A cloud-assisted ADS-B network for UAVs based on SDR

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Abstract—Integration of Unmanned Aerial Vehicles (UAVs) or “drones” into the civil aviation airspace is a problem of increasing interest in the aviation community, as testified by many initiatives developed worldwide. Many traditional surveillance solutions for manned aircrafts employ the Automatic Dependent System-Broadcast (ADS-B) technology, which however might present several drawbacks when used for UAVs, especially smaller ones and/or those flying at very low altitudes. We present in this paper a cloud-based surveillance solution for UAVs, which can be considered as an enhancement of a conventional ADS-B system. The proposed solution leverages inexpensive on-board transceivers for transmitting positional messages from the UAVs to the ground. A network of ADS-B gateways, based on the software-defined radio (SDR) paradigm, format the positional messages into valid ADS-B signals and rebroadcast them in the air, allowing thus to emulate a true ADS-B system and overcoming the main disadvantages of the conventional implementation. A preliminary performance analysis of the proposed approach, based on queuing theory, shows the main tradeoffs of the considered approach. Moreover, a physical-layer laboratory implementation of the proposed solution is presented, based on off-the-shelf SDR hardware, which is programmed using the open-source GNU Radio environment.

Index Terms—Unmanned Aerial Vehicles, Unmanned Aircraft Systems, Automatic Dependent System-Broadcast, Software-Defined Radio, Air Traffic Management, Unmanned Aircraft System Traffic Management.

I. INTRODUCTION

An Unmanned Aerial Vehicle (UAV), shortly known as “drone”, is an aircraft with no human pilot on-board. It represents the central element of an Unmanned Aerial System (UAS), which is the set of the aircraft and all the other elements supporting its service. Without the need of an on-board pilot, drones were originally designed to accomplish military tasks [1]. However, recent advances in drones’ technology have allowed the emergence of a wide new range of applications in the civil domain, as highlighted by the Single European Skies ATM Research Joint Undertaking (SESAR JU) in its outlook study [2]. According to such a study, the role of drones is likely to expand up to 2050 in many civil sectors, including agriculture, energy, public safety and security, e-commerce and delivery, mobility and transport.

In view of the growing demand for civil drone services and their impacts in terms of economic growth and societal benefits, a key problem is to extend traditional Air Traffic Management (ATM) systems to implement Unmanned Aircraft System Traffic Management (UTM) systems, aimed at safely and efficiently managing small UAVs flying in low airspace. To this aim, the SESAR JU started the U-space programme in 2016, defined [3] as a set of services and specific procedures designed to support safe, efficient and secure access to airspace for large numbers of drones. A similar evolutionary pathway is being followed in USA, where UTM is under development in the Next Generation Air Transportation System (NextGen) programme of the Federal Aviation Administration (FAA) [4].

To obtain the required data for flight situational awareness, UTM systems shall rely upon a surveillance infrastructure, which considers both the unmanned traffic and its interaction with manned traffic. Several initiatives have proposed the application of Automatic Dependent Surveillance-Broadcast (ADS-B) for the safe integration of drones in the civil airspace. The current ADS-B network infrastructure is composed by cooperative aircrafts periodically broadcasting their own positional data through Mode-S Extended Squitter (1090 MHz) ADS-B Out messages [5], and receiving nodes called ADS-B In using such information for ATM operations and/or providing global flight tracking services, such as, e.g., Flightradar24[7]. Each aircraft may in turn be equipped with an ADS-B In receiver to enhance its on-board situational awareness and to readily engage separation maneuvers when needed.

ADS-B is already approved for use in civil ATM and represents a cost-effective surveillance technology with great potential for novel applications, such as UTM. For example, the European CORUS (Concept of Operations for European Unmanned Traffic Management Systems) project has defined a U-space Concept of Operations (ConOps), wherein ADS-B is highlighted as a potential surveillance technology for

1Positioning is typically achieved by collecting data from different sensors, such as GPS, ultrasound, LIDARs, cameras, IMUs, and performing sensor fusion by means of Kalman filters [5].

2https://www.flightradar24.com.
the electronic conspicuity, i.e., a capability that enables the broadcast or relay of an ownership’s location or position to other airspace users and ground operators [7]. Moreover, in their white papers about UTM, Amazon [8] and Google [9] have proposed ADS-B as an essential asset for safe and cooperative integration of manned/ unmanned traffic.

However, several problems have been identified when using standard ADS-B for UTM. For example, the analysis in [10] indicates a lack of real-time position information at the Very Low Level (VLL) altitude (under 500 feet), due to the current number of on-board ADS-B receivers and transponders, which is insufficient for the surveillance of high-density drone operations in an urban airspace. To solve this problem, it is proposed in [10] to increase the density of ADS-B receivers for capturing position information, by mandating all aircrafts to employ ADS-B transponders.

Instead, in [11] it is argued that the integration of ADS-B as a core part of the future ATM/UTM systems may be compromised by issues related to severe message losses (caused by the growing traffic on the channel) and open security concerns, due to the cheap and easy availability of Software-Defined Radio (SDR) devices, which can be easily employed to sniff, jam or spoof legitimate ADS-B traffic. Another issue is represented by the power consumption, since standard ADS-B Out transponders use 200 W transmit power, whereas small transponders may consume up to 20 W, which is still too high for a small battery-powered drone [5]. Lastly, specialized ADS-B transceivers for drones are much more expensive than drone themselves due to the certification processes, and are affordable only for bigger drones [5].

In this paper, to solve some of the previously proposed problems, we propose an innovative cloud-based surveillance solution for UAVs, which is a simple add-on to the conventional ADS-B system. The proposed solution leverages inexpensive on-board transceivers for transmitting positional messages from UAVs to the ground. A network of ADS-B gateways based on the SDR paradigm, after formatting the positional messages into valid ADS-B signals, rebroadcasts them in the air, which allows one to emulate a true ADS-B system. The proposed solution employs SDR techniques at the gateways, which is a convenient tool for its fast prototyping and flexibility features. In particular, our SDR implementation is based on the open-source GNU Radio framework [4]. A preliminary performance analysis, in terms of overall system capacity and latency, is also provided, based on queueing theory, under some simplifying assumptions.

A. Related work

Different research projects are facing the challenge of designing ADS-B-based solutions for the surveillance service in UTM. In general, the addressed solutions represent low-power ADS-B variants. Indeed, reference [12] provides an analysis of the impact on ADS-B performance from a shared-use operation by drones. The analysis indicates that the key parameters are drones’ ADS-B transmission power and traffic density, which should be balanced to attain an acceptable demand on the ADS-B channel in high-density traffic areas.

Within its UTM project, the National Aeronautics and Space Administration (NASA) has been analyzing the application of ADS-B for cooperative surveillance of drones since 2015 [13]. For example, one of their research works has provided detailed simulation results of the ADS-B technology and of the related detect and avoid (DAA) algorithms in mixed large-density manned/unmanned environments [14]. Other NASA’s works regard the Integrated Configurable Algorithms for Reliable Operations of Unmanned Systems (ICAROUS) software architecture, that is, a set of highly-assured algorithms for building safety-centric and autonomous application of unmanned aircrafts in UTM systems [15]. Several flight tests have been performed for the ICAROUS Sense and Avoid Characterization (ISAAC) to evaluate: (i) the effectiveness of ADS-B receivers for drones to receive position reports for ICAROUS as a source of cooperative traffic surveillance; (ii) the use of ADS-B for drones. These tests have validated low-powered ADS-B transmissions (0.4 W) as an option for drone-to-drone applications.

Moreover, private companies are working on ADS-B variants for drones. For example, nearly all the new drones released by Da-Jiang Innovations (DJI) will have the AirSense feature, which is an alert system to give drone pilots an enhanced situational awareness about manned aircraft by means of an ADS-B In component [16]. Moreover, uAvionix is working on small ADS-B transceivers for drones, which use the commercial frequencies 1090 MHz and 978 MHz for ADS-B In and 1090 MHz for ADS-B Out [17]. However, ADS-B radio stations are not designed to provide coverage at VLL altitudes [12]. Considering the limitations introduced by interferences and by the buildings in urban high-density traffic environments, it remains unclear how the tracking services will be implemented in UTM infrastructures [17].

It should be noted that some research groups are investigating alternative solutions for ADS-B like systems, aimed at replacing ADS-B for UTM [13]. The proposed solutions are based on different protocols, some of which proprietary ones, such as FLARM (an acronym based on “flight alarm”), others based on wireless standards, such as 4G LTE (Long-Term Evolution), LoRa (Long Range), APRS (Automatic Packet Reporting System), and others (see [5], [19] and references therein).

The performance analysis of ADS-B in terms of packet-loss ratio has been considered in some papers (see e.g., [12], [20]). The analysis in [12] is based on ADS-B messages recorded over a 14-day period with a USRP-based receiver. It shows the impact of several variables, also related to weather conditions, on the packet-loss ratio, with reference to publicly available data of the OpenSky network, in an analysis of the overall (i.e., system-related) packet loss of ADS-B is derived.
In particular, besides providing an accurate assessment with respect to the TX-RX distance, the packet-loss ratio with respect to the network congestion is evaluated. The results confirm that such a congestion is strictly correlated with the packet-loss ratio.

II. THE PROPOSED ARCHITECTURE

The proposed surveillance solution represents an enhanced ADS-B network, which leverages the existing ADS-B infrastructure, i.e., it can be realized simply by implementing new features as an add-on to the existing ADS-B network. The architecture of the proposed network is depicted in Fig. 1 and comprises three segments:

- **Air-segment**: it is composed by aircrafts and larger drones employing ADS-B In/Out devices, as well as smaller drones connected to the Internet.

- **Ground-segment**: it consists of existing ADS-B ground receivers as well as programmable general-purpose transceivers to be used as Internet-connected **ADS-B Radio Gateways** (ADS-B RGs).

- **Cloud-segment**: it is based on strongly reliable Internet **air traffic servers** (ATSs) intended for authenticating, queuing, processing, and routing massive amounts of positional data.

In the following, we describe in more detail the functional requirements of the systems and devices required by the innovative architecture.

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A. Drone on-board system

Drones not equipped with a traditional ADS-B system can still retrieve their own positional data from the on-board situational awareness subsystems. After network authentication, such information is properly encoded, including an identification string, and almost-synchronously sent (nearly at 2 Hz, like in ADS-B) to the ATSs network (i.e., into the cloud) using an Internet connection, which can be based on different radio technologies, such as, e.g., 4G/LTE, 5G, WiFi, or LoRa. Similarly, drones can retrieve information through the same Internet connection about near aircrafts from the ATSs network to correctly manage the self-separation procedures.

The most efficient way to implement the communication protocol between the drones and the ATS is represented by the Request/Reply paradigm, due to the synchronous communication needs and the large number of requests that the ATS server will need to process.

B. ADS-B Radio Gateway (ADS-B RG)

The main goal of an ADS-B RG is to receive from the cloud ATSs network the positional data of the drones belonging to its operation area, format it as ADS-B messages, and rebroadcast, as an ADS-B Out, the resulting ADS-B radio messages, which are used by both ATM and aircrafts equipped with conventional ADS-B receivers. Similarly, an ADS-B RG can work as ADS-B In, by receiving and decoding the ADS-B radio messages coming from aircrafts under its operation area, and send the positional data to the ATSs network.

In order to increase the system capacity, a cellular approach can be used for allowing resource reuse. Indeed, each ADS-B RG is associated with a limited coverage area (i.e., a cell). By reducing the cell dimension, capacity can be efficiently scaled, by allowing the system to serve a larger number of drones.

Since ADS-B off-the-shelf devices have not been designed to change the aircraft ICAO identifier at run-time, a reconfigurable transmitter must be developed to this aim. The SDR paradigm represents a convenient solution to implement such ADS-B gateways, because of its flexibility features and ease of programming. Furthermore, SDR allows one to implement an ADS-B RG by using general-purpose hardware. In particular, packages for efficient networking are already available as core modules of the GNU Radio framework. Moreover, tools for ADS-B message decoding have been developed by the GNU Radio community as out-of-tree (OOT) modules.

Since multiple ADS-B RGs could be used to broadcast the same information, the most efficient way to implement the communication between ATS nodes and ADS-B RGs is represented by the Publish/Subscribe paradigm.

C. Air Traffic Server (ATS)

ATS nodes receive from drones and ADS-B RGs huge amounts of positional data about drones and aircrafts equipped with ADS-B transmitters as request messages. The ATS network must offer high performance in terms of reliability,
availability, and security [24], [25]. The positional datum received by a drone is encoded following the correct ADS-B data format [6] and readily published to be made available to the ADS-B RGs covering the airspace near the drone itself. In the meantime, each ATS node is able to retrieve air traffic information about the airspace the drone is covering from both ADS-B RGs and the global flight tracking services, and encapsulate them into the reply messages for enhancing the drone situational awareness.

### III. Performance Analysis

To obtain some simple analytical results, we consider only the broadcast information coming from drones and transmitted by the ADS-B-RGs. It can be shown that for the reverse path, i.e., the flow from the aircrafts equipped with ADS-B transmitters to the drones, a similar modeling approach can be used.

The following assumptions and notations are considered in the analysis: (i) $K$ ADS-B-RGs operate on distinct cells; (ii) the global requests are memoryless with rate $\lambda$; (iii) $P_k$ represents the probability that one request is received from the cell covered by the $k$-th ADS-B-RG; (iv) all the ADS-B-RGs operate at the deterministic service rates $\mu_1 = \mu_2 = \ldots = \mu_K = \mu = (1/120) \cdot 10^6 \text{ s}^{-1}$ (the duration of an ADS-B message is $120 \mu$s); (v) all the service queues are infinite-length.

We refer to the queueing model of Fig. 2 which represents an architecture where the network of ATSs implements the association between requests and ADS-B-RGs, on the basis of both coverage and positional information, and manages the ADS-B-RG queues. Since the association depends on the users distribution within the covered area, which is not known in advance, we considered a model composed by $K$ parallel M/D/1 queues, where the $k$-th queue is characterized by the arrival rate $\lambda P_k$ and the service rate $\mu_k = \mu$.

![Figure 2. Simplified queueing model (parallel M/D/1 queues) for the performance analysis.](image)

Let $P_{\text{max}} \triangleq \max_{k \in \{1, 2, \ldots, K\}} P_k$, it must be $\lambda P_{\text{max}} < \mu$ to assure system stability. Since the ATSs use infinite-length queues, the system blocking probability $P_{\text{B}}$ will be zero. The average number $N$ of requests and the average waiting time $T$ of requests in the system can be evaluated as

$$N = \sum_{k=1}^{K} N_k = \sum_{k=1}^{K} \left[ \rho_k + \frac{1}{2} \left( \frac{\rho_k^2}{1 - \rho_k} \right) \right]$$

(1)

$$T = \sum_{k=1}^{K} P_k T_k = \sum_{k=1}^{K} P_k \left[ \frac{1}{\mu} + \frac{\rho_k}{2\mu(1 - \rho_k)} \right]$$

(2)

with $\rho_k \triangleq \lambda P_k / \mu$. When the drones are uniformly distributed within the covered area, i.e., $P_1 = P_2 = \ldots = P_K = 1/K$, (1) and (2) simplify to

$$N = \frac{\lambda}{\mu} + \frac{\lambda^2}{2\mu(K\mu - \lambda)}$$

(3)

$$T = \frac{1}{\mu} + \frac{\lambda}{2\mu(K\mu - \lambda)}$$

(4)

with the stability condition becoming $\lambda < K\mu$.

According to the ADS-B protocol, positional messages are sent every 0.5 s, i.e., the transmitting rate produced by each ADS-B user is $R_{\text{ADS-B}} = 2$ Hz. Such a condition allows one to set an upper-bound for the system capacity:

$$N_{\text{max}} < \frac{K\mu}{R_{\text{ADS-B}}}$$

(5)

with $N_{\text{max}}$ denoting the maximum amount of users that can be served. As readily seen by (3) and (4), when $K$ increases a saturation effect of the performance parameters is observed, i.e., the average waiting time boils down to the time duration $1/\mu$ of a single ADS-B message.

As stated in [21], the packet-loss ratio is strictly related to the overall system capacity and congestion: a higher aircraft congestion entails a larger number of collisions on the communication link, i.e., a higher probability for the transmitters to choose overlapping time slots for the transmissions. The performance analysis reported above does not consider possible collisions with ADS-B signals coming from legacy devices. In this respect, since ADS-B-RGs are intended to be implemented using the SDR paradigm, Carrier Sensing Multiple Access (CSMA) could be a suitable technique for managing the packet-loss ratio, introducing a controlled degradation in terms of system capacity. In this case, more complicated approaches should be used for modeling the queueing stack and evaluating performances.

### IV. Results

#### A. Numerical results

In this section numerical results are provided, aimed at assessing the system capacity and latency of the proposed architecture. The performances have been evaluated assuming

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9Following Kendall notation [26], [27], M/D/1 stands for an infinite dimension queue characterized by memoryless arrivals, deterministic service rate, and a single server.

10The average number of requests in the system can be also obtained from the average waiting time of requests in the system exploiting the Little’s theorem [28], i.e., $N = KT$. 

...
uniformly distributed drones among the covered area for different numbers of ADS-B-RGs, i.e., $K \in \{1, 2, 5, 10, 100\}$.

Fig. 3 shows the average number of requests in the system as a function of the number of served drones. It can be readily noted that, although the stability condition is granted, when the number of drones to be served approaches the maximum system capacity the number of requests in the system dramatically increases. A similar behavior can be observed for the average waiting time of requests in the system (normalized to $1/\mu$), reported in Fig. 4 as a function of the number of served drones. In particular, this curve shows that $K$ needs to be properly designed to accommodate the latency constraints of the ADS-B standard.

B. Experimental results

For a first proof-of-concept of the approach, experimental results have been focused on the advances in physical-layer technologies. Specifically, as stated in section II-B, the TX segment of an ADS-B RG has been implemented from scratch as an OOT module into the GNU Radio (v3.8) framework running under Rocky Linux (v8.5). In order to test our ADS-B SDR implementation, a simple C++ application emulating the message passing between the ATS and the ADS-B RG was also developed.

The ADS-B RG TX segment gets the asynchronous ADS-B messages to be transmitted as subscriber of the ATS publisher using the ZeroMQ networking library\[^{12}\] already embedded in GNU Radio. Each ADS-B message (112 bit) is first PPM-binary modulated at 1 MBaud. Then, a short preamble is added, such that a burst of 120 $\mu$s is obtained\[^{6}\]. The output burst coming from the aforementioned ADS-B modulator has to be served at 2 MHz; if the sample rate of the flowgraph needs to be set at an higher frequency, an upsampling procedure must be provided.

\[^{11}\] http://zeromq.org

Two functional experiments have been carried out: the first one considers a “loopback” GNU Radio Companion flowgraph, aimed at validating the correctness of the modulated burst using the ADS-B decoding library provided by the gr-adsb module\[^{12}\]. The second experiment implements the entire ADS-B RG transmitting chain, with the actual RF signal generated by using an Ettus USRP E310\[^{13}\] as RF front-end and the driver module gr-iio provided by Analog Devices\[^{14}\]. The resulting RF signal is demodulated and decoded using a commercial ADS-B receiver (Garrecht Avionik GmbH TRX-1090 ADS-B Receiver).

In both experiments, the parameters of the emulated/ emitted ADS-B signal are set as DF=17, CA=5, TC=11, ICAO=A32DEA. Furthermore, the position varies linearly in altitude, longitude, and latitude, with respect to time. Both functional experiments were successful, i.e., the decoders used for validation (i.e., gr-adsb and the commercial ADS-B receiver) were able to correctly decode the emulated/emitted ADS-B signal. Figure 5 shows as an example the emulated published data from the ATS on the top shell, and the decoded data on the bottom shell.

\[^{11}\] https://github.com/mhostetter/gr-adsb
\[^{12}\] https://www.ettus.com/all-products/e310
\[^{14}\] https://github.com/analogdevicesinc/gr-iio.
V. Conclusion

In this paper we presented a proof-of-concept of a cloud-assisted network for the integration of cooperative small UAVs in the ADS-B surveillance system for unmanned traffic management. With respect to state-of-the-art solutions belonging to the class of ADS-B like systems, the proposed solution is not aimed at replacing ADS-B and does not introduce a different surveillance protocol. Instead, it preserves the current ADS-B network, while integrating and enriching it with cloud-based features to include in the civil airspace those flying vehicles that cannot host ADS-B transceivers.

The proposed solution heavily relies on cloud-computing infrastructures, as an extension of the current ADS-B infrastructure. Indeed, cloud computing allows efficient processing of massive amounts of positional data, solving also some security issues related to the authentication of managed vehicles, by means of network authentication services. Finally, due to their flexibility and efficient networking features, the interface between ADS-B network and cloud infrastructures is implemented by SDR devices acting as ADS-B gateways.

In future work, the functionalities of the cloud segment should be implemented in detail into the simulation setup. Moreover, an exhaustive evaluation of the attainable performances (in terms, e.g., of network capacity, message loss, and latency) should be carried out, which would take into account the actual legacy ADS-B data traffic and the processing delay at each network node.

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