due to air-to-ground and air-to-air antenna gain differences associated with relative aircraft orientation. The desired extended squitter message competes with co-channel interference defined by the air traffic model surrounding the receiver.

We consider a set of transmitting aircraft and ground radars with locations specified by the flight path and the radar information. Let d_j denote the distance of the j-th transmitter from a reference receiver. The reference transmitter is placed a distance d_i. Received power is modeled by path loss with exponent $\alpha > 2$ (default value $\alpha = 2$) and a distance-independent fading coefficient h_j (from the j-th transmitter to the reference receiver). Therefore, the Signal to Interference plus Noise Ratio (SINR) at the reference receiver is:

$$\text{SINR} = \frac{\rho_i g_i d_i^{-\alpha} |h_i|}{\eta + \sum_{j \in \Pi(i)} \rho_j g_j d_j^{-\alpha} |h_j|} \qquad (1)$$

where ρ_i is the transmit power level of the i-th transmitter, g_i is the relative antenna gain of the i-th transmitter to the reference receiver, η is the noise power, and $\Pi(i)$ describes the interferer transmitter i.e., a number of nodes simultaneously transmit. The transmitter decides to transmit a frame depending on SSR interrogators and ADS-B equipage, and irrespective of their channel conditions, which is similar to ALOHA. The gain effects of directional antennas between air-to-ground and air-to-air are taken into account.

TABLE I: Link Budget for simulations. A2G and A2A stand for the air-to-ground and air-to-air, respectively.

	Terminal	En-route	TCAS	Mode-S ES
Range	60 NM	200 NM	10-30 NM	150 NM: A2G 40-90 NM: A2A
TX power	54 dBm	54 dBm	54 dBm	51-57 dBm
TX gain	0 dB	0 dB	0 dB	0 dB
RX gain	4 dB	14 dB	0 dB	0 dB
Cable loss	-2 dB	-1 dB	-3 dB	-3 dB
MTL	-88.5 dBm	-88 dBm	-77 dBm	-84 dBm

The simulation step could be summarized as follows. The simulation model takes as input the locations and transmission characteristics of both the air traffic scenario and the radar information. Then the model attempts to reproduce all of the individual radar interrogations and responses by each aircraft, and it provides as output the time-ordered arrival at the chosen receiver of the 1030/1090 MHz signals. It also generates a log of transmitted messages of Mode-A, C, S transponder, TCAS, and Mode-S ES over the simulation period. The simulation model for each link invokes the receiver/channel model to estimate the performance of the wireless link between each pair of aircraft and ground radars. The measures of performance can then be directly compared to the evaluation criteria to complete the link characterization.

There are a number of assumptions, which are incorporated into the simulation chain:

- It is assumed that all aircraft carry dual 1030/1090 MHz Mode-A, C, S and TCAS capable transponders.
- All target aircraft are assumed to carry an omni antenna.
- The aircraft has the capability to both transmit and receive extended squitter message if ADS-B is equipped.
- The Mode-S ES transmission rate per aircraft is 4.2 Hz (e.g. two position and two velocity squitters per second, and an identification squitter every five seconds).
- The initial radar orientations are randomly sampled and the rotation rate sampled within the assigned limits (4 to 5 seconds for short-range radars and 10 to 12 seconds for long-range radars). Hence, the radars are unsynchronized.

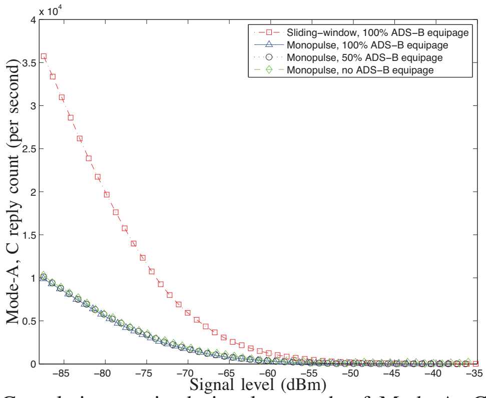


Fig. 4: Cumulative received signal strength of Mode-A, C replies. We count Mode-A, C replies at or above signal level on X-axis per second.

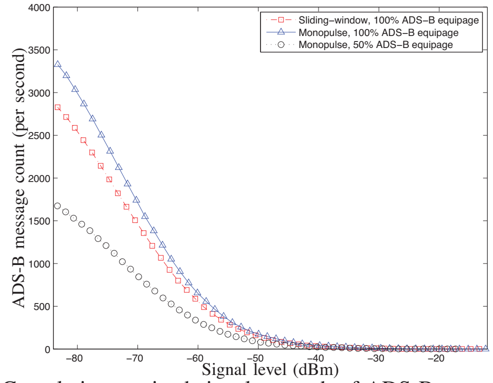


Fig. 5: Cumulative received signal strength of ADS-B messages. We count ADS-B messages at or above signal level on X-axis per second. Note that the scale of the Y-axis is different from Figure 4.

V. Performance Analysis

The focuses of the performance analysis are: (1) interoperability between existing surveillance systems and ADS-B, (2) operational ability of ADS-B to meet the separation assurance and other application requirements, (3) the effect of ground surveillance systems and aircraft density to ADS-B performance along the flight path.

We select aircraft flying through LA ARTCC and simulate these flights for 1 hour. The simulation time step is 20 μs. The default values of the simulation parameters are described in Table I. The relative geometries between the aircraft and the radar have a significant impact on the antenna gain in measured performance, therefore, it is good to study a variety of operational scenarios and present the results.

The validation of the interoperability between existing surveillance systems and ADS-B systems has two parts: (1) interference from ADS-B to existing surveillance systems, and (2) interference effects from existing surveillance systems on the performance of ADS-B. It is important to ensure that the extended squitter messages transmitted by ADS-B avionics do not degrade the ability of ground radars to sense traffic. As the density of ADS-B equipped aircraft grows, transponders in an airspace receive more extended squitter messages by more ADS-B avionics. As a result, transponders devote more of their time to receive ADS-B messages and less of their time responding to ground interrogations.

Figure 4 shows the cumulative received signal strength of the Mode-A, C reply receptions with signal levels greater than or equal to -88 dBm. The cumulative received signal strength is not normalized to compare the number of received replies for different scenarios. Co-site interference is any transmission near enough to the receiver by inhibiting reception. Sources of co-site interference of the 1090 MHz include replies to Mode-A, C, S interrogator, TCAS and ADS-B transmissions.

For modeling future conditions, we increase the aircraft density to two times the current traffic. We also consider different ADS-B equipages (0%, 50%, or 100%) and SSR technologies (sliding-window technology or monopulse technology) assumption. The three curves for each particular ADS-B equipage case can provide insight into whether it matters if the extended squitter messages that act as the interference. The Mode-A, C interrogator is dominant interference with respect to Mode-S interrogator due to higher interrogation rates. Remind that TCAS and Mode-S radars can selectively interrogate Mode-S transponders to avoid interference from other transponders. The Mode-A, C reply rate using the sliding-window technology is significantly larger than the monopulse technology. Monopulse technology can operate with one fourth of the interrogation rate of the sliding-window technology. The interference observed by a ground radar receiver is slightly less for the 50% case than the 100% case. However, there are similar total number of replies on ground radars in both 50% and 100% of ADS-B equipage cases. Therefore, the provision of ADS-B systems requires only the addition of a modest data link interference and protocol control function to the ground radars. The simulation results roughly agree with actual measurements in [9].

Now, we analyse the effect of existing surveillance systems on ADS-B performance. Figure 5 shows the cumulative received signal strength of extended squitter messages at the receiver antenna with signal levels greater than or equal to -84 dBm. Note that the scale of the Y-axis is different from Figure 4. The effects from ownship systems are considered. For an airborne Mode-S ES receiver, it may be appropriate to gate the receiver off when a Mode-S ES transmission is generated onboard, and also during SSR replies. If the receiver is not gated off, the effect would normally be essentially the same, because a reception from another aircraft at a normal signal level would be overshadowed by the strength of a transmission from ownship. The interference of sliding-window SSRs degrades the performance of ADS-B with respect to monopulse SSRs. Hence it might be forced to upgrade or rationalize its radar infrastructure. The growth of Mode-A, C replies might be controlled through upgrades from the sliding-window technology to monopulse technology or upgrades to Mode-S. The self-interference is seen to be a function of the ADS-B equipage. The self-interference from ADS-B systems is two times higher for the 100% case than the 50% case.

The primary objective of the technical assessment of the Mode-S ES is to characterize the update rate and latency of each link with respect to the technical performance criteria

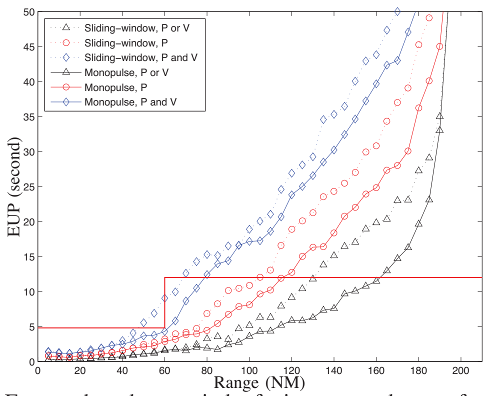


Fig. 6: Expected update period of air-to-ground as a function of different ranges in 5 NM distance bins. The solid line shows the requirement.

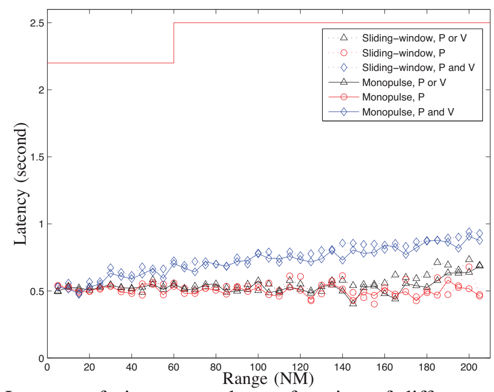


Fig. 7: Latency of air-to-ground as a function of different ranges in 5 NM distance bins.

to meet the separation assurance. The Required Surveillance Performance (RSP) defines the surveillance requirements that are independent of the particular technology to support an air traffic service [19]. We consider the communication requirement of RSP to support 3 NM and 5 NM separation services. The separation between aircraft must be at least safe 3 NM separation services in the terminal area and 5 NM separation in en-route airspace. The performance of the terminal sensor at a range of 60 NM is chosen as the reference system for 3 NM separation and the en-route sensor at a range of 200 NM for 5 NM separation. Limitations in the surveillance update rate have the effect of delaying the detection of the conflict. Furthermore, due to GPSs update rate 1 Hz, its estimates may lag the actual situation during periods of sudden acceleration [10]. This latency may in turn lead to an inappropriate estimation. Any latencies involved in pilot and aircraft response could result in an out-of-phase response that further reduces separation. By the analysis and flight test in [19], a set of update rate and latency requirements for 3 NM and 5 NM separation service is given in Table II.

As each Mode-S ES is received, it is processed to determine whether the extended squitter message is correctly received. We remind that reception times of Mode-S ES are random rather than periodic, and position and velocity are received separately. Performance is evaluated in terms of the Expected State Vector Update Period (EUP), e.g. the elapsed time between successive state vector reports. EUP is measured per target as the expected EUP values for that target. Targets are grouped into distance bins (5 NM wide), in terms of their range from the receiver. The overall EUP is then calculated per distance bin as the EUPs of the targets in the bin. Three options of state vector updates are considered for determining a track update: (1) Track update occurs every successful reception of a position or velocity squitter (`P or V`). This approach supports the ADS-B MASPS requirements [3]. (2) The alternative option is every successful reception of a position (`P`). (3) Track update is considered completed when both position and velocity squitter are received successfully within the same GPS update (`P and V`). The current EUROCONTROL ADS-B requirements ask both position and velocity updates within the specified update periods [9]. The latency for a successfully received squitter is defined as the time interval from the instant the GPS updates the squitter information until the corresponding squitter is received successfully.

TABLE II: Required update rate and latency for 3 NM and 5 NM separation.

	3 NM	5 NM
Maximum update period	4.8 s	12 s
Maximum latency	2.2 s	2.5 s
Area	Terminal	En-route

We analyse both air-to-ground and air-to-air performance. The air-to-air requirements are more restrictive than air-to-ground or ground-to-air, because one can adjust the configuration to achieve the required air-to-ground or ground-to-air link margin. It is assumed that all aircraft have ADS-B equipment (100% case). This assumption should produce conservative Mode-S ES performance estimates.

Figure 6 shows the EUP of air-to-ground as a function of different ranges in 5 NM distance bins when the state vector updates. It also plots the separation assurance requirements of track updates for comparison with the observed Mode-S ES performance. Note that the separation assurance requirements also show the nominal terminal and en-route radar sweep period. The manner in which a state vector update is defined is seen to have a significant effect on the performance of the air-to-ground transfer. Even though there is no final decision on the state vector data, it is expected that the successful reception of a position or velocity extended squitter will suffice, provided the data is processed in a Kalman filter.

In general, the monopulse technology improves the EUP with respect to the sliding-window technology. The requirement of update intervals less than 5 seconds at 60 NM is met for most cases except the `P and V` state vector using the sliding-window technology. However, the en-route requirement of less than 12 seconds update interval at 150 NM is not met for most cases except the `P or V` state vector using the monopulse technology. Note that the air-to-ground range of ADS-B is 150 NM [3]. The results indicate that Mode-S ES does not meet the 150 NM range requirement when the sliding-window technology is used for SSRs because of higher interrogation rates. Air-to-ground reception rates of the `P or V` state vector using the monopulse technology are

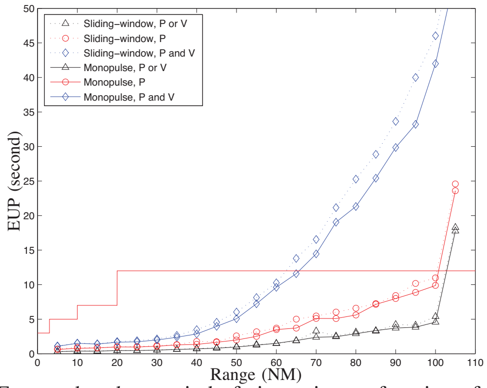


Fig. 8: Expected update period of air-to-air as a function of different ranges in 5 NM distance bins.

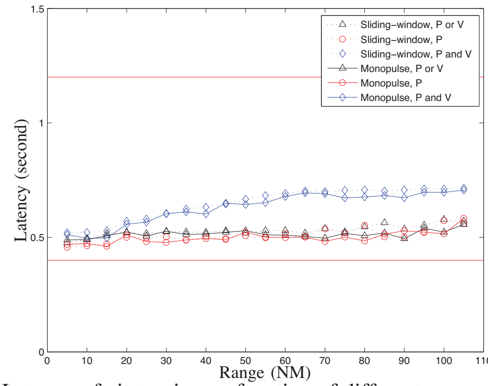


Fig. 9: Latency of air-to-air as a function of different ranges in 5 NM distance bins.

roughly better than the update rates provided by either terminal or en-route radars at 150 NM. The effect of different SSR technologies is small for the `P or V` state vector, less than 1 second difference at 80 NM. The effect is much greater for the case where the `P and V` state vector is used.

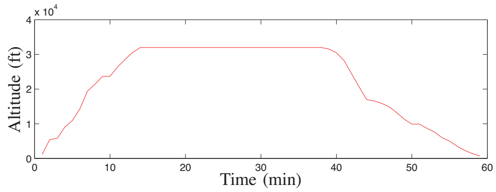
Figure 7 compares the latency of the air-to-ground performance with the latency requirement of the separation assurance. Note that the amount of latency reduces the warning time for a collision by about the same amount. The latency of ADS-B meets the separation assurance requirements since the maximum latency of GPS update is 1 second. The latency of the `P and V` state vector is greater than two options, `P or V` and `P`, due to its strict requirement. In addition, the latency of the `P and V` state vector increases as the range increases because of the lower reception rate. Two options of state update vectors, `P or V` and `P`, are not critical.

Figure 8 compares the predicted Mode-S ES performance for air-to-air scenarios with the ADS-B operational application requirements [3]. The air-to-air performance of the Mode-S ES system in the terminal environment is very robust. Air-to-air ranges of greater than 100 NM are observed, and comparison with ADS-B operational application requirements shows that all airborne requirements are met for `P or V` and `P` state vector updates in the scenarios flown. The effect of different SSR technologies for the air-to-air performance is smaller than the air-to-ground performance.

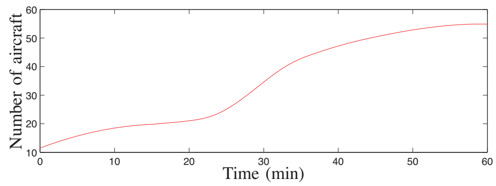
According to the ADS-B MASPS requirement [3], for critical application, the ADS-B transmitter latency should be less than 0.4 seconds, and for less-critical applications less than 1.2 seconds. Figure 9 shows the latency of the air-to-air performance with the ADS-B operational application requirements. The latency meets the performance requirement (1.2 seconds) of less-critical applications. The latency is slightly higher than the requirement (0.4 seconds) for critical applications. One of main reasons is the low update frequency of GPSs, 1 Hz. Furthermore, position and velocity messages are transmitted at a rate of 2 messages per second. The trend of the air-to-air latency is similar to the air-to-ground latency.

We observed that the system range is a function of the interference and aircraft traffic condition. Hence, it is essential to know the rates of existing signal transmission in the 1030/1090 MHz frequency bands. In the following, we investigate the effect of interrogation density and aircraft density to ADS-B performance along the flight path. We assume that all aircraft have ADS-B equipment (100% case). The flight path from PHX to LAX is considered as shown in Figure 2. Figure 10(a) shows the altitude of the flight path. Altitude is nearly constant at 32000 ft. Figure 10(b) also shows the number of aircraft visible from the receiver within 90 NM. The aircraft density increases near the terminal area due to departure and arrival process of LAX. In practice, it is possible to estimate the number of aircraft because each TCAS aircraft transmits self-identifying Mode-S squitter. The main simulation results roughly agree with actual measurements in [10].

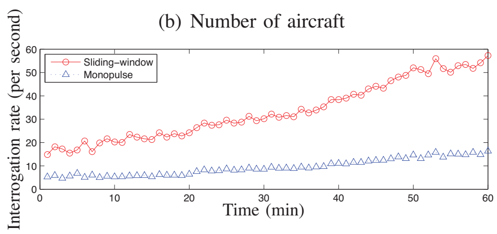
Figure 10(c) presents the interrogation rates that are measured along this flight path with different interrogation technologies: sliding-window technology and monopulse technology. Each plotted point is the average rate of Mode-A, C interrogations received over a 1 minute period of time. The receiver threshold is -88 dBm referred to the antenna. The interrogation rate changes over flight path due to the variation of the ground radar density. In general, those aircraft closer to the terminal and at higher altitudes see the most intense environment. The results indicate that the rate of Mode-A, C interrogations received from ground radars is less than 60 interrogators per second consistently during the flights. Given that typical Mode-A, C interrogators transmit at a rate of about 350 interrogations per second and that the mainbeam width is about 1 percent of 360 degrees, we would expect to receive an average of about 3.5 interrogations per second from any interrogator. Multiplying this by 15 interrogators, which is a number of SSRs around the LAX, yields a total of 52.5 interrogations per second. This is a rough estimate of the average interrogation rate a transponder would receive under nominal conditions. By looking at the increment between sliding-window and monopulse, one can see the improvement of interrogation rates of SSRs. Figure 10(d) also shows the measured EUP of the air-to-air reception performance. It is assumed to update a given aircraft's state vector upon the reception of a position or a velocity message (`P or V`). The reply rate increases for an aircraft flying near a terminal area because the interrogation rate and the aircraft density increase.



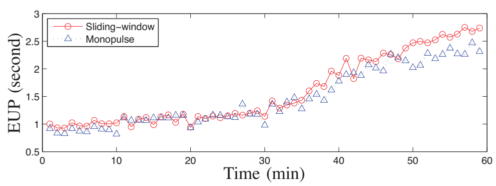
(a) Flight altitude



(b) Number of aircraft



(c) Interrogation rates



(d) EUP

Fig. 10: Flight altitude from PHX to LAX. The results of number of aircraft, interrogation rates, and EUP are obtained while flying on this flight path.

As the number of ADS-S equipped aircraft increases, the transmission of Mode-S ES increases. This would have the effect of the EUP increase by blocking reception of these air-air transmissions of Mode-S ES if they are overlapped by a reply or an extended squitter.

VI. Conclusion

ADS-B is an essential component to achieve a more robust and efficient air transportation system by providing distributed sensing and control solutions. We studied the interoperability of ADS-B with existing surveillance systems and operational ability to assist the flight crew by meeting separation assurance and other application requirements. Our system model simulates a flight through a modeled airspace and measures statistics on the results. The simulation model consists of two main components: the air traffic model including the realistic flight path, air traffic generator, and ground radar information and the surveillance network model including the wireless channel, ground surveillance system, and airborne surveillance system. The provision of ADS-B systems requires only the addition of a modest data link interference to the existing surveillance system. However, as use of the system grows, the existing system is required to upgrade the system to reduce the interrogation. It is shown that ADS-B meets the performance requirements of both air-to-ground and air-to-air requirements to effectively warn flight crews of conflicts. Furthermore, we investigated the effect of interrogation density and aircraft density to ADS-B performance along the flight path.

In contrast to the traditional passive sensing context, it is possible to assign different priorities on sensors depending on the most relevant information to optimize the performance of the overall system. Furthermore, one future direction is developing an efficient avoidance maneuver and verifying overall systems performance from an operating perspective.

Acknowledgment

This work was supported by the National Science Foundation under grant CNS-0931843 (CPS-ActionWebs). The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the National Science Foundation.

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