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# Simulation/Optimization Modeling for Robust Satellite Data Unit for Airborne Network

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**The objective of this paper is to present a Simulink model–based approach for simulation and optimization of a robust satellite data unit (SDU) able to deliver safety and nonsafety aeronautical mobile satellite services, including capabilities to operate in an airborne network. For this purpose, analysis and modeling of the main avionics system signals and data traffic to be treated in an SDU were performed. The main contribution here is the design of the SDU data traffic model, which integrates different simulation models in avionics systems, such as automatic dependent surveillance—broadcast, aircraft communications addressing and reporting system, and in-flight connectivity for future implementation and optimization, thus allowing the characterization of a device onboard in a modular framework. To conclude, this paper describes a modeling and analysis tool aimed at providing the aviation industry with the means to reduce the amount of equipment onboard (and thus the weight of aircraft to reduce fuel consumption) and fulfill passengers' demand for connectivity. Finally, note that this modeling is a step further toward the development of a device that ensures greater operational safety and ease of repair and maintenance.**



## I. Introduction

ALTHOUGH the introduction of Wi-Fi connections using air-to-ground (A/G) on commercial flights is something recent, the fact is that airlines have been experimenting for more than 10 years with the possibility of offering high-speed Internet for airline passengers safely without compromising the security of the aircraft.

Today, more than 1500 commercial and 5000 business aircraft are equipped with this technology [1]. However, this technology does not cover transoceanic flights or remote areas because a direct link with a ground Earth station (GES) is required. A solution to cover this gap would be the development of a collaborative avionic network (CAN) [2], which, using a mobile ad-hoc network (MANET) topology type, allows aircraft Earth station (AES)/GES or AES/air traffic management (ATM) communication using other aircraft in an air-to-air (A/A) coverage. A CAN provides, in principle, a high-speed connection between the service cloud and the furthest AES sending and receiving its data packets by nearby AES. This allows sharing the available resources of the nearby AES, and so in regions with higher air traffic density there will be a greater number of mobile nodes, increasing the alternatives of AES/GES or AES/ATM connection. Additionally, the modernization of ATM by implementing Next Generation Air Transportation System (NextGen) by the Federal Aviation Administration (FAA) and Single European Sky ATM Research (SESAR) by EUROCONTROL programs is gradually allowing the reduction of horizontal and vertical distances between aircraft in aerial corridors, thus facilitating communications A/A. Each AES must be capable of establishing connections to relay, translate, and/or gateway information, as needed. In fact, they must be able to receive and transmit with the same data formats and on the same frequency, receive and transmit with the same data formats but on different frequencies, and receive and transmit with different data formats and on different frequencies or modulations [3].

Nowadays, the coverage of passenger communications services in transoceanic flights is performed via satellite communications (satcom) in L, C, Ku, and Ka bands. Passenger communications services in the AES are, among others, telephony data services, Wi-Fi services, credit card authentication, and telemedicine. They also have access to any other services offered by specific airlines and service providers.

In its simplest form, a satcom link carries a duplex (two-way) communication circuit: The AES transmits to the satellite an uplink carrier wave at a radio frequency (RF) containing safety and nonsafety aeronautical mobile satellite services (AMSS). The satellite antenna and transponder system receive this carrier and, after frequency conversion, amplifies and re-radiates it as a downlink waveform, which is received by the GES. To establish the return link, the GES transmits an uplink carrier at another RF, which is received by aircraft at the converted downlink RF. More generally, the satellite is equipped with several transponders. In the most advanced types of satellites, the signal does not simply incur a frequency conversion in a transponder, but it is subject to more complex operations, including demodulation/re-modulation and baseband processing.

It is at this point that we are interested in taking advantage of the maximum capacity of the channels of communication that satcom offers to join the CAN, bringing safety and nonsafety AMSS, so that a connection between the service cloud (or the ATM) with the furthest AES is provided, sending and receiving its data packets by nearby AES's using a satcom link (Fig. 1). In other words, CAN becomes an airborne network (AN) for civil aviation applications, which unlike a military AN (created for tactical operations, based on a mesh architecture and unpredictable paths due to the nature of the missions), aircraft have a route assigned and programmed into a flight management system (FMS); this allows one to predict the position of mobile nodes in their path and in turn maximize the bandwidth available of nearby aircraft during flight.

The objective of this paper is to present a Simulink model–based approach for simulation and optimization of a robust satellite data unit (SDU) able to deliver safety and nonsafety communications based on ARINC 791 standard and including capabilities to operate

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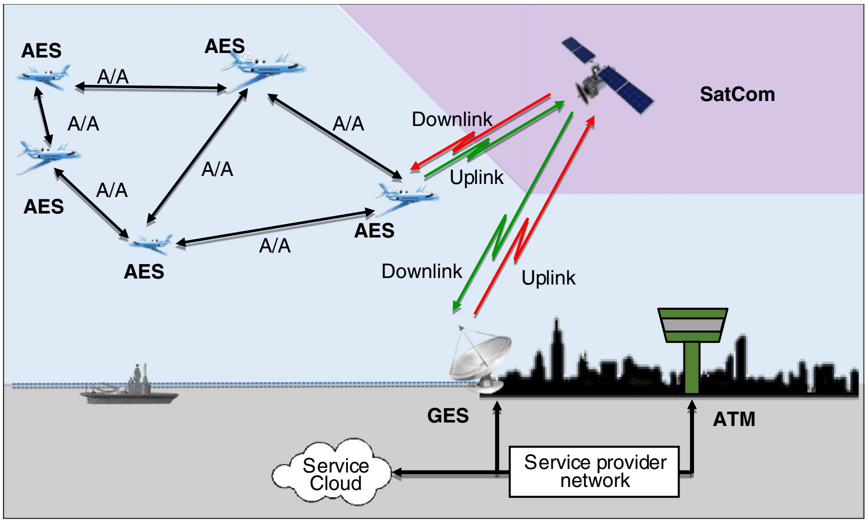


Fig. 1 Overall end-to-end system architecture for CAN satcom.



into an AN. For this purpose, analysis and modeling of the main avionics system signals and data traffic to be treated in an SDU were performed. Next, the priorities of communication systems based on the phases of flight were analyzed.

At first, this paper presents a background of the functioning of an AN, as well as the functioning of an SDU inside airborne avionics configuration. The following section presents a classification of the main avionic system signals in SDU, as well as the priority of these based on the phases of flight. These will be modeled individually for integration with the architecture simulation. Section IV proposes an architecture simulation detailing the processing of data signals via an A/A link going through a satcom link to its reception and decoding in the GES. Finally, results and conclusions are presented in Secs. V and VI.

## II. Background

To support safety and nonsafety AMSS in an AN, many challenges need to be overcome. In Ref. [4] we can see that one of the significant challenges in an AN is the airborne router, or SDU for our case, which must have a robust interface that provides an underlying autonomous reconfiguration capability to select the appropriate communication link for A/G broadband satcom and A/A communication. The underlying autonomous reconfiguration capability should provide seamless end-to-end communications in dynamic heterogeneous environments [4]. For the development of an onboard component like this one, an integrated system architecture is required. The following sections review the main components to be modeled.

### A. Airborne Network

The term *airborne network* was born as part of the project called Global Information Grid (GIG) of the U.S. Department of Defense (US DoD), which aims to interconnect IP-based communications tactics among space, air, and terrestrial segments [5,6].

The AN is defined as an infrastructure that provides communication transport services through backbone in-the-sky, that is, through at least one node that is on a platform capable of flight. Figure 2 shows an AN composed of three AES, which at the same time interconnect each element of tactical missions and the airborne subnetworks (fighters, helicopters, UAVs, etc.) with the Secret Internet Protocol Router Network (SIPRNET) and the Nonsecure Internet Protocol (IP) Router Network (NIPRNET). This connection can be made using DoD satellite links or commercial satellite links. The AN will connect to both the space and surface networks, making it an integral part of the communications fabric of the GIG.

At this point we have defined an AN inside a GIG for defense purposes and previously established missions. However, this research, under the same concept, is oriented to the use of AN with civilian applications in order to maximize the use of available bandwidth in the AES satcom channel during flight. This requires understanding the architecture and operation of hardware currently used for commercial satcom links (to access an ISP and an ATM).

### B. Airborne Avionics Configuration

The general configuration of an airborne avionic is shown in Ref. [7]. The typical airborne avionics configuration (AAC) consists

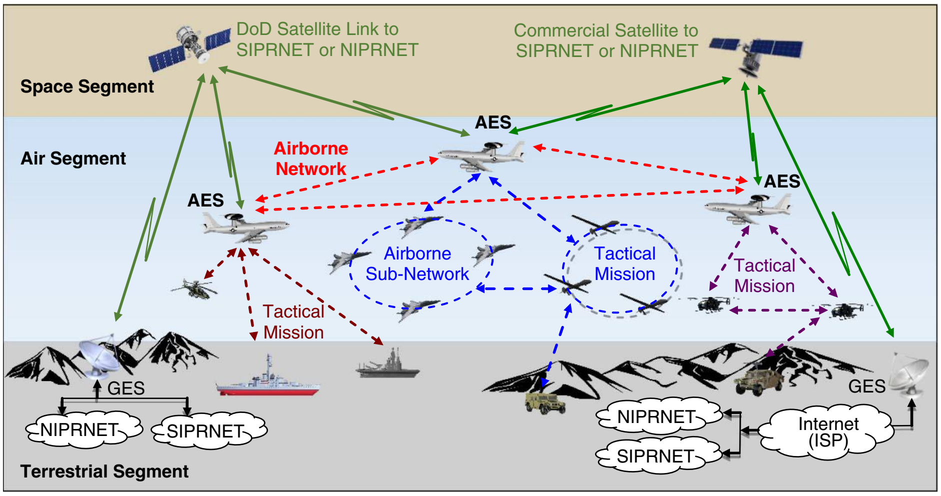


Fig. 2 Network architecture of global information grid (GIG).

of an ARINC 781/791 SDU, which normally contains a radio frequency unit (RFU) and an integrated high-power amplifier (HPA), its associated satcom cockpit of voice and data, plus a diplexer/low-noise amplifier (DLNA), and an ARINC 781/791 antenna, which contains an integrated beam steering unit (BSU).

The SDU is also designed to interface with an external HPA when, for example, the cable run and hence cable loss from the SDU to the DLNA are excessive. The SDU is also designed to interface with legacy top- and side-mounted ARINC 741/781 antenna subsystems, to allow a simple upgrade path to new satcom services for aircraft that are already equipped with ARINC 741/781 equipment. The SDU is capable of sending and receiving various data rates. The rate is dynamically selected by the individual applications and by pragmatic assessment of current operating conditions. The signals are transmitted via geostationary satellite transponders to/from designated supporting Earth stations [7–11]. The operation of each component can be consulted in Ref. [7].

### C. Satellite Data Unit

As explained in Ref. [12], an SDU is an avionics implement installed in an AES that permits A/G communication (information exchanges) via a satcom network. It is an essential part of an AES's satcom system and main component of this study. The SDU connects with a satellite via RF communication link and the satellite then connects to a GES or vice versa (see Fig. 1).

The SDU interfaces with an onboard multipurpose disk drive (MDDU) that holds an updatable table of GES in the AESs current zone and the direction of partiality for choice of which GES to use, which thus informs the choice of satellite. Along with analyzing data continuously dispatched from all GES, the SDU receives information on the aircraft's position and orientation from another onboard system (ADS-B, IRS, ACARS, etc.), which it passes to the BSU to manage the beam patterns of the AES to the selected satellite [12]. For the development of this study, we will take as a starting point the ACC of Ref. [6]. This model will allow us to study the waveforms to be treated in the SDU to perform the appropriate way of incoming and outgoing signals in SDU.

## III. Signal Generation and Priority of Communications

To modeling a robust SDU for AN we need to know what kind of signals will be treated within this unit, as well as the priority they have. These signals contain information automatically extracted from the data bus (or in other cases information entered manually by the crew of AES) to be sent via radio or via satellite to air traffic control (ATC) or to GES. Similarly, data from in-flight connectivity (IFC) service offered to passengers are treated in this device for sending via satellite to the cloud service. That is why at this point we are going to model and analyze the signals to be treated in our SDU model.

### A. Main Avionic System Signals in SDU

As we know, the main function of an SDU is to transmit, receive, and process signals via satcom providing AMSS between AES and GES in Ku or Ka band; however, it is important to differentiate these services [8,9].

1) Safety AMSS are communications services that require high integrity and quick response. These include

a. Safety-related communications carried out by the air traffic services (ATS) for ATC, flight information, and alerting

b. Communications carried out by aircraft operators, which also affect air transport safety, regularity, and efficiency (aeronautical operational control [AOC])

2) Nonsafety AMSS are communications services that do not compromise flight safety. These include

a. Private correspondence of aeronautical operators (aeronautical administrative communications [AAC])

b. Public correspondence (aeronautical passenger communications [APC], including IFC).

Table 1 shows the summarized classification of AMSS. Nonsafety AMSS may be authorized by administrations in certain frequency bands allocated, as long as they cease immediately, if necessary, to permit transmission of messages for safety and regularity of flights (i.e., ATS and AOC, according to priority 1 to 6 of Article 51 of ITU Radio Regulations) [9,13].

**Table 1 Summary of safety and nonsafety AMSS [8]**

| AMSS | APC | AAC | AOC | ATS |
|---|---|---|---|---|
| Nonsafety | ✓ | ✓ | ✓ | |
| Safety | | | ✓ | ✓ |

For purposes of this publication, we will consider mainly three kinds of communication systems: 1) ACARS, 2) ADS-B, and 3) IFC. These will be processed by the SDU. ACARS and ADS-B will be classified as safety AMSS, and IFC will be classified as nonsafety AMSS. Next, we will provide the description of the generation of safety AMSS signals.

#### 1. *Aircraft Communications Addressing and Reporting System (ACARS)*

ACARS is a network of A/G communications that is used to transmit or receive data automatically or manually. ACARS was first introduced to enable aircraft to send their takeoff and landing reports automatically to airline computers; today the system is installed in almost all commercial aircraft and is being used for applications that require a very reliable service [14].

ACARS was originally specified in the ARINC 597 standard but has been revised as ARINC 724B [15]. A significant feature of ACARS is the ability to provide real-time data on the ground relating to aircraft performance. This has made it possible to identify and plan aircraft maintenance activities [16].

ACARS messages may be sent using a choice of communication methods, such as VHF or HF, either direct to ground or via satellite, using minimum-shift keying (MSK) modulation. ACARS can send messages over VHF if a VHF ground station network exists in the current area of the aircraft. VHF communication is line-of-sight propagation and the typical range is up to 200 n miles at high altitudes. Where VHF is absent, an HF network or satellite communication may be used if available. Satellite coverage may be limited at high latitudes (trans-polar flights) [16].

*a. ACARS Frequencies.* Frequencies used for the transmission and reception of ACARS messages are in the band extending from 129 to 137 MHz (VHF). Different channels are used in different parts of the world [15].

*b. ACARS Message Structure.* The structure of the ACARS message is detailed in the standard ARINC 618 [17]. In the following tables, the structures of the A/G downlink and G/A messages are summarized, which will be used later.

*c. Data Coding.* The data exchanged between the ACARS management unit and the VHF radios in the aircraft are achieved using 1.2 and 2.4 kHz tones.

A zero-bit is coded by a positive half period of 1.2 kHz when it is the first of a string of zero-bits (even if the string only comprises this single bit) or by a 2.4 kHz period starting by the negative half period when this is not the case.

A one-bit is coded by a negative half period of 1.2 kHz when it is the first of a string of one-bits (even if the string only comprises this single bit), or by a 2.4 kHz period starting by the positive half period when this is not the case.

The transmission rate of this coding is 2.4 Kbps from aircraft to ground and vice versa. The transmitted data are characters from the ISO alphabet No.5 except the block check sequence field at the end of transmission.

*d. ACARS VHF Waveform.* To accomplish ACARS messages to be generated, we rely on the ARINC 618, 619, 620, and 724 standards [17–19]. The first step is to make the MSK modulation according to the specifications described above. MSK can be thought of as a special case of offset quadrature phase shift keying (OQPSK) with sinusoidal pulse weighting [17]. Consider the OQPSK signal, with the bit streams offset; the resulting signal is represented by Eq. (1).

$$s(t) = a_I(t)\mathrm{Cos}\left(\frac{\pi t}{2T}\right)\mathrm{Cos}(2\pi f_c t) + a_Q(t)\mathrm{Sin}\left(\frac{\pi t}{2T}\right)\mathrm{Sin}(2\pi f_c t) \tag{1}$$

where $f_c$ is the carrier frequency and $a_I(t)$ and $a_Q(t)$ encode the even and odd information, respectively, with a sequence of square pulses of duration $2T$. $a_I(t)$ has its pulse edges on $t = [-T, T, 3T, 5T \ldots]$ and $a_Q(t)$ on $t = [0, 2T, 4T, 6T \ldots]$.

Using the trigonometric identity, this can be rewritten in a form where the phase and frequency modulation are more obvious [20].

$$s(t) = \mathrm{Cos}(2\pi f_c t) + b_k(t)\left(\frac{\pi t}{2T}\right) + \phi_k \tag{2}$$

where $b_k(t)$ is $+1$ when $a_I(t) = a_Q(t)$, and $-1$ if they are of opposite signs, and $\phi_k$ is 0 if $a_I(t)$. is 1, and $\pi$ otherwise. Therefore, the signal is modulated in frequency and phase, and the phase changes continuously and linearly (see Fig. 3).

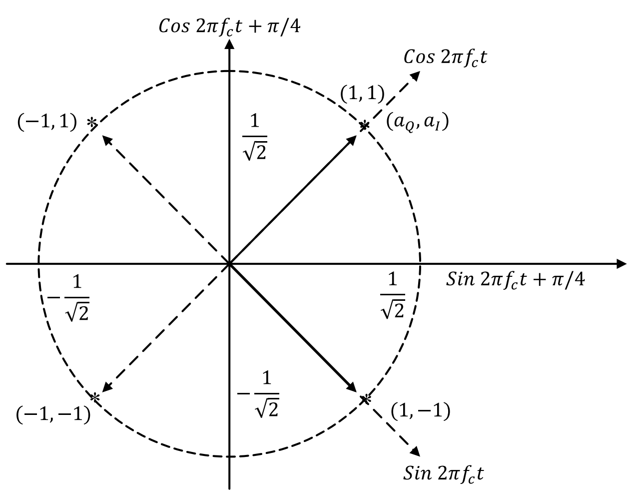


**Fig. 3 Signal space diagram for QPSK and OQPSK.**

First thing is the implementation of our MSK modulator, always respecting the periods for a one- or zero-bit. Thus we obtain as a result the waveforms of Fig. 4.

Next we develop the ACARS message generator, which will aim to convert into in bits the ACARS message structure A/G based in Tables 2 and 3.

Each message frame consists of at least 50, and up to a maximum of 272 characters or bytes. Each character uses a 7-bit ACSII code with an additional eighth parity bit. Bit 8 is an odd parity bit used for the text field of the ACARS message, and the content may be free text or a mixture of formatted and free text [16]. The 16 prekey characters are all binary 1 values, thus resulting in the 0.05 s 2400 Hz beep that can be heard at the start of every message. The block check sequence (BCS) field contains the value of an error-detection polynomial that can be used to determine if the entire message was received free of errors. Once obtained from the message, it can be sent in AM. Moreover, bits will be sent to the SDU via the ARINC 429 bus for transmission via satellite to a GES or to an AES within the AN.

### 2. *Automatic Dependent Surveillance—Broadcast (ADS-B)*

ADS-B is a surveillance technique in which an AES transmits via a data link a number of parameters extracted from the navigation and positioning systems onboard.

The idea is therefore that the AES, equipped with a Global Positioning System (GPS), calculates its own data (identity, position, speed, intent, altitude, etc.) and sends it regularly by radio (1090 MHz) to GSs and other AES equipped with ADS-B that are present in the flight area.

ADS-B has two fundamental characteristics: it is automatic; that is, it does not need the intervention of the pilot for AES data to be sent to the control tower, and is dependent, because the necessary information is generated in the same AES that is dependent on onboard systems.

*a. ADS-B IN and ADS-B OUT.* ADS-B IN concerns the reception of ADS-B messages transmitted by other AES. In this case, the AES is also equipped with a cockpit display of traffic information (CDTI) to display ADS-B OUT messages from other AES and information sent from GSs. The information displayed on the CDTI can be combined with information from other systems, such as aeronautical charts, contour lines, and data from traffic information services—broadcast (TIS-B) and flight information system—broadcast (FIS-B) [21].

ADS-B OUT concerns transmission of ADS-B messages by AES. An ADS-B transmitter can send the position, altitude, and identification of an AES to GSs to be analyzed and displayed on the

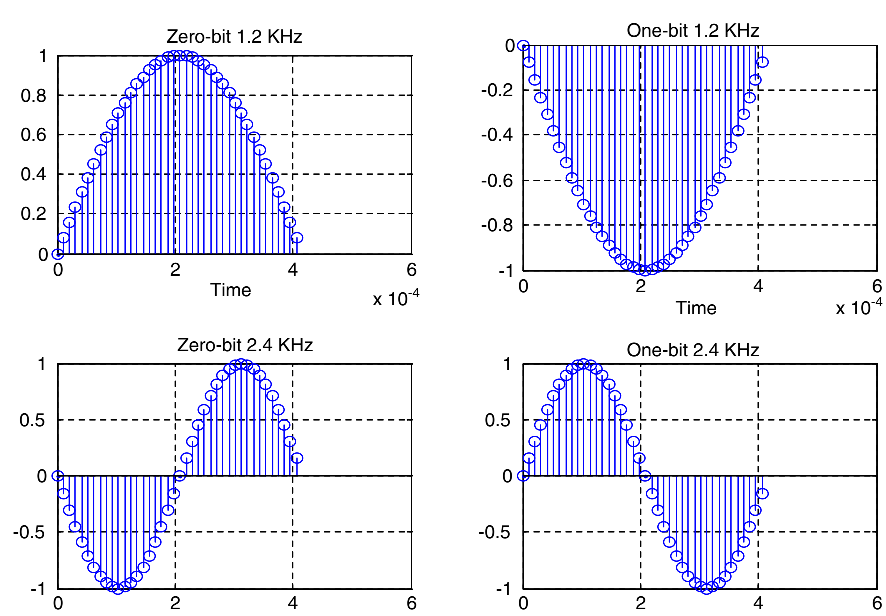


**Fig. 4 Waveform from MSK modulator.**

**Table 2 General format of A/G downlink message**

| Name | SOH | Mode | Aircraft registration number | TAK | Label | DBI | STX | MSN | Flight ID | Application text | Suffix | BCS | BCS suffix |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Size | 1 | 1 | 7 | 1 | 2 | 1 | 1 | 4 | 6 | 0-210 | 1 | 2 | 1 |
| Example | ⟨SOH⟩ | 2 | .N123XX | | 5Z | 2 | ⟨STX⟩ | M01A | XX0000 | | ⟨ETX⟩ | | ⟨DLE⟩ |

BCS, block check sequence; DBI, downlink block identifier; DLE, data link escape; ETX, end of text; MSN, message sequence number; SOH, start of header; STX, start of text; TAK, technical acknowledgment; and UBI, uplink block identifier.

**Table 3 General format of G/A uplink message**

| Name | SOH | Mode | Aircraft registration or flight ID | TAK | Label | UBI | STX | Application text | Suffix | BCS | BCS suffix |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Size | 1 | 1 | 7 | 1 | 2 | 1 | 1 | 0-210 | 1 | 2 | 1 |
| Example | ⟨SOH⟩ | 2 | .N123XX | | 5Z | 2 | ⟨STX⟩ | | ⟨ETX⟩ | | ⟨DLE⟩ |



screens of ATC. The ADS-B signal is broadcast from the AES approximately twice per second, and in the event that the AES is within the coverage radius of an ADS-B GSs, data are transmitted to ATM facilities [21].

*b. ADS-B Message Structure.* ADS-B uses 1090ES system ("1090 MHz Extended Squitter"), which is an extension of the transponders of Mode-S secondary radar, which is transmitted via pulse position modulation (PPM) at 1090 MHz. In AES equipped with Traffic Alert and Collision Avoidance System (TCAS) and Mode-S, these transponders can send and receive messages of 56 bits, used in the TCAS. A modification allows them to send messages of 112 bits, enough for the ADS-B OUT, and eventually receive them (ADS-B IN). The added message information of 56 bits to the Mode-S message is inserted between the 24-bit aircraft address (AA) and the parity information (PI) (see Fig. 5).

1090ES contains a preamble of 8 $\mu$s and the data block containing the message to send. The message bits are sampled at a rate of 1 $\mu$s and then they are modulated using pulse-position modulation (PPM). ME block contains 56 bits that will determine the ADS-B message type and will occupy a place between the 256 data registers (BDS) in the transponder; message types can be consulted in Ref. [22].

*c. ADS-B Message Generator.* To create the ADS-B messages we will use the model of Ref. [21] (Fig. 6); based on Ref. [21] the idea is to get the bits of the ADS-B message with a total length of 120 $\mu$s, taking into consideration the preamble (8 $\mu$s) and message length (112 $\mu$s).

The model shows the block "ADS-B signal generator" that is linked to block "ADS-B message." This block allows building any ADS-B message type by manually entering data in hexadecimal format (4 bits) from the ADS-B data entry graphical interface (Fig. 7).

This model simulates step by step the treatment of ADS-B message from its creation (simulating the extraction of 4D data manually), generating bits and inserting the preamble at the beginning of the data block previously modulating in PPM. Then this message is sent to an AM modulator for transmission at 1090 MHz. The model also allows adding Gaussian noise.

*3. In-Flight Connectivity (IFC)*

*In-flight connectivity* is a term that we derive from in-flight entertainment and communications (IFEC), which comprises a broad gamut of services offered to passengers (audio, video, Wi-Fi, etc.) during the flight. The IFC system comprises data services such as Wi-Fi and mobile telephony that help the passengers keep in constant touch with people on ground.

To generate the signal for IFC we will use a Bernoulli Binary Generator (BBG) of the Simulink library that generates random binary numbers using a Bernoulli distribution. An important and little known element to consider is the mean data rate that is generated by an AES [2]. Table 4 shows minimum and maximum expected mean data rate per aircraft type and number of passengers for IFC projected for 2020.

As we can see, in terms of data rate, for IFC, these could be from 29.71 Mbps and up to 300 Mbps approximately. These values are obtained by setting the sample time at the BBG to 33.66 ns for a data rate of 29.71 Mbps or 3.33 ns for a data rate of 300 Mbps.

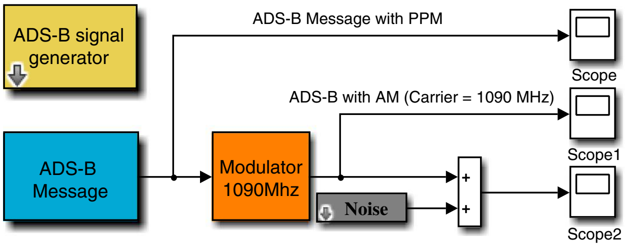


**Fig. 6 ADS-B generator and modulator.**

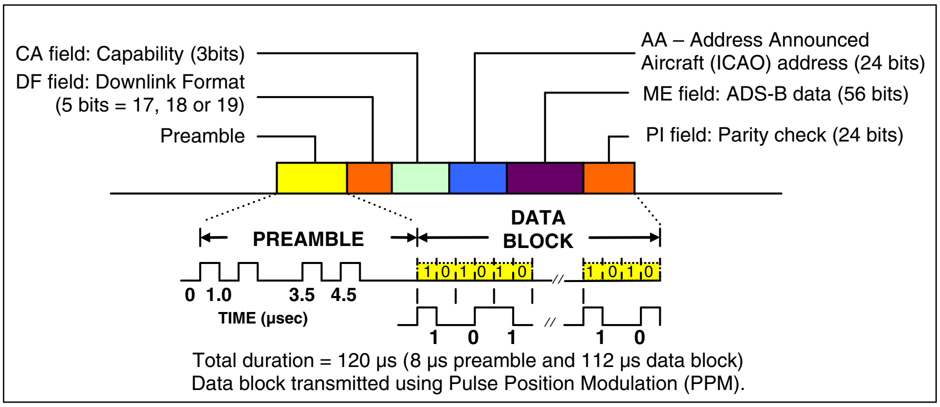


**Fig. 5 Mode-S extended squitter format [21].**

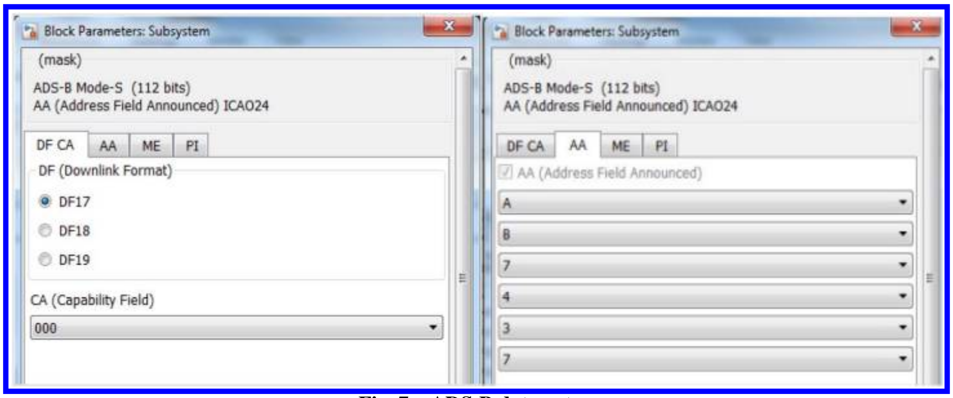


**Fig. 7 ADS-B data entry.**



**Table 4 Number of passengers, and minimum and maximum expected mean data rate per aircraft type [2]**

| Aircraft | Number of passengers | Minimum expected mean data rate, Mbps | Maximum expected mean data rate, Mbps |
|---|---|---|---|
| A320 | 150–180 | 52.43 | 62.91 |
| A330 | 253–440 | 88.43 | 153.79 |
| A350 | 270–550 | 94.37 | 192.23 |
| A380 | 555–853 | 193.98 | 298.14 |
| B737 | 85–215 | 29.71 | 75.15 |
| B777 | 301–550 | 105.20 | 192.23 |
| B787 | 210–330 | 73.40 | 115.34 |
| B747 | 467–605 | 163.22 | 211.46 |

### B. Priority of Communication System Based on the Phases of Flight

The priority of communications during the flight is determined by the degree of commitment to flight safety. For this purpose, ACARS and ADS-B are used during all phases of flight (as AMSS) as these services contain information of the state of AES as well as the 4D information for better control from the ATC, unlike IFC, which contains only communications for passengers.

## IV. Simulation Architecture

The simulation model of the SDU inside an AES for AN is based on a one-way communication by sending safety and nonsafety information from AES to GES using a satcom channel. In Fig. 8 the stage of the simulation as well as the architecture of the Simulink model is shown.

This architecture allows us to transmit simulation data from ACARS, ADS-B, and IFC message generators, obtained in the previous, from the SDU of the neighboring AES (NAES) to the SDU of the AES (Fig. 9). The AES immediately will send the data received by adding their own data, using an A/A link [6]; that is, the goal is to ensure the sending of not only the messages of AES in AN but also data from NAES via AMSS. This link is performed considering the random noise, which is added in the transmission and controlling the signal-to-noise ratio (SNR) for simulation purposes [23].

It should be mentioned that both the NAES SDU and the AES SDU have the ability to make an own satcom link. However, the proposed scenario assumes that the AES SDU provides greater capacity and better SNR within the AN and availability in terms of traffic, bandwidth (BW), and quality of service (QoS).

In a real scenario, the SDU must have resource allocation techniques enabling it to verify and assign the size, availability, and QoS communication channel to share. This could be implemented in a software-defined radio (SDR). SDRs offer benefits of 1) easy replacement and upgrades of protocols, 2) low-cost integration of new aircraft standards, 3) flexible development and use of monitoring tools for QoS, and 4) upgrades to signal processing as spectrum efficiency practices evolve, all ensuring the scalability and future adaptability of the AN system.

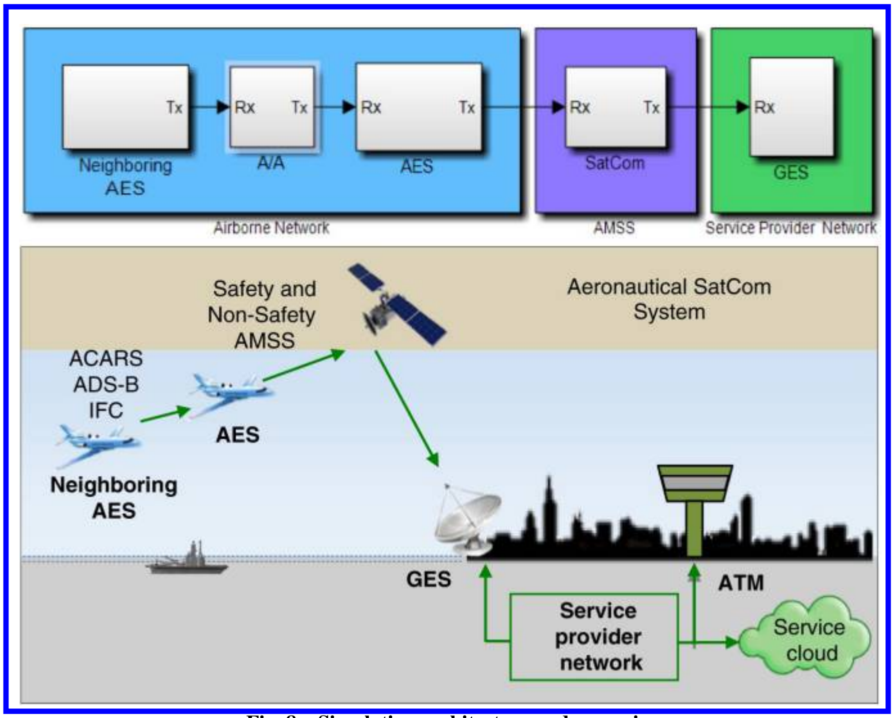


**Fig. 8 Simulation architecture and scenario.**

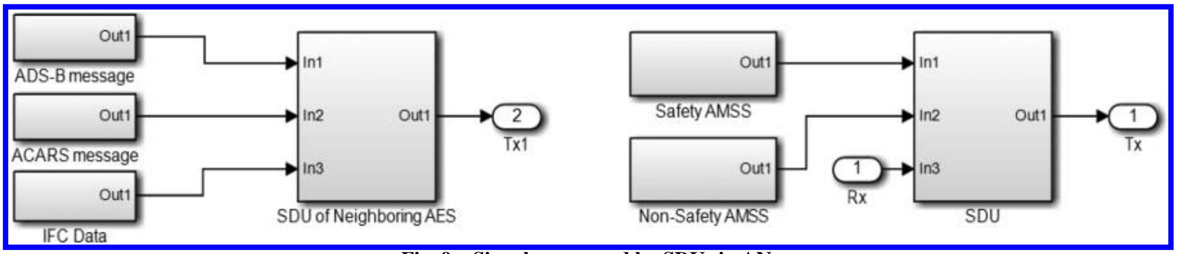


Fig. 9 Signals processed by SDUs in AN.

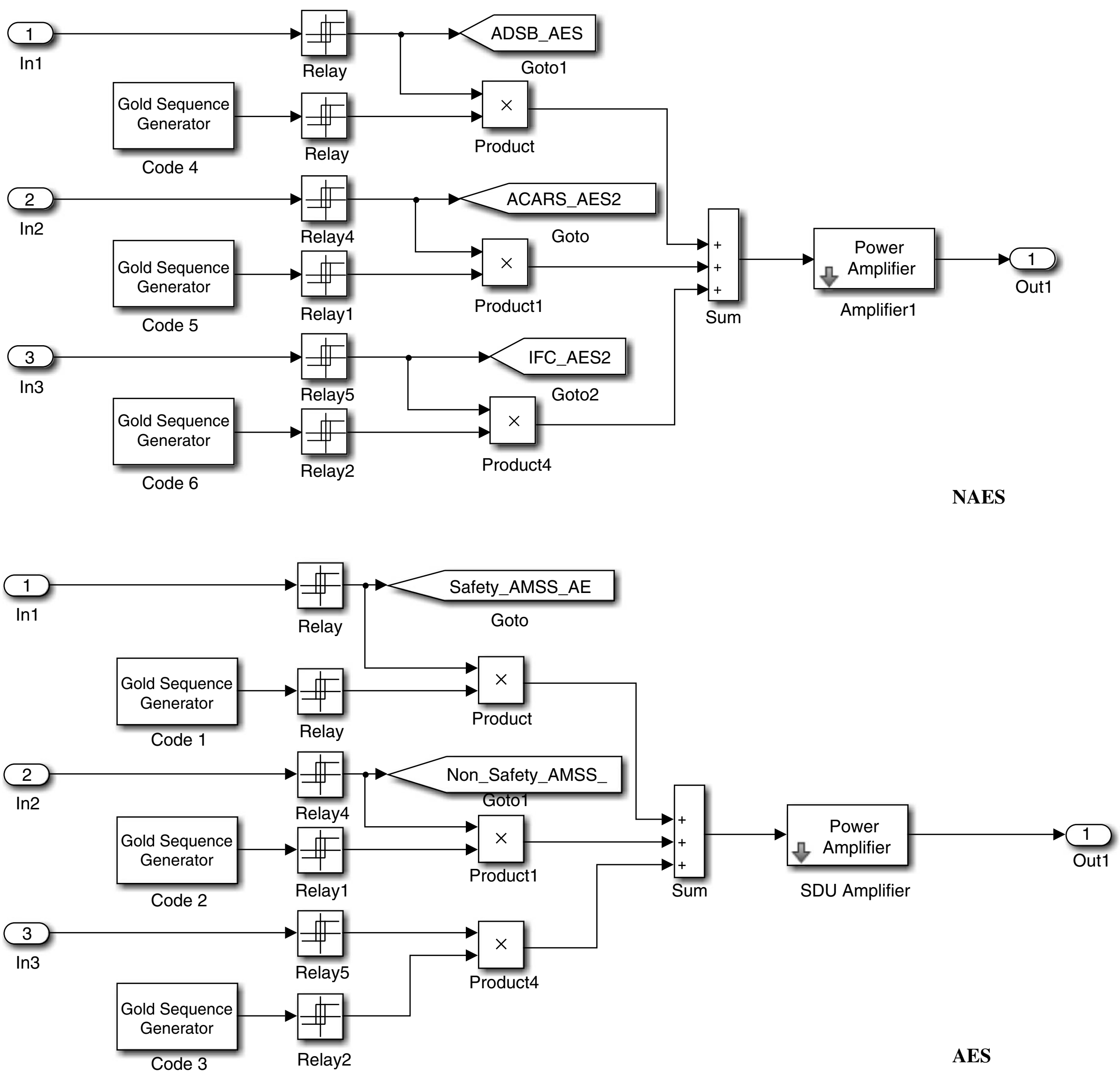


Fig. 10 SDU architectures (NAES and AES).

### A. Signal Processing Inside SDUs

Within our SDU, one of the problems is how to coordinate various systems (ACARS, ADS-B, and IFC) using a single channel of communication via AMSS, so that they can manage several messages simultaneously. This concept is called multiplexing or media access control. Without an organized approach, interference may prove troublesome, or directly impede communication.

To solve this challenge, we will use a spread spectrum technology and a special coding scheme, whereby each message generator will assign a unique code, chosen so that it is orthogonal to the rest (Fig. 10). It is worth mentioning that in this study we are not going to develop the RF aspect but rather the treatment of signal through the SDU. To do so, inside the SDU each entry is multiplied by Gold codes or Gold sequences[§] (to minimize correlation and so maximize separability of signals broadcast in the same frequency range).

In Fig. 11 we can observe that for each input for AES and NAES, there is a Gold sequence generator block. Gold sequences are unique for each SDU input and are emitted with a bandwidth significantly higher than data.

Take, for example, Fig. 12; to the left of the figure, the spectral density of the ADS-B message from NAES (ADSB_AES2 in Fig. 11), which occupies a 2 MHz BW, is shown. To the right of the

[§]Gold codes are binary sequences commonly used in communications systems, mainly in GPS and mobile cellular telephony, which have characteristics that resemble random noise [24].

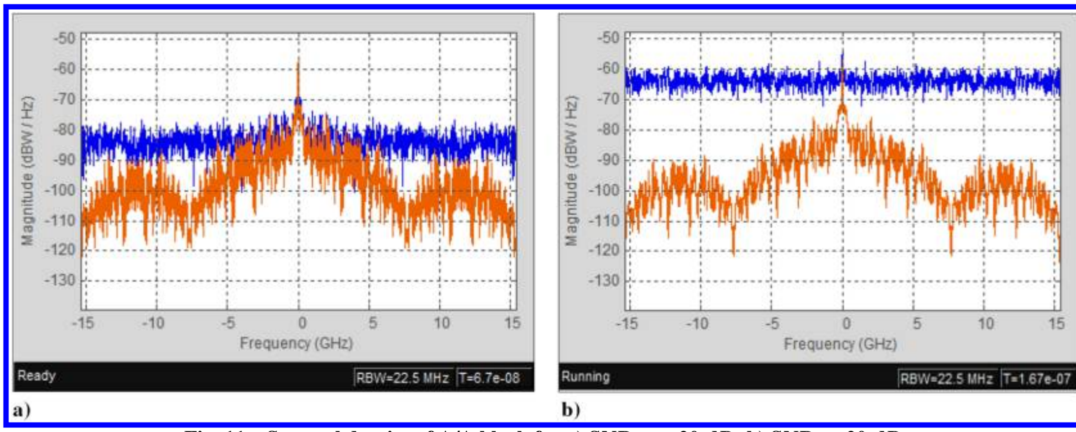


**Fig. 11 Spectral density of A/A block for a) SNR = −20 dB; b) SNR = 20 dB.**

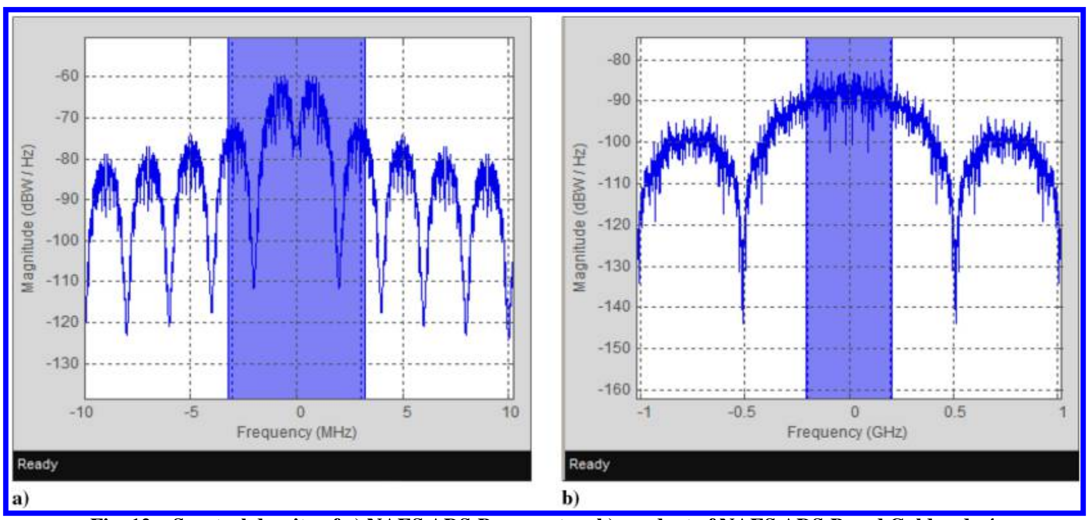


**Fig. 12 Spectral density of a) NAES ADS-B generator; b) product of NAES ADS-B and Gold code 4.**

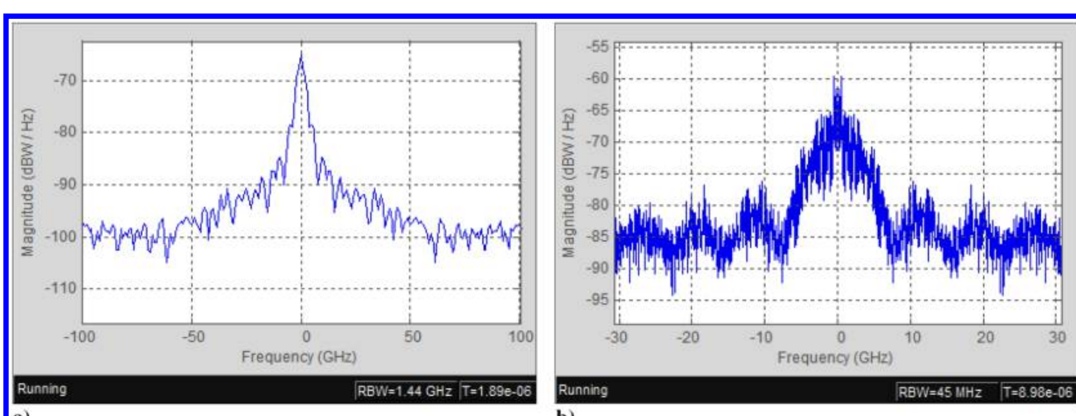


**Fig. 13 a) Spectral densities in GES receptor for SNR = 10 with SF = 256. b) Spectral densities in GES receptor for SNR = 10 with SF = 8.**

figure we can see the spectral density of the product of the ADS-B message from the NAES (ADSB_AES2 in Fig. 11) and the Gold code (Code 4) that was generated: this waveform occupies a BW of 512 MHz. To do this, based on Ref. [24], we process the messages of the ADS-B generator with a spreading factor (SF) of 256,[¶] a data rate of 2 Mbps and Gold code data rate of 512 Mbps.

More clearly, the Gold code generated by the block Code 4 (Fig. 10) uses the preferred pair of polynomials: $[1] = [9 \quad 4 \quad 0]$ and $[2] = [9 \quad 6 \quad 4 \quad 3 \quad 0]$. For more details on how these sequences are generated, see Ref. [25]. As we know, a BW required by a signal is $1/T$, where $T$ is the time used in the transmission of a bit; therefore, the BW of transmitted data is $1/0.5$ $\mu$s and the spread spectrum signal is 1/1.95 ns. Since 1.95 ns $\ll 1/0.5$ $\mu$s, the bandwidth of the emitted signal will be greater than the original signal.

The ACARS message that occupies a 2.4 KHz BW, coming from the NAES (ACARS_AES2 in Fig. 11), will be multiplied by its assigned Gold code (Code 5). This block uses the preferred pair of polynomials $[1] = [1 \quad 0 \quad 3 \quad 0]$ and $[2] = [1 \quad 0 \quad 8 \quad 3 \quad 2 \quad 0]$. In this case, we process the messages of the ACARS generator with an SF of 256, a data rate of 2.4 Kbps, and Gold code data rate of 614.4 Kbps. The spectral density of the product of the ACARS message and the Gold code generated occupies a BW of 614.4 KHz.

[¶]The SF is the ratio of the chips (UMTS = 3.84 Mchips/s) to baseband information rate. SF varies from 4 to 512 in FDD UMTS [24].

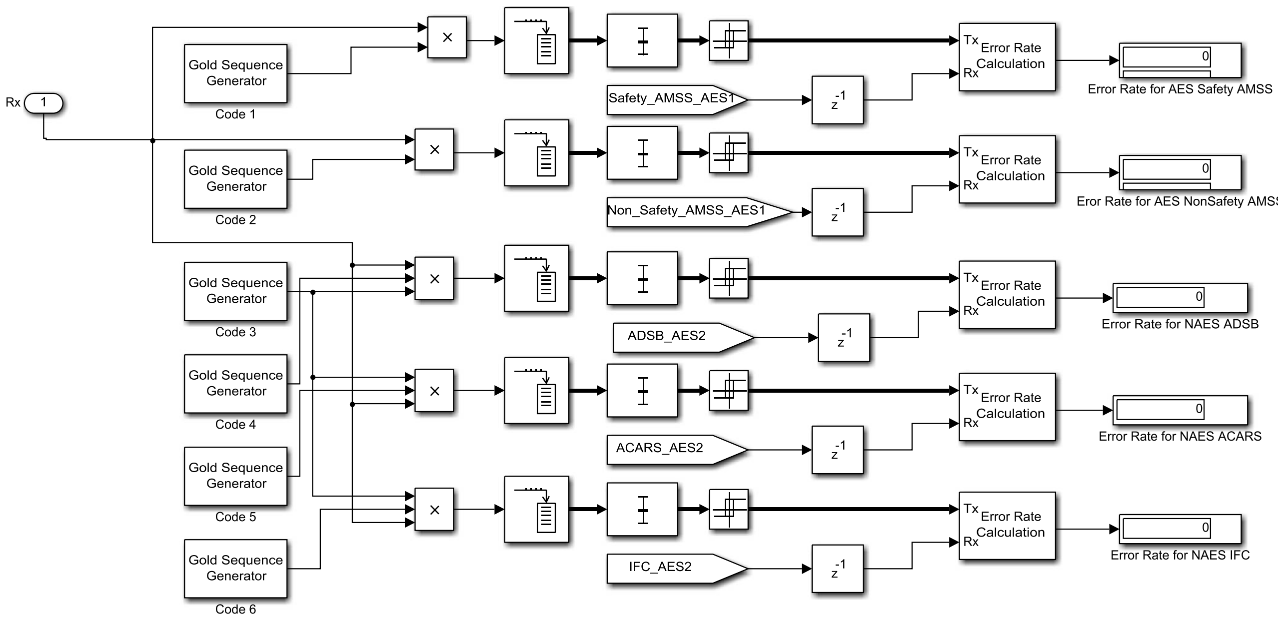


**Fig. 14 Data error rate at GES.**

**Table 5 Bit Error Rate values**

| | | SF | | | | | |
|---|---|---|---|---|---|---|---|
| SNR, dB | Data signal | 4 | 8 | 32 | 64 | 128 | 256 |
| −40 | Safety | 0.004217 | 0.003454 | 0.002108 | 0.001355 | 0.000733 | 0.000151 |
| | Nonsafety | 0.004056 | 0.003203 | 0.002349 | 0.001396 | 0.000582 | 0.000161 |
| | ADS-B | 0.005070 | 0.004829 | 0.005120 | 0.005050 | 0.005151 | 0.004518 |
| | ACARS | 0.005201 | 0.005181 | 0.005100 | 0.004729 | 0.004729 | 0.004719 |
| | IFC | 0.005070 | 0.005261 | 0.005070 | 0.004719 | 0.004749 | 0.004689 |
| −30 | Safety | 0.001998 | 0.000994 | 0.000121 | 0.000000 | 0.000000 | 0.000000 |
| | Nonsafety | 0.002028 | 0.000984 | 0.000100 | 0.000000 | 0.000000 | 0.000000 |
| | ADS-B | 0.005050 | 0.004809 | 0.004990 | 0.005201 | 0.005090 | 0.004508 |
| | ACARS | 0.005181 | 0.005160 | 0.004980 | 0.004809 | 0.004679 | 0.004759 |
| | IFC | 0.005070 | 0.005271 | 0.005020 | 0.004769 | 0.004759 | 0.004679 |
| −20 | Safety | 0.000020 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | Nonsafety | 0.000040 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | ADS-B | 0.004890 | 0.004739 | 0.004920 | 0.005020 | 0.004990 | 0.004398 |
| | ACARS | 0.004980 | 0.004960 | 0.004779 | 0.004659 | 0.004839 | 0.004709 |
| | IFC | 0.004809 | 0.005030 | 0.005000 | 0.004679 | 0.004669 | 0.004659 |
| −10 | Safety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | Nonsafety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | ADS-B | 0.003133 | 0.003504 | 0.003695 | 0.004056 | 0.004187 | 0.003916 |
| | ACARS | 0.003253 | 0.003454 | 0.003735 | 0.004177 | 0.004347 | 0.004327 |
| | IFC | 0.003313 | 0.003464 | 0.004046 | 0.004106 | 0.004408 | 0.004317 |
| 0 | Safety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | Nonsafety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | ADS-B | 0.000211 | 0.000442 | 0.001968 | 0.002771 | 0.003213 | 0.003554 |
| | ACARS | 0.000161 | 0.000532 | 0.001867 | 0.002861 | 0.003323 | 0.003896 |
| | IFC | 0.000221 | 0.000572 | 0.001737 | 0.002691 | 0.003373 | 0.003886 |
| 10 | Safety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | Nonsafety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | ADS-B | 0.000000 | 0.000070 | 0.001275 | 0.002179 | 0.002841 | 0.003353 |
| | ACARS | 0.000000 | 0.000060 | 0.001155 | 0.002239 | 0.003072 | 0.003755 |
| | IFC | 0.000000 | 0.000040 | 0.001004 | 0.001968 | 0.003042 | 0.003624 |
| 20 | Safety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | Nonsafety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | ADS-B | 0.000000 | 0.000060 | 0.001225 | 0.002068 | 0.002671 | 0.003253 |
| | ACARS | 0.000000 | 0.000050 | 0.001124 | 0.002189 | 0.002982 | 0.003554 |
| | IFC | 0.000000 | 0.000040 | 0.000974 | 0.001857 | 0.002952 | 0.003554 |
| 30 | Safety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | Nonsafety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | ADS-B | 0.000000 | 0.000060 | 0.001220 | 0.002060 | 0.002669 | 0.003250 |
| | ACARS | 0.000000 | 0.000040 | 0.001120 | 0.002184 | 0.002978 | 0.003548 |
| | IFC | 0.000000 | 0.000030 | 0.000974 | 0.001852 | 0.002946 | 0.003542 |
| 40 | Safety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | Nonsafety | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| | ADS-B | 0.000000 | 0.000060 | 0.001218 | 0.002042 | 0.002660 | 0.003242 |
| | ACARS | 0.000000 | 0.000040 | 0.001116 | 0.002172 | 0.002960 | 0.003538 |
| | IFC | 0.000000 | 0.000030 | 0.000973 | 0.001847 | 0.002938 | 0.003537 |

In the case of IFC, we process messages of the IFC system (IFC_AES2 in Fig. 10) for a data connection of 30 Mbps with an SF of 256, which means that a data rate of 30 Mbps and Gold code data rate of 7.68 Gbps will be necessary. The Gold code block uses the preferred pair of polynomials: $[1] = [7\quad 3\quad 0]$ and $[2] = [7\quad 3\quad 2\quad 1\quad 0]$.

The three data signals encoded in the SDU of NAES are added before amplification and transmission to the receiver of the SDU of AES passing through the A/A block (Fig. 8). In the A/A block we can control the SNR level for purposes of simulation of the complete system; within this block Gaussian noise is added to the signal data sent to the SDU of AES. The waveform of the spectral density measurements for different values of SNR (data input signal in orange and data signal output in blue) is shown in Fig. 11.

The result of the A/A block, to be received in the receiver AES SDU, will be multiplied with the Code 3 block and this in turn will again be added to the signals resulting from the data signals safety AMSS (which is multiplied by the Code 1 block) and nonsafety AMSS (which is multiplied by the Code 2 block) of AES (Fig. 10).

The BW of the transmitted signal will be directly proportional to the highest data rate required by systems to transmit, which means that in the case of the SDU of NAES the BW will be 7.68 GHz. As we can see, the IFC is the AMSS that demands largest/highest BW; in other words it is what determines our SDU BW within an AN. This means also that to comply with the maximum estimated capacity of Table 4, it would require a larger BW in 2020.

Inside the AES SDU, we find the same internal architecture as the NAES SDU with the difference that this SDU has a channel that allows the reception and forwarding of the received signal. The AES SDU must not compromise its own satcom connection, and so it must check availability in terms of traffic, BW, and QoS before allocating capacity to AN service.

## B. Receiving and Decoding

After passing through the satcom block, which consists of the same architecture as the A/A block (in order to control the SNR), the data signal of the SDU arrives at GES. In Fig. 13, we can see the spectral density at the receiver for SNR $= 10$ and SF $= 256$ and 8.

The next step is to recover the signals sent, which is done by cross-correlation of the captured signal with the code of the system of interest, as well as the rejection of the rest of the signals and interference produced in the transmission of the source signal [25].

In our case, we calculate the mean value of the result of multiplying the received signal with the corresponding Gold code, recovering the original signals (see Fig. 14). It is worth mentioning that to make an effectively cross-correlation at reception, the GES must know the

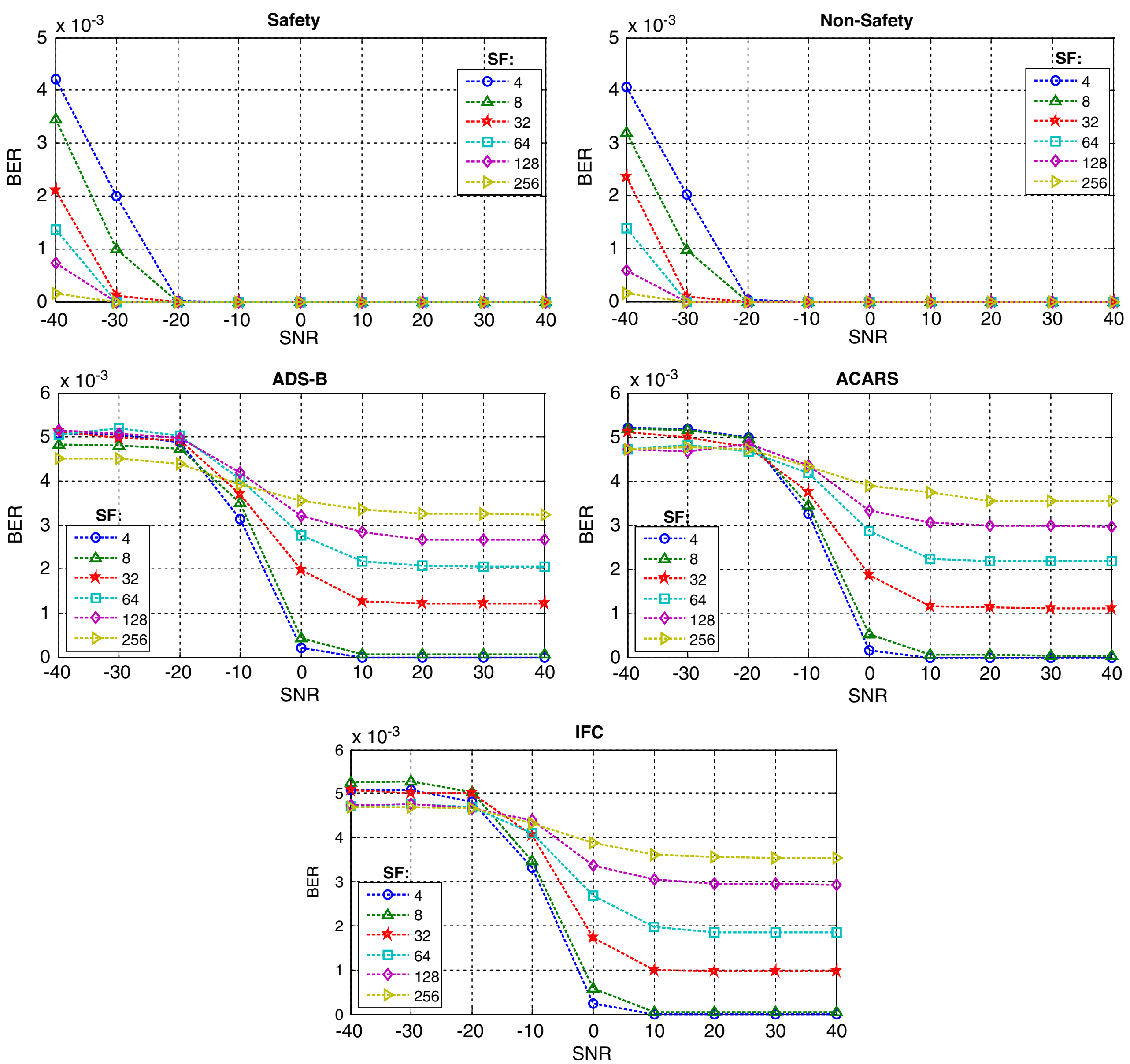


**Fig. 15 Bit error rate values for different SNRs.**

golden codes of the architecture—in a real case, a real-time algorithm that would do this task. This solution not only allows us to improve the capacity of the communication system in the AN, increasing with the number of simultaneous AES, but also allows maximum use of the BW available.

## V. Results

To evaluate the performance in the SDU it is necessary to measure the bit error rate (BER) in all channels. SDU optimization suggests reducing the BER in communication channels, to thereby ensure the reliability and robustness of AES and NAES messages (one or more); in the same way, these measures will allow us to decide on, in future work, the appropriate adaptive coding and modulation (ACM).

To do this, we use communications of 2 Mbps with a BW of 512 MHz. Then we send 2 Mbits per channel varying in each simulation the SNR system values as well as the SF. The main objective is to verify the reliability of the system, mainly by maintaining a low error rate in the sending of their own data signals (safety and nonsafety communications). Table 5 presents the obtained results.

As results, in Fig. 15 we can see that in the SDU for the safety and nonsafety AMSS communications cases, from an SNR equal to or greater than $-20$ dB, the system keeps a good performance; regardless of the SF variation, the BER is kept at zero. For SNR values lower than $-20$ dB, the increase in the SF value allows better performance in these communication channels, maintaining a BER in the order of $10^{-3}$. Although $10^{-3}$ is not a recommended value for satcom data, we must consider that this model does not have forward error correction (FEC), with which the BER would be considerably reduced. Therefore, the SDU is reliable for its own data signals, unlike the information channel that acts as a gateway between the GES and NAES via satcom.

In the case of the communications from the NAES (ADS-B, ACARS, and IFC) to the GES, it is observed that for SNR lower than $-20$ dB, increasing the SF improves the BER due to the levels of noise; however, for SNR greater than $-20$ dB the results show that it is advisable to maintain lower SF values due to the power of the received signal. These SF variations as a function of the BER will be useful for future integration with ACM methods to be implemented in the SDU.

In a real scenario, the implementation of algorithms requires a continuous crossing of information within the AN to determine which AES will be the backbone of the AN. Also, the biggest challenge in the implementation of an SDU model under this scheme in an AN is the requirement of the hardware, because although the bit rate is not high, spectrum spreading code rate is, thus requiring high-speed transmitters.

## VI. Conclusions

In this paper, the simulation/optimization modeling for a robust satellite data unit (SDU) for airborne network (AN) integrating different simulation models on avionics systems, such as ADS-B, ACARS, and in-flight connectivity, has been presented.

A review of the main elements in an AN presenting an SDU architecture based on spread spectrum technology has also been provided. In this way, this work intends to contribute to the aviation industry with the development of a device that ensures greater operational safety and ease of being implemented in a flexible platform.

Key contributions of this paper include signal processing architecture and design from NAES to ground Earth station via the SDUs, and the demonstration of the flexibility of SDUs in an AN for coordinated optimization of network service while locally maintaining performance of the individual AES's own data communication service. Also, it is important to emphasize the reliability of SDU as messages within the waveform are difficult to detect or intercept if you do not have the correct Gold Code.

The development of this solution in a physical platform will require high-speed and complex transmitters. Similarly the development of the SDU can accommodate a Global Aeronautical Distress and Safety System (GADSS [26]) by sending information from an AES not only to a satellite but also to other nearby AES in an AN [27].

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