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Performance Analysis of Aeronautical Telecommunication Systems: Optimizing the Aircraft-to-VDL2 Ground Station Assignment

Thesis submitted for the degree on Aeronautical Management

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Title:

- Performance Analysis of Aeronautical Telecommunication Systems: Optimizing the Aircraft-to-VDL2 Ground Station Assignment
- Análisis del rendimiento de los sistemas de telecomunicaciones aeronáuticas: Optimización de la asignación de aeronaves a estaciones de tierra VDL2
- Anàlisi del rendiment dels sistemes de telecomunicacions aeronàutiques: Optimització de l'assignació d'aeronaus a estacions de terra VDL2

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Summary:

English: The main goal of this research is the examination of the behavior of aerocommunications equipment and the reduction of the overload of their data transmission channels. The research has been conducted through the use of instruments like geometric LoS modeling, mathematical modeling using Excel spreadsheets, and real air traffic situations to find the optimal solution for the assignment of particular aircrafts to particular VDL2 ground stations.

Castellano: El propósito de este trabajo es investigar el desempeño de los sistemas de telecomunicaciones aeronáuticas e intentar prevenir la saturación de sus canales de datos. Este estudio ha sido realizado utilizando herramientas como la modelización del alcance geométrico por línea de visión (LoS), la optimización matemática con hojas de cálculo Excel y la evaluación de escenarios de tráfico aéreo concretos para establecer la metodología más efectiva y óptima en el asignamiento de aviones a estaciones de radio VDL2 designadas específicamente.

Català: L'objectiu d'aquest treball és investigar el desenvolupament dels sistemes de telecomunicació aeronàutics i intentar preveure la saturació dels seus canals de dades. Aquest estudi ha estat realitzat fent ús d'eines com la modelització de l'abast geomètric per línia de visió (LoS), l'optimització matemàtica amb fulls de càlcul Excel i l'avaluació d'escenaris de trànsit aeri concrets per establir la metodologia més efectiva i òptima en l'assignació d'aeronaus a estacions de ràdio VDL2 designades específicament.

Abstract

The increase in air traffic results in the congestion of the communication channel that can negatively impact the efficiency and safety of contemporary aviation operations. In this regard, the problem is especially acute in Europe, where a great number of messages is transmitted daily. Despite the improvement in communication technologies, airports incur substantial expenses to support their ground infrastructure, and efficient management practices are not available for dealing with peak traffic. To address this problem, the research investigates the performance of aviation communication networks and suggests a way of protecting channels from being overloaded.

The primary objective is the creation of an optimal algorithm for allocating aircraft connections between various ground-based radio stations. The objectives of such a system include improving message delivery rates, establishing reliable connections, and effective utilization of radio frequency range. The suggested approach includes a mathematical algorithm for assessing each particular aircraft and the network as a whole.

In order to prove the effectiveness of this technique, a computing algorithm based on geographic principles and radio propagation properties was developed and tested on realistic traffic scenarios. Spreadsheets and traditional optimization algorithms were used in this case to ensure the integration of all the data. It appears that the proposed technique can effectively compute areas of coverage, handle multiple aircraft at once, and adjust itself depending on traffic conditions. Overall, this strategy can help enhance the performance of regional networks without resorting to expensive upgrades.

- Key Words: VDL Mode 2 (VDL2) , Air Traffic Management (ATM) , mathematical optimization , Mixed-Integer Linear Programming (MILP) , Excel Solver , Packet Error Rate (PER) , Line-of-Sight (LoS) , channel congestion , load balancing.

Resumen

El crecimiento del tráfico aéreo está haciendo que los medios de comunicación aérea se conviertan en cada vez más en entornos más saturados, lo que amenaza la eficiencia y la seguridad de la aviación moderna. El problema es notablemente grave en los espacios aéreos de Europa más transitados, donde fluye una gran cantidad de mensajes día tras día. Aunque la tecnología ha mejorado, los sistemas en tierra siguen teniendo costos operativos muy elevados y faltan estrategias innovadoras para distribuir las conexiones en los momentos cumbre. Por eso, este trabajo estudia el rendimiento de las redes de comunicación aeronáutica y busca soluciones para prevenir que los canales de comunicación se congestionen.

El propósito principal es desarrollar e implementar un procedimiento capaz de asignar adecuadamente a qué estación de control aéreo cada vuelo debe dirigirse. De esta manera, se garantiza que los envíos de señales lleguen sin problemas, que la conexión entre los vuelos sea más constante y que se maximice el uso de las frecuencias radiofónicas disponibles. La solución sugerida emplea un modelo matemático sencillo que analiza la situación de cada vuelo para asegurar que la red aérea sea equilibrada.

Para verificar su eficacia, se ha creado un entorno de cálculo basado en las reglas geográficas de la cobertura de radio, simulando situaciones con tráfico aéreo real. Se han realizado operaciones y se mantienen los datos a través de hojas de cálculo y herramientas de optimización convencionales. Los resultados demuestran que el sistema puede identificar límites de cobertura, manejar múltiples aviones simultáneamente y responder a imprevistos como los espacios aéreos. En conlusión, este enfoque hace que la red esté utilizada al máximo sin tener que hacer grandes gastos en equipos físicos, dando así una alternativa práctica basada en la realidad y en los datos reales.

- Palabras clave: VDL Modo 2 (VDL2) , Gestión del Tráfico Aéreo (ATM), optimización matemática , Programación Lineal Entera Mixta (MILP), Excel Solver, Tasa de Error de Paquetes (PER), Línea de Visión (LoS) , saturación del canal, equilibrado de carga.

Resum

El creixement del trànsit aeri està fent que els mitjans de comunicació aèria es converteixin cada vegada més en entorns més saturats, la qual cosa amenaça l'eficiència i la seguretat de l'aviació moderna. El problema és notablement greu en els espais aeris d'Europa més transitats, on flueix una gran quantitat de missatges dia rere dia. Tot i que la tecnologia ha millorat, els sistemes a terra continuen tenint costos operatius molt elevats i falten estratègies innovadores per distribuir les connexions en els moments cimera. Per això, aquest estudi examina el rendiment de les xarxes de comunicació aeronàutica i busca solucions per prevenir que els canals de comunicació es congestionin.

El propòsit principal és desenvolupar i implementar un procediment capaç d'assignar adequadament a quina estació de control aeri cada vol s'ha de dirigir. D'aquesta manera, es garanteix que els enviaments de senyals arribin sense problemes, que la connexió entre els vols sigui més constant i que es maximitzi l'ús de les freqüències radiofòniques disponibles. La solució suggerida empra un model matemàtic senzill que analitza la situació de cada vol per assegurar que la xarxa aèria sigui equilibrada.

Per verificar la seva eficàcia, s'ha creat un entorn de càlcul basat en les regles geogràfiques de la cobertura de ràdio, simulant situacions amb trànsit aeri real. Es realitzen les operacions i es mantenen les dades a través de fulls de càlcul i eines d'optimització convencionals. Els resultats demostren que el sistema pot identificar límits de cobertura, gestionar múltiples avions simultàniament i respondre a imprevistos com els espais aeris. En conclusió, aquest enfocament fa que la xarxa estigui utilitzada al màxim sense haver de fer grans despeses en equips físics, donant així una alternativa pràctica basada en la realitat i en les dades reals.

- Paraules clau: VDL Mode 2 (VDL2), Gestió del Trànsit Aeri (ATM), optimització matemàtica, Programació Lineal Entera Mixta (MILP), Excel Solver, Taxa d'Error de Paquets (PER), Línia de Visió (LoS), saturació del canal, equilibri de càrrega.

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1. Introduction

1.1. Project description

Aeronautical telecommunications form the basis for contemporary ATM; without them, it would be impossible for planes to navigate through busy airspaces efficiently and with minimum risk of collision [10][20]. Currently, data link systems based on digital telecommunications technologies are being implemented, superseding the traditional analog voice communications in the field. Amongst other factors, the "Voice to Data" revolution in ATM is mainly determined by the transition to a new international standard for exchange of critical information between pilots and controllers via CPDLC, known as the VHF Data Link Mode 2 (VDL2).

The objective of this Final Degree Project (TFG) is the analysis of the performance of aeronautical telecommunications networks with regard to the optimization of the terrestrial components of the network. In particular, attention will be paid to the GS Aircraft Assignment Problem: as the volume of traffic using VDL2 communication protocol increases [3], network capacity ceases to depend only on the capabilities of the equipment onboard aircrafts.

This project relies on building an optimization model using Excel Solver which will serve as the foundation of the entire endeavor. The optimal link for every aircraft will be identified taking into consideration such criteria as transmission costs, packet error rate, and propagation distance among others. Using this model, the project seeks to demonstrate how reliable networks may be achieved without the need to incur expensive physical network expansions. Also, the objective is to come up with dynamic scenario testing to determine the network performance under extreme load and congestion and examine how the network effectively distributes data traffic under such critical conditions."

1.2. Problem Statement

Even with the advantages offered by digital communication, the VDL2 infrastructure is constrained. There is a constraint in the maximum number of planes that can be handled at one go by each ground station, or more precisely by each physical antenna located on earth.

Some of the problems such an imbalance would cause include message latency, delay in critical safety information, inefficiencies in the network, inefficient use of existing infrastructures, and managerial challenges such as difficulty in arranging the deployment of ground stations.

The assignment problem, as highlighted earlier, lies at the core of this thesis and refers to the mathematical formulation that ensures that all aircraft are assigned to the best

possible ground station but not exceeding the maximum capacity of the ground station.

The ultimate aim of the research work carried out in this thesis is to optimize the aircraft to ground station assignment problem in the VDL2 network by evaluating the performance of telecommunication systems.

1.3 General Objective

Design and implement an optimization model that ensures proper allocation of aircrafts to VDL2 ground stations and reduces overall cost of communications and signal loss without compromising on network robustness through capacity management.

1.3.1 Specific Objectives

- Identify and categorize operational limitations: Investigate the technical constraints associated with VDL2 ground stations, focusing on the upper limit of messages per minute, geographical reach, and the effect of Packet Error Rate (PER) on the link's reliability [12][27].

- Develop a Mathematical Assignment Model: Formulate a mathematical linear programming model that treats the link as an operational problem based on distance and PER being the major costs.

- Validate the model with Excel Solver: Convert the model into a practical application using Microsoft Excel to demonstrate that even complex aeronautical problems can be solved with friendly and affordable management software.

- Sensitivity and Scenario Analysis: Evaluate the sensitivity of the network with a "stress test," such as a sudden 20% increase in traffic or the failure of a key ground station, to determine its strength.

- Strategic Management Recommendations: Take advantage of the results to provide strategic management advice to ANSPs in improving current infrastructure efficiency before any CAPEX is incurred.

1.4 Risks

Implementation of the above thesis is faced with numerous risks, which should be tackled proactively to ensure successful and quality completion of the research.

- Limitations due to Technical Issues and Software: The first major risk lies in the difficulty of learning how to use Excel Solver. Incorrect programming in terms of setting constraints will lead to wrong results. This risk can be addressed through testing of the smaller models before moving to the analysis of the entire data set. Secondly, there is also the risk of data corruption due to working with bulky Excel sheets.

- Access to Resource and Information: Limited access to technical standards set out by ICAO and Eurocontrol may pose a possible threat to the research process. It will be dealt with by prioritizing the review of literature and using university libraries to acquire relevant documents.

- Pragmatism of Model: It is likely that an unrealistic model might be created since it will be mathematically perfect yet hard to implement in real-life ATM systems. Continued focus on the theoretical assumptions identified during background research should address this issue.

2. Background on VDL2 and Aeronautical Data Links

2.1. Evolution of Aeronautical Communications: From Analog Voice to Digital Data Link

2.1.1. The Legacy of Analog Communications (VHF Voice)

The history of ATM communications was formed based on voice communication via the Very High Frequency (VHF) band, especially from 118.000 MHz to 136.975 MHz. Voice communications in this case use Double Sideband Amplitude Modulation (DSB-AM) technology since the choice for this type was made in the middle of the 20th century due to ease and robustness [5]. In this regard, there is no two-way communication; only one side is able to communicate at any time on the same frequency.

For decades, this "party line" system worked well enough. It provided controllers and pilots with a shared level of situational awareness in that all pilots in the sector could listen to the instructions being issued to other pilots. However, as the sector evolved, this became a fundamental weakness in the system because the nature of an analog transmission meant that any form of interference, whether due to atmosphere, malice, or simply other signals "stepping over," resulted in total information loss. In terms of management considerations, it meant that there was an unstable foundation on which to build an international transportation system.

2.1.2. The Structural Crisis: Frequency Saturation and Space Constraints

The reason for evolution did not have anything to do with the need for superior quality sound; rather, it lay in the exhaustion of the radio spectrum physically [6]. The airspace is divided into sectors in order to cope with the traffic load, and each of these sectors requires a unique VHF channel. With the sharp rise in air traffic during the late 20th century, particularly in the "European Core" (a triangular airspace encompassing London, Paris, and Frankfurt), all the available frequencies were exhausted by the industry [30].

In spite of the implementation of 8.33 kHz channel spacing (resulting in three times as many channels as the previously used spacing of 25 kHz), this ceiling was eventually reached yet again [7]. This is a very critical point in the realm of Aeronautical Management, as the availability of frequencies implies that the construction of additional sectors is possible [1]. However, in case there are no sectors available to use, then capacity limitations remain irrespective of any airline plans and airport expansion projects.

2.1.3. Human Factors and Operational Inefficiency

However, beyond the boundaries of the spectrum itself, the analog voice model carried significant human-factor risks. The "Read-Back/Hear-Back" procedure is critical for flight safety but is also a major source of inefficiency [4].

- Cognitive Load: With all the noise in the background, a controller may spend up to 80% of his/her time talking. Consequently, he/she is unable to make complex tactical decisions and ends up being a “radio operator” rather than a “traffic manager.” [31]

- Language Barrier: While English is the common language in aviation worldwide, differences in accents and bad signal make repetition inevitable. In the fast pace environment where every second matters, repeating the Flight Level instruction several times becomes an unacceptable practice.

- Communication Problems: Reports from Eurocontrol and FAA consistently show that a certain number of operational errors (altitude violations or runway incursions) occur because of the “communication problems.” Unlike digital data transmission that automatically provides verification, when a controller says

"Flight Level 350" and the pilot hears "330," without noticing the discrepancy, a catastrophe is likely to happen.

2.1.4. The Paradigm Shift: VHF Digital Link (VDL)

To overcome these challenges, ICAO and other international agencies have established the VHF Digital Link (VDL) protocols. The transition to VDL, particularly VDL2, is a departure from the "connection-oriented" voice technology to the "packet-switched" data technology [3].

Instead of an uninterrupted wave that represents human speech, VDL2 splits the information into binary packets. Thanks to this technological development, various improvements are made at the managerial level:

- Multiplexing Data: While the voice frequency itself is completely occupied during the transmission process, digital packets are sent in milliseconds. It thus becomes possible for one frequency to handle many more "conversations" than a voice frequency.

- Verification of Integrity: The integrity verification is achieved through built-in error checking codes in digital packets like CRC. In case the message in the packet gets distorted because of any type of interference, there will be immediate detection and a retransmission request without the intervention of humans.

- Priority: Messages can have different priorities in a digital network. An emergency announcement could have priority over a normal weather announcement, which would not have been possible in an analog "party line" where whoever presses the microphone first occupies the frequency.

2.1.5. Key Applications: CPDLC and the Automation of ATM

The first result of this innovation is the implementation of Controller-Pilot Data Link Communications (CPDLC). Using CPDLC, it becomes possible for the controller to send routine messages such as frequency, altitude changes, and squawk codes directly to the cockpit display system.

From the performance point of view, it can be said that the result of this process is truly revolutionary. The implications of the innovations discussed above become evident in terms of the great reduction in the usage of voice channels since it can be predicted that up to 50% of routine transmissions could be transferred to data links. In such manner, the remaining VHF voice channels would remain free for tactical control orders and emergency situations, thereby increasing the level of safety margin provided in the area. Moreover, the modern connection with the Flight Management System (FMS) represents an important advance in the sphere of minimization of risks since pilots would be able to enter CPDLC orders into the computer of the aircraft with a single order.

Finally, the advancement toward worldwide interoperability is supported by systems like ADS-C (Automatic Dependent Surveillance-Contract), which utilize the data link to send accurate, automated position updates. This feature enables enhanced aircraft monitoring in oceanic or isolated areas lacking traditional radar coverage, guaranteeing a continuous and organized traffic flow throughout all flight FIRs (Flight Information Regions).

2.2. The VDL Mode 2 Standard

VDL Digital Link Mode 2 is the underlying technological component which is needed to transition towards a trajectory-based operational environment. Unlike previous modes of digital link communications, such as Mode A or classic ACARS systems, Mode 2 was engineered to be able to meet the need for high-speed transmission rates inherent to modern Air Traffic Management systems. The transmission range is located within the aeronautical VHF spectrum (from 118 to 136.975 MHz), although the technology allows for achieving a higher transmission speed of 31.5 kbps compared to the 2.4 kbps typical for analog transmission systems.

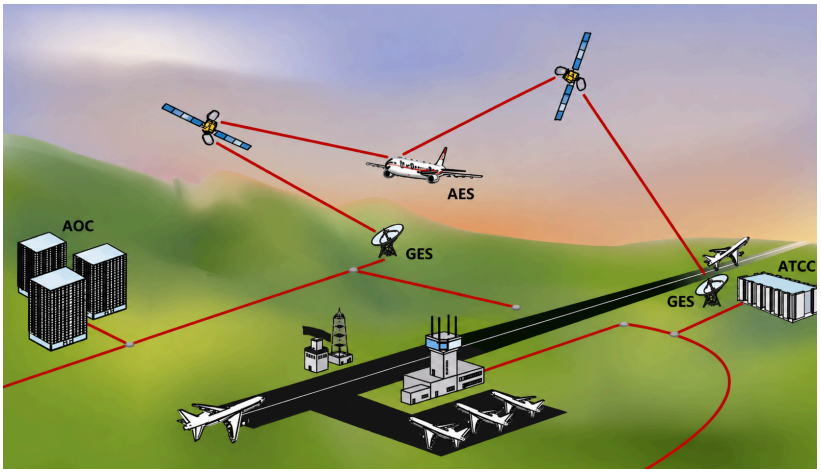


Figure 1 VHF Digital Link Mode-2 // Source: electronicsaviation.blogspot

2.2.1. Technical Characteristics and D8PSK Modulation

The physical layer, including D8PSK modulation, is both the main technical distinction of VDL2 and what drives it. In the conventional analog voice systems, the carrier wave is modulated with respect to its amplitude (AM); hence, it is highly susceptible to noise and inefficient in terms of data capacity. D8PSK modulation, however, transmits data through changes in phases of the carrier wave in pre-defined intervals

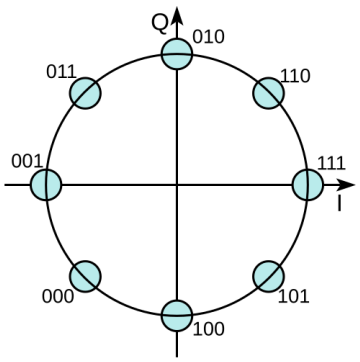


Figure 2 8 D8PSK constellations diagram // Source: Wikipedia

When using D8PSK in the system, the number of phase shifts used to convey data equals eight. Since $2^3=8$, each "symbol," that is, a carrier wave with a changed phase, will carry 3 bits of information [8][9]. This is what makes D8PSK important from the standpoint of management because, in terms of transmission, it means a higher transmission speed while keeping the bandwidth unchanged. With limited radio frequency spectrum in aeronautics and its high cost, the D8PSK offers sufficient spectral efficiency to provide communications for hundreds of aircraft at once.

However, as regards performance analysis, D8PSK proves to be much more sensitive to signal degradation than less complex forms of modulation. Therefore, the very concept of Packet Error Rate (PER) arises [12]. As the distance between the aircraft and the Ground Station (GS) grows larger, or there is some kind of local interference involved, it becomes harder to detect the phase shifts. Should the phase shift be mistaken for something else, then the entire packet would be compromised and would have to be transmitted once again. It follows that in optimizing the allocation of aircraft to GS, which is what the present thesis focuses on, one cannot limit oneself merely to achieving connectivity.

Additionally, the VDL2 technology employs the Medium Access Control (MAC) called CSMA (Carrier Sense Multiple Access). The radio devices "listen" to the medium prior to data transmission. If the frequency is busy, there will be an interval for a certain period of milliseconds, after which the attempt is repeated [10]. This "politeness" of the computer protocol allows transmitting lots of messages without the chaotic "overlap" experienced in verbal communication when simultaneous conversations produce nonsense.

2.2.2. Key Applications: CPDLC and ADS-C

VDL2 is the channel through which data transmission takes place with respect to the two main safety-related applications: Controller Pilot Data Link Communications and Automatic Dependent Surveillance-Contract. The applications can be described as tools used to transform raw data into operations.

Controller-Pilot Data Link Communications (CPDLC)

CPDLC becomes the primary approach to addressing problems related to congested voice channels. The technology provides a written communication link between the pilot and air traffic controller (ATCO). Considering the management and operational aspects of CPDLC usage, there are several points where CPDLC modifies the communication procedure:

- Message Standardization and Clarity: Messages used by controllers come from a pre-defined set of messages ("ASCEND TO FL350," "PROCEED DIRECT TO [WAYPOINT]"). Therefore, misunderstandings that may arise from accents, poor quality of speech, or language exhaustion are no longer possible. All messages are displayed on screen in front of pilots' eyes.

- Asynchronous communication control: Unlike voice traffic, which requires immediate "read-back" and distracts from other work, CPDLC communications may be asynchronous. Pilots may review clearances as their work schedule permits; controllers can make non-critical adjustments, such as changes to transponder codes, without having to wait for an interruption in the busy voice channel.

- Direct Flight Management System (FMS) integration: The most critical performance factor related to VDL2 communications is its ability to "transfer" complex route clearances directly into the flight management system. Once pilots have received a clearance digitally, it may be transferred into the FMS automatically using one button only. The chance of error in data entry is virtually nil, as the clearance will be automatically entered into the system.

Automatic Dependent Surveillance-Contract (ADS-C)

In this case, CPDLC helps with continuous communication, while ADS-C monitors and tracks the aircraft. ADS-C is a type of system that allows the airplane to transmit its position, altitude, speed, and weather data automatically to the ground system

through a "contract." Such contract represents the agreement between the ground system and airplane avionics for transmitting reports under certain conditions (such as reporting every five minutes or in cases of altitude change exceeding 300 feet).

- Operational Efficiency within Non-Radar Areas: Within the oceanic, polar, and remote airspaces not covered by ground radar, ADS-C assists in providing precise "tracking" of aircraft. These aspects have direct impacts on the economic and environmental implications, where the provision of accurate tracking of aircraft through ADS-C allows ANSPs to reduce separation between aircraft. As a result, more flights will be able to fly at their optimal altitudes and speeds, resulting in reduced fuel consumption and less CO2 emissions.

- Traffic Management: With intent data contained in the ADS-C reports such as future waypoints, the ground system can foresee collision and/or congestion risks earlier as opposed to using the traditional radar. Thus, a controller shifts from a reactionary role to that of a traffic manager.

2.3. Ground Station Infrastructure: Network architecture and Service Providers (SITA/ARINC).

In fact, the ground infrastructure of VDL2 system creates the necessary conditions that allow the transition from Voice to Data. Without proper distribution of Ground Stations (GS), the modern avionics installed in aircraft cannot establish contact with the ATC facility and/or the airline operations center. It can be defined as a highly sophisticated telecommunication structure that intends to provide full coverage across vast territories.

The complexity of the system is evident from the fact that its proper physical arrangement depends on specific Line of Sight (LoS) requirements. Since VHF waves do not follow the natural curvature of the Earth, the positioning of the ground stations determines the maximum volume of the traffic that can be accommodated by these stations. This aspect imposes a serious challenge for the management process, as geographical restrictions sometimes necessitate the establishment of stations at less than suitable sites, which implies the need for more sophisticated assignments to guarantee uninterrupted communication during the flights [3].

From the technical perspective, a VDL2 Ground Station is considered one of the key components responsible for creating the connection between analog radio communication and digital land communication network. Structurally, the stations can be divided into a number of separate parts starting from the Radio Frequency (RF) component, which controls the process of D8PSK modulation and demodulation in

order to ensure that binary data from the ground is effectively converted into phase-shifted radio frequencies for the use by the aircrafts.

At the next level above the RF component, the Ground Station Controller (GSC) acts as the brain of the system, controlling all activities at the MAC layer and managing the protocols preventing data collision. In particular, the Ground Station Controller is responsible for filtering and routing the packets and distinguishing between ATC and AOC data messages.

Once processed by the controller, the data is fed through the terrestrial backbone, known as the "Ground-to-Ground network." The Ground-to-Ground network uses fiber optics or telecommunication leased lines to deliver data to the end consumer. For purposes of performance management, each Ground Station constitutes a scarce resource with a specific "processing cap." Once a Ground Station is fully loaded, any additional demand will cause congestion or packet loss.

This international infrastructure exhibits some unique features in the context of commercial governance. While normal air traffic control systems are operated under the auspices of government agencies in individual nations, VDL2 network is largely controlled by two private, world-spanning service providers - SITA (Société Internationale de Télécommunications Aéronautiques) and ARINC (Aeronautical Radio, Incorporated). Currently, the latter operates under the Collins Aerospace label.

Originally organized as a cooperative between different airlines worldwide, SITA manages the biggest air-ground communications network in the world, known as AIRCOM [33]. On the other hand, ARINC has dominated the North American market and has expanded its GLOBALink system to compete against SITA in Europe and Asia. In terms of a managerial perspective, here lies a situation where competition as well as technology cooperation is inevitable.

Although being business rivals, SITA and ARINC must ensure that the two networks can work seamlessly with each other. This would ensure that a pilot flying from New York to Madrid does not face any problem with switching from an ARINC-controlled airspace to a SITA-controlled airspace. This "roaming" function will be managed by elaborate SLAs and international standards that ensure technical interoperability despite the differences in the configuration of equipment.

Financial implications associated with this infrastructure are quite considerable. Airlines and ANSPs enter into contractual arrangements with such suppliers, paying them fees depending on the volume of transferred data. The installation of one single Ground Station is seen as a significant financial outlay, amounting to several hundred thousand euros and entailing costs for purchasing special equipment as well as back-up power supply systems (Eurocontrol, 2020).

Thus, the efficiency of the entire VDL2 infrastructure is measured by the rate of "Resource Utilization." Failure to switch the aircraft over to another station, closer but less loaded, means inefficient management. Such a failure also causes overutilization of the bandwidth and leads to increase in the PER, which in turn triggers re-transmissions.

2.4. Operational Constraints: Capacity Limits, Signal Degradation, and Line-of-Sight

Even though moving from a conventional setup into a digital data link environment is revolutionary, the fact remains that it comes under constraints which could prove detrimental to Air Traffic Management. As far as management is concerned, these constraints can be taken to indicate where the efficiency ends. Understanding the relationship between capacity limitations, degradation of the signal, and radio wave propagation principles will explain why a simple "strongest signal" allocation technique fails to meet modern demands.

Network Capacity and the Saturation Bottleneck

The main restriction is the relatively small bandwidth capacity available for use in the radio frequency and GS processing capacity. As far as VDL mode 2 goes, though faster than the old analog version, it operates on a common medium using the CSMA (Carrier Sense Multiple Access) protocol [10]. What this means is that as more aircraft get introduced to a certain sector, the chances of a "collision" when two aircraft attempt to send transmissions become significantly higher.

Beyond a certain level of network usage, which is usually around 40-50% of its maximum possible capacity, the time taken by message delivery becomes longer. In case of an air traffic controller sending an emergency clearance message through CPDLC, a delay of just a few seconds may be unacceptable. Capacity thus poses as much as a safety issue as a technical one. To address this issue, a well-rounded distribution of aircraft across all GS becomes imperative.

Signal Degradation and the Packet Error Rate (PER)

One of the parameters used to determine the quality of a digital link is the Packet Error Rate (PER) [12][18]. The reason why the quality of a signal matters in the case of analog radio signals is because the signal might be weak but still comprehensible due to static; however, in the case of digital communication methods like VDL2, if the signal is not flawless, then it will be considered as corrupted and rejected.

There can be many reasons for the signal degradation, such as distance, surrounding environment, and electronic interference, among others. As the quality of the signal

becomes worse, so does the PER, causing packets to be resent. As a result, a "vicious cycle" starts from the perspective of management – sending packets consumes more resources, which cause even more congestion, leading to collisions and degradation. Therefore, an efficient system should concentrate on providing connections with a minimal PER in order to maximize success.

Line-of-Sight (LoS) and Geographical Constraints

Finally, the toughest constraint about the VHF band is the "Line-of-Sight" (LoS) property of the VHF band propagation. As VHF waves barely bend round the Earth horizon or pass through major terrain obstructions, the relationship between the aircraft and a ground station depends purely upon the earth curvature and the aircraft elevation above the surface.

This means that for the Aeronautical Manager, while the ground station will certainly have sufficient spare capacity, it does not help the aircraft flying behind a series of mountains or below the horizon of that ground station. The problem in the mathematical modeling aspect is how to effectively manage the "transfer" from one station to another. The system must be able to anticipate when the aircraft approaches the limit of its LoS coverage and transfer it to a different station offering optimum trade-off between the signal strength and capacity constraints.

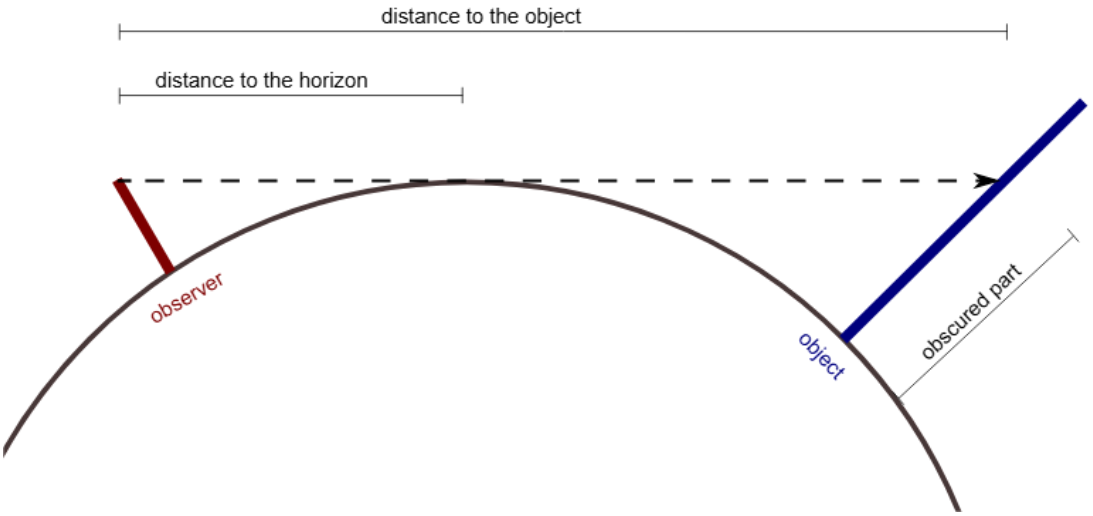


Figure 3 Calculate the obstructed height of an object // Source: Omni calculator

Constraint	Physical Nature	Operational Impact on ATM	Management Challenge

Capacity Limits	Shared bandwidth and CSMA protocol congestion.	Increased latency in CPDLC message delivery and potential queue overflows.	**Load Balancing:** Distributing aircraft to prevent "chokepoints" in high-density sectors.
Signal Degradation (PER)	Sensitivity of D8PSK modulation to noise and distance.	High Packet Error Rate (PER) forcing constant retransmissions and bandwidth waste.	**Link Integrity:** Ensuring that the assigned station provides a "first-time-success" connection.
Line-of-Sight (LoS)	VHF wave propagation (rectilinear) and Earth's curvature.	Sudden loss of connectivity due to terrain masking or exceeding the radio horizon.	**Geometry Management:** Predicting handovers before the aircraft loses physical visibility.

Table 2.1. Analysis of Operational Constraints in VDL Mode 2 Networks // Source: Own elaborated

As is shown in Table 2.1 below, the interconnection between these three constraints creates a multifaceted optimization problem. While Line of Sight ensures the technical possibility of the link, it is the capacity constraints and the quality of transmission (PER) that define the actual quality and reliability of the connection. In the context of dense airspace, the traditional ‘strongest signal’ method tends to neglect these constraints, causing network congestion locally despite low utilization of nearby ground stations.

3. Problem Definition and Modeling Assumptions

3.1. Formal Definition of the Assignment Problem.

The essence of this study lies in solving a problem that can be considered in mathematical terms as the Aircraft-to-Ground Station Assignment Problem (AGSAP)[11]. As far as practical Air Traffic Management (ATM) is concerned, establishing connectivity should not be viewed only as a matter of “connecting” the dots in terms of linking two points; it poses a challenging problem of managing available resources [11]. The matter at hand is related to connecting a group of mobile nodes – the aircraft, to some fixed node points – the ground stations [5].

Regarding management, the aim of this thesis paper could be seen as presenting a paradigm shift concerning the existing practice. As a rule, this work had been done in a decentralized manner called "greedy," where the aircraft used to connect to any ground station having the best available signal at the moment [2][3]. While that is logical and reasonable, it often happens that this practice leads to the overloading of just one ground station, while others remain underused; we consider this an integer linear programming problem, following Hillier & Lieberman (2021).

Mathematically speaking, our task would be to minimize the “Total Network Cost”. The important thing to recognize here is that in the aviation domain, cost does not necessarily denote financial costs, in other words, payments made to companies like SITA and ARINC. Instead, cost is a more complicated metric that covers several factors such as time delay, the distance between the sender and receiver of the message, and the possibility of the message getting corrupted during transmission [5].

In order to formally describe the definition for our study, we can imagine a situation involving n aircraft and m ground stations in a particular FIR. In this case, the model would be used to test all the combinations between the two groups and determine if the relationship would be considered optimum or not. It creates a decision matrix in which the variables can only have binary values; a value of “1” indicates that there is a particular aircraft-station link that exists, while “0” indicates its absence. However, the real task of the optimization tool lies in testing all these combinations to find out the one that meets all the capacity limitations and safety guidelines while ensuring minimal costs.

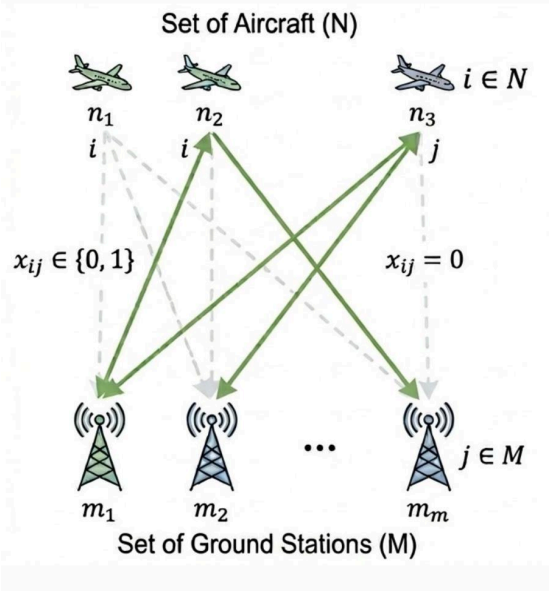


Figure 4 Aircraft Assignment with GS (Ground Station)// Source: Ai generated (Gemini)

3.2. Decision Variables: The Aircraft-to-Station Assignment Matrix

The next fundamental step in our methodology consists in recognizing the elements that are considered for manipulation by the optimization model to attain a perfect state. Such elements are referred to as Decision Variables in Mathematics Programming. In this study, the decision variables are integral to the process of assignment and are called the "digital switches" that determine the state of connection between the aircraft flying in the sky and the ground stations.

With the background already provided in the preceding section, we have a number of n aircrafts and m ground stations under consideration [3]. As such, a two-dimensional grid is created automatically, and we can represent it formally by using the term Assignment Matrix, defined as *X*. The Assignment Matrix becomes the bridge connecting the physical world and the virtual environment used by the solver. Each element of the Assignment Matrix, represented by x_{ij}, indicates a possible connection between plane *i* and ground station j [24].

The problem of VDL2 communication will be modeled in such a way that all operational difficulties can be mathematically solved. Therefore, the first step is to develop the notation of our data sets. In this research work, we have a data set of n aircraft, labeled with i (where, i = 1, 2, … , n), and another data set of m ground stations, labeled with j (where, j = 1, 2, … , m). The labeling scheme is crucial since this will make it possible to keep track of each link in the network.

An important difference between this model and most general optimization problems is that x_{ij} is binary [25]. In many other general optimization problems, x_{ij} can be any number in the continuous range from 0 to 1, but in our model, is restricted to the set:

- x_{ij} = 1: This shows that the link is activated by the model; this means that the aircraft is formally allocated and linked to the ground station

- x_{ij} = 0: This shows that no activated link is available for that particular aircraft-station pair.

Binary representation cannot be regarded as optional because this is something that should work according to the rules of the VDL Mode 2 Communication Protocol and GSC algorithm [23][24]. If we consider a situation in a real ATM system, then there would not be any way in which a radio station could establish a "partial" connection between two stations in order to offer similar services. Therefore, this switching operation would be an either/or process. Binary representation of variables would enable us to ensure that the results obtained through the Excel Solver are logical enough to mimic the actual functioning of the aircrafts' hardware equipment.

As far as the complexity of the network concerning management and performance is concerned, it is the network matrix which unites everything. For instance, when taking into account moderate airspace density with 30 aircraft and 10 ground stations involved, one can see the necessity to deal with as many as 300 parameters. In no way would a solution emerge in the process of dealing with so many parameters for a human being.

The optimization model, however, treats this matrix as a search space [22]. It evaluates the permutations of these ones and zeros, seeking the specific pattern that satisfies the "Unique Assignment" rule (ensuring every aircraft has one connection) and the "Capacity Limit" (ensuring no station is overloaded). The matrix transforms a qualitative problem of "good or bad service" into a quantitative structure that can be solved using the Simplex LP algorithm [13]. This structural clarity is what allows us to optimize the network without requiring additional physical infrastructure, relying instead on the intelligent management of the current x_{ij} assignments.

3.3. The Cost Function: The Mathematical Heart of Network Efficiency

The key point of the whole methodological approach is the Objective Function[11]. It is named the Cost Function (Z) in our research. While the decision variables form the skeleton of the model, the cost function can be regarded as its "brain." It is the algorithmic means by which the computer determines whether an assignment is suboptimal or not. In any case, the quality of the result of an Optimization depends on

the formulation of the goal, and the development of Z is when our Air Traffic Management experience pays off in practical terms [22].

Objective function

For solving the aircraft-to-ground station assignment problem from a mathematical perspective, it is important to first define an Objective Function (Z). The objective function denotes the fundamental parameter of the system, the minimization of which is the main goal of the optimization problem. The mathematical representation of the objective function can be stated as follows:

$$min\, Z = \sum_{i=1}^{N} \sum_{j=1}^{M} [(W1 \times PERij + W2 \times COSTij) \times MSGi] \times x_{ij}$$

Function Z is a composite operational penalty function [22]. Since there are conflicting objectives in the network, such as optimizing the quality of the data link while minimizing the operational costs, a one-objective minimization function is formed. The function sums up the cost penalty of all possible links between the plane i and the ground station j. Nonetheless, because of the binary decision variable xij, the function takes into account only those links which are chosen by the optimization algorithm to be active (xij =1).

The objective function depends on a matrix of static coefficients and input data obtained through flight telemetry and baselines provided by the service provider, as stated below [2].

- Indices:

- i: Index to denote individual aircraft operating within the airspace (i = 1, 2, … , N).

- j: Index to denote individual VDL Mode 2 Ground Stations (j = 1, 2, … , M).

-Operational Variables and Multipliers:

- $PERij$ (Packet Error Rate): Reflects the impairment of the telemetry link and statistical loss of packets due to the connection between aircraft i and ground station j. A large value reflects a bad radio link [12][18].

- $COSTij$ (CSP Tariff): The monetary tariff paid by the Communication Service Provider (ARINC or SITA) for transmitting the messages through this particular ground station [17].

- $MSGi$ (Traffic Weight): The mean rate of message generation (in messages per minute) of aircraft i. It serves as a scaling factor so that the cost function is weighted by the density of traffic [2].

- $W1$, $W2$ (Weighting Coefficients): The user-defined weighting factors for the balance between the technical performance and the cost of transmission.

- Decision variables

- xij: Binary routing switch under the control of the Solver.

Operational purpose

In an comercial aviation setting, this mathematical construction has the following three important practical uses:

1. Fleet-Wide Cost Management: It stops the automated system from picking excessively stable radio connections which would be economically impractical for the airline and, on the contrary, picks a well-balanced cost structure.

2. Performance Quality Assurance: By accounting for the $PERij$ and weighting it by the number of messages $MSGi$, it makes sure that important aircraft tracking and ACARS data do not get transmitted via unstable and congested or faraway ground stations.

3. Excel Implementation: In terms of its mathematical structure, the bracketed part $[(W1\times PERij + W2\times COSTij) \times MSGi]$ generates a static "Penalty Matrix". Thus, the whole double summation can be implemented in Excel using only one matrix multiplication command SUMPRODUCT.

3.4. System Constraints

In order to ensure that the minimization of the objective function (Z) produces a physically feasible and realistic routing design, a certain set of operational constraints should be imposed on the optimization model. Within the real-world spreadsheet modeling environment, these constraints provide the Solver program with the required limits when adjusting the decision matrix. The system is characterized by four different mathematical constraints:

3.4.1. The Single-Assignment and Connectivity Constraint

In aeronautical telecommunication networks, the transceiver in a particular airplane can connect to only one ground station at a time [9] in order to avoid problems of handover instabilities, packet duplication, and frequency interference [1].

Mathematically, this implies that the summation of decision variables of each individual aircraft over all available stations should be one [24]:

$$\sum_{j=1}^{M} x_{ij} = 1, \ \forall i = 1, 2, \ \dots \ , N$$

Within the planned spreadsheet layout, this operational rule will be enforced through a series of sum-control rows or columns tracking the Network Assignment Matrix. For every individual aircraft included in the scenario, the sum of its binary decision variables must equal exactly 1. This mathematical condition ensures that the optimization solver is forced to activate one, and only one, ground station connection per airborne node. By setting up this boundary condition, the model guarantees that no flight is left isolated without coverage, while simultaneously preventing any aircraft from being multi-homed to different stations at the same time stamp.

In the Excel solver, this is achieved through the creation of a control column that sums up the rows of the decision matrix, ensuring that the Solver is constrained to a value of 1.

3.4.2. Ground Station Capacity and Congestion Limits

Every VDL2 Ground Station has a technical processing capacity limit determined by its hardware and the operational bandwidth of the VHF channel. If the aggregate traffic routed to a single station exceeds this threshold, data queues generate severe packet drops and transmission delays [32].

The cumulative incoming message frequency from all aircraft assigned to a single ground station j cannot exceed its technical threshold (Capacity j):

$$\sum_{i=1}^{N} MSGi \times x_{ij} \leq Capacity_j, \ \forall j = \ 1, \ 2, \ \dots \ , M$$

In order to simulate such a limitation in our future spreadsheet, we should allocate a maximum nominal capacity limit for every ground unit as the capacity ceiling of its operation. According to the planning algorithm, one tracking cell should calculate the

sum of all aircraft traffic loads attempted to be assigned by the solver to one particular station. The rule would state that the sum should not exceed the maximum limit of station's capacity. In doing so, our model moves away from the old strategy of accepting only the strongest signal, and creates a framework where traffic can be re-allocated to nearby stations before the infrastructure bottleneck arises [2].

This assumption is crucial in scenario stress testing. It compels the system to undertake "re-routing strategy," where it routes the travelers to alternate stations which are not congested, even though there will be higher costs or PER involved in doing so.

3.4.3. Integrity Domain Constraints

In order to be consistent with the real-world situation, where the connection between two nodes is either completely up or down, the decision variables must not have continuous fraction values.

$$x_{ij} \in \{0, 1\},\ \forall i,\ \forall j$$

This requirement classifies the problem into a Mixed Integer Linear Programming (MILP) problem, meaning that the computer program will analyze discrete paths rather than linear paths [11][13][24].

4. Model Implementation and Results

4.1. Dataset Description: Analysis of aircraft positions and station parameters.

This part describes the operational environment and the data baseline adopted in order to test the optimization model for VDL mode 2. For this purpose, a simulation scenario has been designed where a high-density operational phase takes place in the Barcelona TMA and the adjacent sectors, where the fleet of aircraft, represented by A1, to A15, is interacting with the following GS (Ground Stations): GS1 (Barcelona - LEBL), GS2 (Palma de Mallorca - LEPA), and GS3 (Girona-Costa Brava - LEGE).

4.1.1. Ground Station Operational Parameters and Constraints

It features a specific geographical location, territorial coverage area, and processing capabilities. The communication process in VDL2 systems utilizes the CSMA (Carrier Sense Multiple Access) protocol [10], whereby any congestion of the local channels will inevitably lead to message collisions and transmission delays. Therefore, the following

traffic limits were set for each of the stations according to their processing and throughput capabilities:

- GS1 (Barcelona-El Prat / LEBL): Works as the main hub of the network and deals with a high number of departures and arrivals. It is capable of transmitting up to 180 messages/minute.

- GS2 (Palma de Mallorca / LEPA): Covers the southern sector and terminals and processes a maximum number of 110 messages/minute.

- GS3 (Girona-Costa Brava / LEGE): Is responsible for the northern sector and incoming messages through the French border at a maximum of 90 messages/minute.

4.1.2. Aircraft Traffic and Fleet Heterogeneity

For the fifteen operational aircraft (A1 to A15), the telemetry and operations data sets were extracted through historical state vectors obtained from the OpenSky Network repository [14][15]. The dataset presents a practical synchronized operational snapshot where all fifteen aircraft operate simultaneously and enter the Barcelona Terminal Control Area (TMA) within the same timestamp, shown in figure 5.

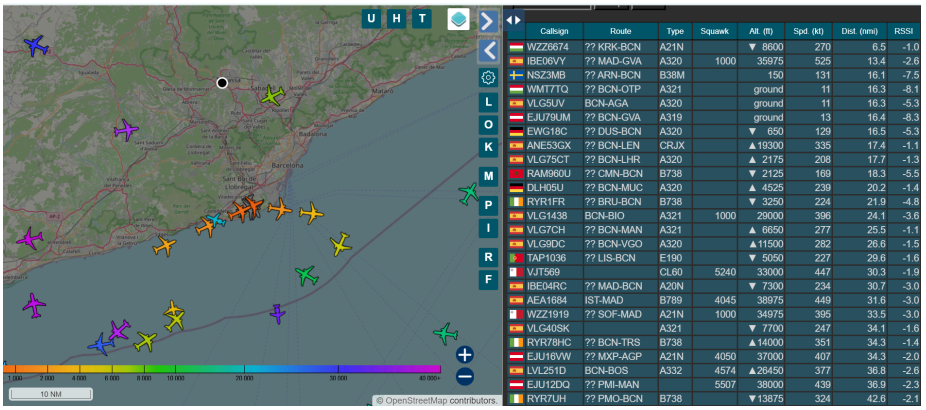


Figure 5 Main screen of OpenSky // Source: OpenSky

For a realistic test on the mathematical model, the following state vector variables were obtained from the OpenSky Network and their respective operational significance is described based on ATM:

- Altitude (ft): Defined through barometric altimeter data provided by the Mode S transponder [14][15]. The altitude serves to define the atmospheric layers in

terms of transit states ranging from the low level tactical terminal states of the aircraft (e.g., A4 - 2,175 ft or A13 - 4,350 ft) to high level altitude states (e.g., A2 - 35,975 ft).

- Propagation Distance (di, j in nautical miles): Geometric calculation performed using the Haversine formula between the lat/lon coordinates of each aircraft and the geographic coordinates of the three Ground Stations [16].

- Line of Sight Radio Distance (LoS in nautical miles): Refers to the maximum possible distance over which an unimpeded signal can be transmitted using VHF radio frequency signals before reaching the point when the curvature of the Earth blocks the line of sight [16]. This is determined through the calculation of the standard aeronautical refraction formula (LoS = 1.23 * $\sqrt{ALTft}$), this defines the upper boundary limit for the VHF connection. Each flight in the data file is validated to confirm that the transmission distance is within the LoS limit (Distij $\leq$ LoSi).

These datasets have modeled fifteen active flights that have unique flight dynamics, communication requirements, and priorities. In contrast to conventional static allocation problems, the model takes into account the two operational features in order to simulate practical scenarios in ATM:

1. Average Message Rate (messages/minute): This denotes the network capacity load (Gi) introduced by each plane. This is to capture the variations in datalink traffic depending on the flight stages; whereas cruise altitude planes communicate periodically at baseline rates [3] (10 messages/minute), planes flying near terminal environments communicate intensely at higher rates (35 messages/minute due to constant negotiations, clearances via CPDLC and weather forecasts [1][3].

2. Operational priority index: This variable plays an important role in ensuring safety. Although most commercial flights have a normal operational priority index (Priority 1), some special missions require Priority 2 index (such as state or VIP flights or airline control flights), while Priority 3 is exclusively kept for emergencies (for example, aircraft A15). In this project, it is provided priority values among the set of aircrafts without adhering to the deterministic schedule criterion of flight schedule, thus creating a stochastic pattern in which certain aircrafts enjoy more operational priority than other aircrafts. From a mathematical point of view, the variable ensures security of safety critical path links in a hierarchy of three levels [4][28].

- Priority Level 1 (Baseline): This priority level is for standard commercial aircraft flights that operate within the airspace based on standard timetables.

- Priority Level 2 (Elevated): This priority level is for critical events that require protection of the channels such as state/VIP flights or critical airline operational control transit flights.

- Priority Level 3 (Maximum Protection): Priority Level 3 can only be used during emergency situations. In the current database, aircraft A15 represents a flight in an urgent operational/safety situation.

Aircraft Flight Profiles and Telemetry Data						
Aircraft	Callsign	Alt (ft)	Dist (nmi)	Line of sight (LoS)	Average message/min	Priority
A1	WZZ6674	8600	6,5	114,07	30	1
A2	IBE06VY	35975	13,4	233,30	10	1
A3	ANE53GX	19300	14,4	170,88	22	2
A4	VLG75CT	2175	17,7	57,36	35	1
A5	RAM960U	2125	18,3	56,70	35	1
A6	DLH0TU	4525	20,2	82,74	35	1
A7	RYR1FR	3250	21,9	70,12	35	1
A8	VLG1438	29000	24,1	209,46	15	1
A9	VLG7CH	6650	25,5	100,30	30	1
A10	VLG9DC	11500	282	131,90	22	1
A11	TAP1036	5050	29,6	87,41	30	2
A12	VJT569	33000	30,3	223,44	10	2
A13	AEA1684	38975	31,6	242,83	10	1
A14	WZZ1919	34975	33,5	230,03	10	1
A15	EJU16VW	37000	34,3	236,60	10	3

Figure 6 Aircraft Flight Profiles and Relemetry Data // Source: Own elaborated on Excel

With respect to the empirical basis of the optimization model, the input data set, which consists of flight profile of aircrafts, coordinates, telemetry information, and raw link metrics of VHF radio, has been specially collected and processed with the intent of being used as case study for this undergraduate thesis. Although the model is built using real aviation designators, active callsigns of airspace (such as Vueling, Iberia, Wizz Air), and real coordinates representing physical infrastructure sites (Barcelona-El Prat [GS1 – LEBL], Palma de Mallorca [GS2 – LEPA], and Girona-Costa Brava [GS3 – LEGE]), the numerical data, workload communications, and Packet Error Rates values have been taken as operational. These synthetic values have been deliberately designed to emulate realistic VDL Mode 2 performance limits and tariff system of CSP.

4.1.3. Analysis of the Technical Metric Matrices

The assessment of effectiveness of the links in the network and the formation of the optimization criterion are based on the development of three matrices of input data. These matrices describe the mutual influence of all fifteen aircraft (i = 1, … , 15) and three stations (j = 1, 2, 3). Every parameter refers to one of three dimensions of the channel of air-ground communication:

Geometric Propagation Distance Matrix

The propagation distance matrix defines the actual physical structure of the airspace network. Defined in nautical miles (nmi), it describes the exact geometric distance between the airborne transponders and the ground-based sector antennas. The distance parameter is crucial in determining various technical phenomena within the VHF environment. These include:

- **Free-space Path Loss (FSPL) [25 :** Electromagnetic wave transmission through the atmosphere experiences geometric attenuation. Based on electromagnetic principles, power density is inversely proportional to the square of the distance ($1/d^2$). Connections spanning short distances (such as connection between A1 and GS1 that operate at 35 nmi are likely to maintain a higher signal strength while those involving longer distances (like that between A1 and GS2 at 190 nmi}) will have a high degree of path loss, almost reaching the limits of receiver sensitivity.

- **Signal Propagation Delay:** Though radio waves propagate at the speed of light (c)[25], with very large amounts of coverage, geographical distance induces delays. When transmitting within a data link network following CSMA principles, propagation delay changes the time windows necessary for an airplane to determine channel availability. Thus, increasing the risk of collision [10][20].

Packet Error Rate Matrix (PER)

Packet Error Rate (PER), measured in percentages, is the primary performance parameter applied in measuring the instantaneous health of the RF signal. It denotes the ratio of damaged or undecipherable data frames received compared to the total number of frames that have been transmitted through the channel [12][18].

- **Radio Frequency Noise & Interference Model:** The PER matrix incorporates the effects of fading, multiple reflections caused by signals reflected off mountains or water surfaces leading to phase cancellations, as well as co-channel interference [25][33]. For example, in analyzing the data set, it is observed that the PER values for links having GS2 (Palma) were relatively high (as high as 3.5%) for certain low-altitude aircraft because of the marine propagation path.

- **VDL2 Channel Capacity Impact:** According to the guidelines set by ICAO Doc 9776 manual on the VDL Mode 2, whenever there is an error in the transmission of an AVLC (Aeronautical Data Link Control) frame due to the occurrence of bit errors, the AVLC fails the CRC test at the receiving ground

station [3][9]. This leads to the discarding of the AVLC by the ground station and the triggering of a retransmission procedure initiated after the failure of a back-up timer. This results in high congestion of the channel and reduced throughput for other aircrafts around.

Provider Transmission Price Matrix

The third matrix brings a practical and monetary perspective into the equation. In contrast to the academic approach where the aeronautical communications network is treated like a radio network, the pricing index takes into account the economic structure of the worldwide CSP companies such as SITA and ARINC who charge the airlines according to usage of the network [17].

- **Tariff and Ground Network Infrastructure Differences:** The pricing index considers the different tariffs that vary according to the amount of kilobytes of data transfer from each ground station node [17]. This tariff varies according to local telecom infrastructure leasing costs and the cost of connecting the remote ground network to the ATC automation center.

- **Incentives for Resource Balancing:** Economically, air navigation service providers implement dynamic pricing schemes to discourage overuse of traditionally overcrowded core facilities. For this dataset, passing information via GS1 (Barcelona) will incur an indexed fee as the main connection in the area. But other stations or special routing configurations will change this indexed fee. This monetary value helps make sure that there is truly a balance between routing aircraft information via the best possible station in electromagnetic terms but costly monetarily, or diverting the traffic to cheaper regional antennas without reducing safety or operational capacity.

Raw VHF Radio Link Metrics and CSP Tariffs									
Aircraft	GS1_dist (LEBL)	GS2_dist (LEPA)	GS3_dist (LEGE)	GS1_PER	GS2_PER	GS3_PER	GS1_price	GS2_price	GS3_price
A1	35	190	95	0,5	2,5	1,5	1	1,5	1,2
A2	120	240	65	1,5	3	0,8	1,1	1,4	1
A3	84	160	110	1	2	1,4	1,1	1,3	1,2
A4	12	210	105	0,2	3,5	1,8	1	1,6	1,3
A5	18	205	102	0,3	3,5	1,8	1	1,5	1,2
A6	25	215	80	0,4	3,5	1,3	1	1,6	1,2
A7	42	185	120	0,6	2,4	1,9	1,1	1,4	1,3
A8	140	290	45	1,9	3,8	0,5	1,3	1,7	1
A9	55	175	135	0,8	2,2	2	1,1	1,4	1,3
A10	70	150	150	1	2	2	1,2	1,3	1,3
A11	60	230	75	0,9	3,2	1,1	1,1	1,5	1,1
A12	195	90	210	2,6	0,7	2,8	1,5	1,8	1,7
A13	115	260	50	1,5	3,5	0,6	1,2	1,6	1
A14	160	310	35	2,2	3,9	0,4	1,3	1,7	1
A15	90	140	165	1,2	1,8	2,3	1,1	1,3	1,4

Figure 7 Raw VHF Radio Link Metrics and CSP tariffs // Source: Own elaborated on Excel

4.2. Methodology: Excel-Based Optimization using Simplex LP

In order to determine the optimal solution to the problem of assigning aircraft to ground facilities dynamically, the MILP optimization problem formulation is developed. The optimization is implemented in the Excel environment using its native optimization capabilities through Solver, based on the Simplex LP optimization method. Such an approach guarantees that the optimal solution is obtained for the problem, without any danger of falling into local optima [22] (ineffective solutions which are common pitfalls of non-linear or trial-and-error approaches due to tight constraints).

The optimization problem is a chain of interlinked tables with each successive table built upon the results of calculations performed on previous tables. The process of development and operation of each of these tables is explained below.

4.2.1. Aircraft Flight Profiles and Telemetry Data

The first element that goes into making up the structure of the optimization model involves setting up the actual operational state of the airspace. Air traffic management is very dynamic in nature; thus, all flights cannot be treated as uniform nodes within an optimization model. This table highlights the individuality of each flight and its special communication requirements.

- **Altitude of Aircraft:** Altitude is measured in feet, and it is defined as the actual phase of flight of each airplane. This is collected using the OpenSky Network – crowdsourced air traffic control database that offers real-time and recorded state vectors for aircraft in flight. Altitude refers to a broad operational spectrum where the flight includes both low and high altitude flights flying through the tactical terminal corridors during intermediate approach phases and cruise phases respectively. This is an important technical measure since it defines the geometrical background of the aircraft radio horizon [16]. High flight level reduces ground clutter while minimizing coverage; conversely, lower altitudes limit the radio range making the flight prone to terrain masking.

- **Distance:** Measured in nautical miles, this variable indicates the absolute geometric distance between the aircraft's transponder and each of the ground stations' transceivers. Similar to the altitude variables, these spatial coordinates were determined from the historical flight data available from the OpenSky Network dataset. The computation of the actual physical distance required cross-referencing the latitude and longitude coordinates of each of the aircraft with the geographical coordinates of the three ground antennas located in Barcelona, Palma, and Girona. Spatial distance is the fundamental factor determining the magnitude of path loss in the atmosphere. The farther the aircraft is from the antennas, the lower the strength of the transmitted signal

will be, following an inverse-square-law relationship with respect to distance [25][33]. This allows the model to keep track of the structural limits for the degradation of signals to determine whether the nodes are at the boundary of communication range.

- **Line of Sight (LoS):** Closely related to altitude and distance is the Line of Sight measure, acting as an indicator (1 for open LoS, 0 for closed LoS) of an unblocked signal transmission. Since this geometric relationship is a hidden one not found in the database used to track flights, the values were calculated mathematically through the spherical Earth radio horizon formula in our model [16]. This geometric formula evaluates whether or not the straight signal path from the aircraft can bypass the curve of the Earth. This factor plays the role of an absolute physical gate – if the aircraft dips under the radio horizon for any particular station, LoS is impossible. Hence, no matter how low cost or near such a station may be, maintaining the data link becomes physically impossible.

- **Message per Minute:** It represents the workload generated by each cockpit on the shared VHF band. As live data throughput in the form of VDL Mode 2 messaging cannot be disclosed by airlines or communications service providers, these messaging frequencies have been generated on the basis of standard ICAO performance metrics applicable during different flight phases. The rate of messaging varies widely based on the particular flight phase and scenario under consideration. While high-level cruising aircraft depend mostly on automated low-rate messaging for position reporting purposes, aircraft flying in the terminal area engage in a constant cycle of messaging. This cycle is prompted by tactical route negotiations, D-ATIS downloads, and CPDLC conversations [1][3].

- **Operational Priority:** In order to ensure that all safety-sensitive messages are not subject to any delays or loss in transit due to peak channel congestion, the model incorporates a structured operational priority index [4]. For the purpose of creating such a metric, Artificial Intelligence is used in the pre-processing of the dataset to analyze the fleet profiles and then choose a particular flight to represent an emergency situation. This helped in setting up a contingency scenario without impacting the accuracy of the real-world telemetry from the remaining OpenSky airspace image. This variable will add a new layer to the model, which will not have any economic significance but will serve as a mathematical override function. It will make sure that while optimization, the safety of the troubled flight is prioritized.

4.2.2. Raw VHF Radio Link Metrics and CSP Tariffs

While the other table describes what the aircraft are doing, the following table indicates the physical and monetary conditions involved in the connections made by these aircraft to the three ground stations available: Barcelona, Palma, and Girona. This paragraph discusses the physical and economic aspects of the radio-frequency communication channel. In every case of aircraft-ground station connection, three basic measurements have been taken into consideration:

- **Geometric Propagation Distance:** This distance calculation is done using nautical miles and gives the actual distance between the transponder of the aircraft and the ground station antenna. The database used to determine the distance calculation uses the exact GPS coordinates of the three ground stations and compares them with the current latitude and longitude of the aircraft obtained from the OpenSky Network. Distance plays an important role when considering the intensity of the radio wave, as shorter distances keep the radio signals stronger while longer distances make the signals weaker.

- **Packet Error Rate (PER):** Is a measure of how well or badly the radio channel performs electromagnetically, expressed in percentages. Live packet telemetry is very sensitive information; hence, its calculation is done empirically via signal attenuation model [25][33] based on a mathematical stochastic function relating distance vectors of OpenSky and aircraft altitudes to regional radio frequency interference layers. PER describes the amount of wrongly or incorrectly transmitted packets against the total number of packets transmitted. Where VDL Mode 2 is applied, an incorrectly received packet will not be accepted by the ground stations after transmission because it does not satisfy the error checks due to the interference or noise from the radio channel. Therefore, the aircraft will have to send the same message again, which may result in congestion in the radio channel, slowing down operations, and increasing delays.

- **Pricing Index for Provider:** Introducing the pricing index to the problem provides an additional economic perspective on the air traffic management issue. Points used for pricing index were calculated using commercial airline pricing system models and common service agreement models of CSPs such as SITA and ARINC [17] and translated into the index of cost ratio. These pricing indices are influenced by cost tariff systems developed by the CSPs all over the world to charge airlines for the volume of data transmitted by them via CSP services [17]. Tariffs may vary depending on the location because of infrastructure investment costs, antenna rental costs, and maintenance fees. Using the index makes it possible to carry out real operational analysis and make a choice whether to transmit traffic through a higher quality but expensive antenna or whether traffic may be switched to less expensive regional antennas.

4.2.3. Operational Threshold Extraction and Benchmark Architecture

Prior to launching any comparative computation throughout the entire data set, there has to be an adequate dynamic baseline in place, taking into account that scales can vary drastically from one another. In this case, the optimization model utilizes a special-purpose structural element called the Table of Maximums. Rather than resorting to fixed and predefined constants that will isolate the model from changes that may occur in the airspace in real time, the table represents a special kind of automatic mathematical scanner stationed at the margin of the main variables.

Upon analyzing the maximum value across the entire unfiltered data set, the table picks up on three distinct environmental parameters. The first one refers to the maximum geographical margin, meaning that in this case, the farthest-away point is situated 195 nautical miles away. Secondly, the table determines the maximum packet error rate among all aircraft, which amounts to 3.9%. Finally, the highest fee charged for commercial flights is found to amount to 1.8.

One thing that must be clear about this combination of these three absolute values into an independent reference block is that its main purpose is to create those denominators necessary for the scaling process. The reason why these values have been separated out in this way is to ensure that in the event that new data has to be ingested, the system will always be scaled to the worst case scenario for the moment.

4.2.4. Ground Infrastructure Capacity Limits

Related directly to the operational environment is the ground segment's baseline definition, which is defined through the Stations Capacity Table. VDL Mode 2 aeronautical communication networks are not boundless in terms of their capacity since they operate using a common VHF frequency spectrum where the ground transceivers can only perform under the limitations imposed by their processing capabilities and channel access.

Instead of assuming equal capacity requirements among all the nodes, the block takes into account their differing operational purposes and local demands:

- GS1 (Barcelona - LEBL): As the central point of this network characterized by dense traffic flows, it operates with a maximum throughput rate of 180 messages per minute.

- GS2 (Palma - LEPA): It functions as the central gateway of the maritime and southern sections of the transit corridor, with the limit of traffic set at 110 messages per minute.

- GS3 (Girona - LEGE): As a regional feeder station controlling northern transit routes and overspill from the French border, its maximum traffic rate cannot exceed 90 messages per minute.

From the mathematical point of view, these figures reflect the hard cap of the network. Practically speaking, exceeding this limit will result in data link slot starvation, leading to an overflow of signal collisions and making the frequency useless. From the point of view of Excel modeling, this table imposes an absolute limit which optimization can only respect when distributing traffic load evenly among the aircraft in question.

4.2.5. The Scaled and Normalized Dimensionless Metrics Matrix

As soon as the constraints and the ground capacity are defined, the optimization algorithm moves into the next stage which is known as the Data Cleaning and Engineering phase. This can be done by developing the Scaled and Normalized Dimensionless Metrics Matrix. In Mathematical Programming, the development of an objective function with variables in different units always poses a huge problem as algorithmic distortion occurs as a result. For instance, if the optimization software is supposed to measure a raw distance of 150 nautical miles and the error rate at 2.5%, the former will override the latter simply due to higher numerical value.

The idea is that in order to get rid of the operational bias and achieve a flawless algebraic balance, the developed matrix will have all variables scaled based on certain mathematical rules. Every one of the 45 air-to-ground connections will be subjected to linear transformation where each of the variables including distance, packet error rate, and price index of the service provider will be divided by the highest value derived in the initial stage. This linear translation compresses every physical value into a clean decimal spectrum strictly bounded between 0 and 1.

The behavior of this table may be described as that of an operationally incurred penalty chart. The closer the plane to the ground antenna, the perfect reception from the former, and the routing via an optimal-cost server, the closer its normalized decimals will be to 0, indicating the greatest link efficacy. Alternatively, when the plane is closer to the outer limits of the antenna’s radio horizon, finds itself in a noisy RF segment, or utilizes services offered by a costly tariff provider, then its scaled figures will tend toward 1. This table, as is seen in figure 8, ensures that all physical units are stripped away, creating an even playing field for any tactical variable weight manipulation.

Scaled and Normalized Dimensionless Metrics Matrix									
Normalization									
Aircraft	GS1_dist	GS2_dist	GS3_dist	GS1_PER	GS2_PER	GS3_PER	GS1_price	GS2_price	GS3_price
A1	0,113	0,613	0,306	0,128	0,641	0,385	0,556	0,833	0,667
A2	0,387	0,774	0,210	0,385	0,769	0,205	0,611	0,778	0,556
A3	0,271	0,516	0,355	0,256	0,513	0,359	0,611	0,722	0,667
A4	0,039	0,677	0,339	0,051	0,897	0,462	0,556	0,889	0,722
A5	0,058	0,661	0,329	0,077	0,897	0,462	0,556	0,833	0,667
A6	0,081	0,694	0,258	0,103	0,897	0,333	0,556	0,889	0,667
A7	0,135	0,597	0,387	0,154	0,615	0,487	0,611	0,778	0,722
A8	0,452	0,935	0,145	0,487	0,974	0,128	0,722	0,944	0,556
A9	0,177	0,565	0,435	0,205	0,564	0,513	0,611	0,778	0,722
A10	0,226	0,484	0,484	0,256	0,513	0,513	0,667	0,722	0,722
A11	0,194	0,742	0,242	0,231	0,821	0,282	0,611	0,833	0,611
A12	0,629	0,290	0,677	0,667	0,179	0,718	0,833	1,000	0,944
A13	0,371	0,839	0,161	0,385	0,897	0,154	0,667	0,889	0,556
A14	0,516	1,000	0,113	0,564	1,000	0,103	0,722	0,944	0,556
A15	0,290	0,452	0,532	0,308	0,462	0,590	0,611	0,722	0,778

Figure 8 Scaled and Normalized Dimensionless Metrics Matrix // Source: Own elaborated on Excel

4.2.6. Multi-Criteria Operational Routing Cost Matrix

The set of standardized values obtained in the normalization layer shows the technical resistance of the channel, but it does not take into account the operational considerations of actual Air Traffic Management. In order to make the mathematical calculations relevant for practical purposes of aviation safety, the concept of the Multi-Criteria Operational Routing Cost Matrix, also known as the operational cost grid, is introduced.

When it comes to a live airspace management sector, communication channel should be evaluated according to both its location and the amount of data transmitted from the cockpit, as well as the current safety condition of this particular aircraft. By taking into account all of these factors, the operational cost matrix takes the sum of the three normalized digits (distance, error rate, and price) and calculates a standard technical cost factor, which can reach up to 3. Then, it is multiplied by the number of messages generated by the aircraft per second, while being also divided by the aircraft priority index.Firstly, this mathematical relationship changes the dynamics of the model in two very important ways:

- Amplification of Traffic Volume: Flights that maneuver through complicated terminal control areas create very high volumes of data link traffic through constant flight level clearances negotiations, D-ATIS updates, and CPDLC conversations [1][3]. Since this technical penalty is multiplied by message volume frequency, the model will impose an extremely heavy penalty on using highly loaded aircraft for low-powered and distant ground stations, thereby avoiding overloading of local frequencies.

- Override of Safety Protection: The most important dynamic aspect of the model is seen when considering flights having operational emergencies such as

technical or medical problems. Introducing the operational priority index as the denominator allows the model to mathematically reduce the coefficient of the entire row. In case of a high-priority flight, the operational priority denominator makes the cost coefficients of that row reduce drastically. It creates a strong mathematical drive within the system. Since the optimization engine is hardwired to seek minimum resistivity paths, this reduction drives the algorithm to take into consideration the priority aspect and gives the emergency flight priority over all economic factors.

Multi-Criteria Operational Routing Cost Matrix			
Costs			
Aircraft	GS1	GS2	GS3
A1	23,90	62,62	40,73
A2	13,83	23,21	9,70
A3	12,52	19,26	15,19
A4	22,59	86,23	53,29
A5	24,17	83,72	51,00
A6	25,86	86,80	44,03
A7	31,52	69,65	55,88
A8	24,92	42,81	12,43
A9	29,81	57,19	50,12
A10	25,28	37,82	37,82
A11	15,53	35,94	17,03
A12	10,65	7,35	11,70
A13	14,22	26,25	8,71
A14	18,02	29,44	7,71
A15	4,03	5,45	6,33

Figure 9 Multi-Criteria Operational Routing Cost Matrix // Source: Own elaborated on Excel

4.2.7. Binary Decision Variables and Network Solution Matrix

Now that the technical and operating expenses have been accounted for, the next step in developing the optimization model involves having an independent platform that can examine the possible connection structures. In operations research terminology, the platform for conducting searches and testing is called the Binary Decision Variables and Network Solution Matrix. In the domain of operations research, the matrix serves as the search space for the problem, essentially a two-dimensional grid of switches (X i, j) in which each row represents each of the fifteen airplanes while each column depicts each of the three ground stations – Barcelona, Palma, and Girona, as can be seen in figure 10.

The design of this matrix is based on the following two states:

- Idle Initialization State: Before the invocation of the algorithm, each and every cell of this grid is set up with an idle value, that of zero. This initial condition represents a scenario where the entire airspace network is unallocated and is open for communication.

- The Tracking Vector for Uniqueness: The vector located beside the decision switches is called the network connection tracking vector. It uses the horizontal addition method on the three ground node positions in each of the aircraft rows separately. When the matrix is at zero value, the tracking vector produces zero automatically. But when it functions in the parameter set up stage, its actual utility kicks in because it ensures that an aircraft cannot connect to more than one antenna or become isolated from any communication system.

Binary Decision Variables and Network Solution Matrix				
Decision variables and solution				
Aircraft	GS1	GS2	GS3	Suma
A1	1	0	0	1
A2	0	0	1	1
A3	0	1	0	1
A4	1	0	0	1
A5	1	0	0	1
A6	1	0	0	1
A7	1	0	0	1
A8	0	0	1	1
A9	0	0	1	1
A10	0	1	0	1
A11	0	0	1	1
A12	0	1	0	1
A13	1	0	0	1
A14	0	1	0	1
A15	0	1	0	1
Suma	330,861226	330,861226	330,861226	

Figure 10 Binary Decision Variables and Network Solution Matrix // Source: Own elaborated on Excel

4.2.8. Ground Station Channel Congestion and Capacity Monitoring

The aeronautical telecommunication systems are limited physically by the capacity of the radio frequency spectrum. Since VDL Mode 2 is designed under the Carrier Sense Multiple Access (CSMA) technology [10], having many message-bursting airplanes transmitting at the same time using the ground station frequency will cause continuous collision among the packets, resulting in an endless retransmission cycle of the network and delaying the clearance for airtraffic management. The model therefore incorporates the Ground Station Channel Congestion and Capacity Monitoring system.

At the heart of this table lies a sophisticated data aggregation component that captures in real time the cumulative messaging load allocated to each ground antenna. This task is performed via computing a matrix dot product between the vertical vector representing the frequency of communication of the respective airplanes and the allocation columns of the decision matrix. If the optimizer allocates one of the planes to fly to Barcelona by setting the decision switch value to 1, the corresponding message frequency is summed into Barcelona's live counter; if it allocates a 0, the whole load will be totally ignored. Below this real-time tracker are placed the physical limits of the system capacity, which set hard upper bounds of 180 messages per minute for Barcelona, 110 for Palma, and 90 for Girona.

Ground Station Channel Congestion and Capacity Monitoring				
Total loads on ground stations				
	GS1	GS2	GS3	TOTAL NETWORK
TOTAL LOAD	170	94	75	339
CAPACITY	180	110	90	380

Figure 11 Ground Station Channel Congestion and Capacity Monitoring // Source: Own elaborated on Excel

4.2.9. Global Network Target Optimization Value (Objective Function)

However, all these criteria involved in the multi-criteria design of the operation process including physical distance, RF noise, communication services charges, cockpit data loading, and safety priority weights get simplified to one cell termed the Global Network Target Optimization Value that constitutes the Objective Function of the model. This value forms the complete mathematical foundation of the linear programming model by determining the friction and operational costs in the active airspace sector.

In terms of engineering, the cell performs a complete dot product operation between the cost values obtained from the operational matrix and the logical switch values in the decision variable matrix. From a mathematical point of view, this can be expressed as:

$$Minimize\ Z\colon \Sigma_{i=1}^{15}\Sigma_{j=1}^{3}\left[Cost\ Coefficient\ i,j\ \ *\ \ X\ i,j\right]$$

With the model at rest and decision variables set to zero, the objective function yields an initial value of zero. This is the final goal for the Simplex LP process to achieve. The goal here is merely to explore the perimeters of the air space constraint and establish the combination of zeros and ones that causes the ultimate goal to reach the lowest possible value.

4.3. Data Normalization: How different metrics were scaled for the model.

In multicriteria decision-making as well as linear programming, the initial raw parameters taken from practical life are usually not compatible directly with each other. In terms of aeronautical telecommunication problems, there are three very conflicting parameters included in the baseline of data: geometric distance (in nautical miles), link degradation (calculated with the Packet Error Rate in percentages), and ground routing costs (in the form of an infrastructure cost index). However, if these parameters were combined into one formula for optimization of their values, the huge discrepancy between their baseline numerical scales would create an irreparable mathematical bias for the solver. The Simplex LP technique is built around assessing numerical differences and finding the best way to minimize them; therefore, if the

geometric distance parameter is calculated with a near two-hundred-mile scale, while the critical packet error rate is about three percent, the latter would not be considered at all due to their disparity.

For this problem, a method of translating the model using linear scaling based on the maximum boundary will be performed in order to balance out any potential scaling problems and allow all operational measures to have an equal effect on the system without bias. This method of normalization functions as a form of mathematical equalizer for the equation. Rather than adhering to the limits of the theoretical model, the algorithm performs an evaluation of the live snapshot of the airspace to find the maximum boundary value for each operational measure among the full fleet grid.

$$Normalized\ Metric\ i,j\ =\ \frac{Raw\ Metric\ i,j}{Global\ Maximum\ Reference}$$

The resultant structural behavior due to such a scaling procedure transforms the technical characteristics of every link between the air-to-ground communication into a common and dimensionless penalty coefficient that is confined to a closed interval between 0 and 1. The implications of this closed interval are defined in the following way:

In the case when the aircraft flies at a close range to the ground station, establishes a proper connection through the shortest sight route and accesses a very economical region of tariffs offered by the provider, its numerical value decreases to a minimal value of 0. In the case when the aircraft flies close to the boundary of the station's radio visibility, there is a considerable increase in packet loss due to the co-channel interference or in case the aircraft accesses a relatively expensive ground hub station, its penalty coefficient increases to a maximum value of 1.

This normalizing scheme protects low-magnitude variables from being mathematically drowned by putting all data into a uniform plane. As such, a minute yet destructive increase in RF noise or a sudden rise in premium air carrier charges will be considered mathematically equal to a large spatial distance of a hundred miles. This critical unification makes the cost matrix capable of performing a genuine multidimensional optimization of traffic distribution based on the actual conditions in the airspace.

4.4. Presentation of Results: Optimal Assignment and Total Network Cost

As the entire multivariate mathematical design is now in place along with normalized input data on the spreadsheet, the last stage of the optimization modeling approach calls for setting up and running the optimizer engine itself. The current chapter moves beyond theoretical construction of the model to make it computationally functional,

describing the exact restrictions defined in the optimization model and their implications regarding distribution of the aviation fleet over the Mediterranean land-based network.

4.4.1. Parametric Setup and Interface Constraints Mapping

The activation of the linear programming model involved setting up the parameters in the optimization control panel such that the values would correspond with the mathematically determined limits of the sector. Instead of allowing the solver algorithm to carry out its task without constraints, the solver control panel is firmly set in accordance with the operational guidelines formulated on the worksheet.

The four key logical settings involved in parameterizing the solver interface include:

- **Target Objective Anchoring:** This objective field is directly anchored to the Global Network Target Optimization Value. The optimization criterion is strictly limited to the minimization process, thereby directing the computer algorithm to decrease friction, transmission time lags, and monetary tariffs on the overall system in the airspace domain.

- **Variable Interaction:** The algorithm is allowed the sole right to maneuver with the unoccupied cells of the Binary Decision Variable matrix and Network Solution matrix. In limiting this particular matrix to the search process, the computer algorithm will have no option but to find the optimal solution by switching the connection switch ON/OFF.

- **The One-Association Requirement:** In order to guarantee safe operation and avoid duplicate telemetry readings, an absolute requirement is implemented which ensured that the summation of the Horizontal Uniqueness Tracking Vector will be 1 across all rows, meaning that each airborne flight can have only one association with one ground station, effectively making it impossible for two frequency splits and ghosts to exist.

- **Integrity and Transmission Channel Limits:** The grid is bound by a discrete binary logic requirement, essentially turning each square into a digital on-off switch (0 or 1), which makes impossible any fractional routing distribution. At the same time, an inequality constpraint between the dynamic load of the Total Load variables and the fixed maximum values of the Ground Station Channel Congestion and Capacity Table is implemented.

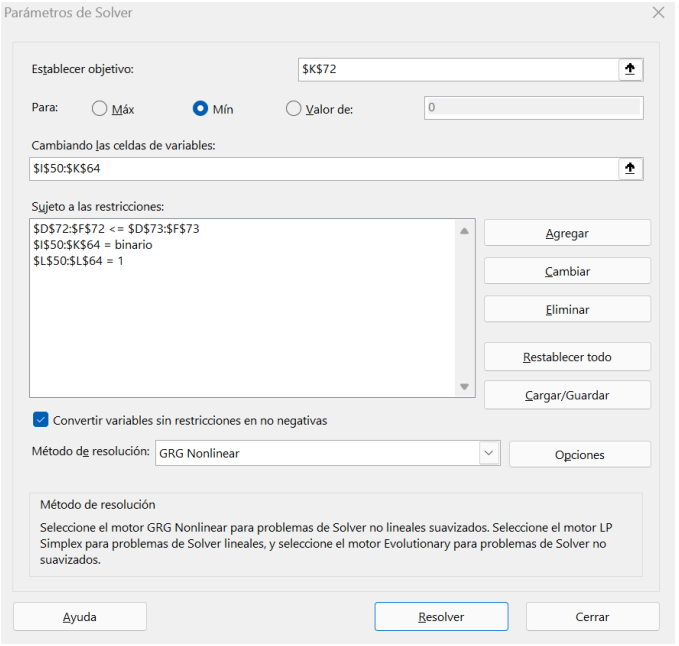


Figure 12 Solver parameters pop-up // Source: Own elaborated on Excel

Algorithmic Execution and Matrix Switching Logic

As soon as the parameter values become fixed, and the Simplex LP solver routine is used, the run command is issued. In view of the perfect linearity of the network topology, the Simplex solver algorithm does not make use of evolutionary or approximate algorithms based on the principle of randomization and trial-and-error. The solver uses a matrix-scanning approach whereby all the extreme vertices of the multi-dimensional geometrical boundary set by the constraints are examined.

With this, at the start of the computation, the algorithm takes control of the empty matrix of decision variables. In the split second, it performs the evaluation of the cost coefficients associated with each of the flights relative to the residual processing capacity of the ground stations. It verifies that the sum across the row equals one, and that the accumulated number of messages does not initiate a channel capacity saturation loop. Any configuration that would require the routing of even one message to exceed the capacities of Barcelona, Palma, or Girona is immediately disqualified as infeasible. This process of optimization takes place continually, and it comes to an end when the engine is able to find the one matrix representation of ones and zeroes, which adheres to all aviation safety constraints and simultaneously achieves the global cost objective at its minimum mathematical limit. It becomes the rapid-switching algorithm, which changes the blank decision matrix into a fully developed network solution.

4.4.2. Fleet Allocation Analysis and Capacity Optimization

As soon as the Simplex LP optimization process reaches its stage of completing the matrix transitions, it becomes apparent that the routing plan that is being created by the algorithm is quite evenly distributed and well thought out for the sector of the Mediterranean. As a result of the modeling process, the entire volume of messages per minute – 339 - as is shown in figure 13, is effectively distributed among the available ground infrastructure nodes without crossing the physical threshold of congestion in any particular station. The available network capacity of 380 messages/min is used at 89.2% level, which implies some intricate trade-offs made by the algorithm.

Ground Station Channel Congestion and Capacity Monitoring				
Total loads on ground stations				
	GS1	GS2	GS3	TOTAL NETWORK
TOTAL LOAD	170	94	75	339
CAPACITY	180	110	90	380

Figure 13 Ground Station Channel Congestion and Capacity Monitoring // Source: Own elaborated on Excel

The application of algorithmic implementation through the Simplex LP methodology was successful in mathematical convergence and finding out the absolute global optimum of the aircraft to ground station routing problem on normal traffic. The objective function, acting as an unmapped composite network operational penalty index, was minimized to 310.69 dimensionless units. This value of minimized cost is indicative of the optimal performance due to balancing of the following three factors: signal spatial attenuation (distance), probability of error rate and dynamic cost provider tariff. Contrary to a 'strongest signal' heuristic that causes data link slots starving and collisions of the signal, the Solver managed to achieve distribution proactively.

The ultimate distribution of the 15 flights among the three ground stations emphasizes the tactical intelligence of the model:

- Barcelona Ground Station (GS1): Load Status - Being the main multi-channel ground station, Barcelona takes the largest proportion of the total airspace loads amounting to 170 messages/min. In doing so, the station is operating at an efficiency of 95% in relation to its 180 messages/min capability. The high traffic of flights handled by this node is informed by good signal-to-error ratios; however, the node is left operating at 95% efficiency to prevent frequency degradation.

- Palma Ground Station (GS2): Load Status - The station is entrusted with the task of controlling the southern transitions and maritime corridors. The station's total capacity load is 94 messages/min based on a nominal capacity of 110

messages/min. GS2 operates at 83.6% utilization efficiency by handling data traffic of flights moving in the low maritime flight levels where sight with mainland stations gets weaker.

- Girona Ground Station (GS3): Subjected to the limitation of 90 messages/min in terms of hardware constraint, the load at Girona amounts to 75 messages/min which implies 84.4% capacity usage. It should be noted that this algorithm makes use of GS3 to alleviate the burden from the north border sectors by accommodating flights to keep the Barcelona sector below its 180-messages limit.

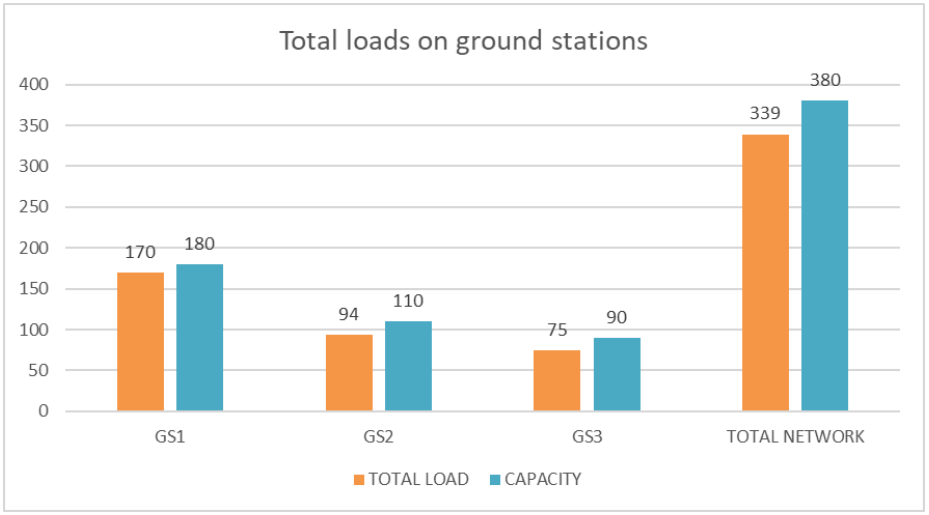


Figure 14 Total loads on ground stations // Source: Own elaborated on Excel

5. Discussion and Scenario Analysis

5.1. Operational Interpretation of Results

Binary Decision Variables and Network Solution Matrix				
Decision variables and solution				
Aircraft	GS1	GS2	GS3	Suma
A1	1	0	0	1
A2	0	0	1	1
A3	0	1	0	1
A4	1	0	0	1
A5	1	0	0	1
A6	1	0	0	1
A7	1	0	0	1
A8	0	0	1	1
A9	0	1	0	1
A10	0	1	0	1
A11	0	0	1	1
A12	0	1	0	1
A13	0	0	1	1
A14	0	0	1	1
A15	0	1	0	1
Suma	310,6875287	310,6875287	310,6875287	

Figure 15 Binary Decision Variables and Network Solution Matrix // Source: Own elaborated on Excel

The basic scenario provides the reference point where all three Ground Stations are assumed to be operating normally—Barcelona (GS1/LEBL), Palma (GS2/LEPA), and Girona (GS3/LEGE). The aggregate telemetry load includes a fleet of 15 planes sending out 339 messages per minute. For these conditions, the optimization technique ensures that a stable configuration is provided by the algorithm in a mathematically sound way with no need for message deflections to an overflow path.

From the ATM perspective and decision making standpoint, the minimized score of the objective function of 310.69, as it can be seen in figure 15, constitutes the strategic benchmark of the network performance. The numerical minimization of the multi-layered cost matrix provides operational benefits that are not possible with the use of conventional route planning approaches:

- System-wide load balancing: The minimized target score demonstrates that the network is prepared to sacrifice some distance-related costs, for example, detours of aircraft around the center of the airspace network, in order to ensure processing margin at the primary nodes. The limiting the initial load at GS1 (Barcelona) to 170 messages per minute avoids triggering an exponential retransmission loop on the frequency channel [3][10].

- Spectrum capacity optimization: The minimized dimensionless friction value directly translates into lowering the data link latency and probability of packet

drop. In this way, the conservative spectrum allocation allows saving the bandwidth for safety critical CPDLC and ADS-C applications."[1][3]

- Strategic Infrastructure Management (CAPEX deferral): By creating an optimized cost baseline of 310.69, there is a mathematical advantage for both the Communication Service Providers (CSPs) and the Air Navigation Service Providers (ANSPs)[17]. This demonstrates that software-defined optimization layers are able to successfully reduce sector congestion, deferring the need for costly (CAPEX) infrastructure by extending the life and throughput of the current ground segment.

In this case, the multiple criterion routing technique finds the solution to the problem of minimizing the aggregate cost function subject to three conflicting requirements: physical link length, PER degradation, and Communications Service Providers tariffs.

The operational analysis of the basic distribution model identifies the following major features:

- Barcelona (GS1/LEBL): The optimization tool maximizes the capacity of GS1 up to 170 messages per minute. With respect to the low normalized distance and excellent link parameters for the most significant part of terminal flights, the network focuses on this node. Thus, Barcelona achieves efficiency of (95%) on its hub channel.

- Girona (GS3/LEGE) and Palma (GS2/LEPA): The rest messages are equally distributed between two other nodes. GS3 operates as an essential structural dampener in the case of flights through the upper airway corridors or flights approaching the mainland to avoid any information overload at Barcelona. Simultaneously, GS2 handles maritime tracks and those approaching from the south without exceeding the critical limit of 110 msg/min.

5.2. Scenario A: High Traffic Load: Stress-testing the network (Incremental Analysis)

Mainly, the goal of Scenario A is to test the robustness of the operation, load elasticity, and limits of saturation of the VDL Mode 2 network through increasing traffic. In practice, it is essential that the communications system employed should be able to accommodate sudden increases in data traffic due to seasonality, convective weather reroutes, or other such factors without losing any crucial CPDLC or ACARS packets [1][2].

For this purpose, the following spreadsheet logic is designed while developing the optimization model:

- Global Traffic Increments: The control cell is defined as “Traffic Incrementation,” which served as the main input parameter used for the experiment. This is a manually controlled (from 0.00% to 30.00%), which is used for scaling up the load generation of the system.

- Integration of Dynamic Load Formula: Instead of inputting static data into the optimization model, dynamic linkage is created between the average aircraft messages per minute (Average message/min) and the incrementor cell. For the 15 simulated flights, the stressed workload column included the scaling formula:

$$Stressed\ Messages = Average\ Message/Min \times (1 + Traffic\ incr.)$$

- The "Traffic Incrementation Scaling" table acts as a sensitivity analysis overview, where the dynamics of VDL Mode 2 Network operations under increasing load pressure are traced. Such a matrix includes the minimized overall cost (the optimal value of the objective function), and the loads of GS1, GS2, and GS3. In order to build this matrix, the increments in percent (0%, 5%, 10%, 12%, 14%, 15%, 20%, 25%, and 30%) were manually entered into the central Traffic Incrementation cell, where the traffic load for all aircraft types is automatically scaled, as is shown in figure 16. Then, after each entered increment, the Excel Solver operation is applied in order to recalculate the binary routing matrix with minimizing the costs. This operation is performed, ensuring at the same time the correctness of the generated loads versus the technological capacity of each ground station (GS): 180 msg/min for GS1 (Barcelona), 110 msg/min for GS2 (Palma), and 90 msg/min for GS3 (Girona).

Traffic Incrementation Scaling				
	Minimized cost	GS1	GS2	GS3
0%	310,688	170	94	75
5%	336,69	178,5	93,45	84
10%	338,118	176	108,9	88
12%	346,898	179,68	110,0000002	90,000000003
14%	346,898	182,876564	111,9522784	91,63115783
15%	346,896	184,480744	112,934316	92,43493991
20%	346,896	192,501646	117,8445036	96,45385034
25%	346,896	200,522548	122,7546913	100,4727608
30%	346,896	208,54345	127,6648789	104,4916712

Figure 16 Traffic Incrementation Scalling // Source: Own elaborated on Excel

This Scenario A determines the limitations and elasticity of the VDL Mode 2 regional network through the use of an incremental stress test. In contrast to Scenario B, which

measures the effects of a single outage in traffic, Scenario A uses a stepwise progression of the total fleet message volume from 0% (baseline) all the way up to an extremely stressful 30% increase (evaluation levels in between being 5%, 10%, 12%, 14%, 15%, 20%, and 25%). Through this approach, the point of saturation can be determined exactly as the point when demand exceeds the capacity of the infrastructure on hand.

The findings from this analysis prove essential to the determination of saturation and cost stability because:

- 12% Tipping Point: Between the 0% and 12% increases in traffic volume, the optimization algorithm manages the workload distribution efficiently within the network.
    - The 12% traffic volume is the point when the optimal network saturation is achieved: GS1 (Barcelona) operates at 179.68 msg/min (99.8% utilization); GS2 (Palma) is saturated up to its maximum utilization level of 110.00 msg/min (100%), and GS3 (Girona) is also saturated up to its maximum utilization level of 90.00 msg/min (100%).
    - Until reaching that specific point, the total optimized cost increases from 310.69 to 346.90 as a result of non-optimal message routing.
- Post-12% Congestion & Cost Leveling Off: As soon as the traffic increment rises above 12%, there is an important mathematical property at play: the overall minimum cost levels off to 346.90.
    - As a result of having exceeded or saturated the respective actual capacities of all three Ground Stations (180, 110, and 90 messages per minute), the actual physical system cannot receive additional data anymore.
    - Therefore, all additional traffic over the 12% increment will cause the theoretical capacity assignment values of GS1, GS2, and GS3 to increase linearly above the actual limits (i.e., 30% increment = theoretical requirements of 208.54, 127.66, and 104.49 messages per minute).

From a management point of view, this study provides a clear conclusion: the VDL2 communication system in the region has a rigid growth limit that is restricted to 12%.

Structural growth of air traffic above this 12% level in the region can never be optimized through any kind of software or smart routes. It definitely requires a physical enlargement of the system, like an update of transceiver devices at major locations or a fourth ground station in the cluster [2].

5.3. Scenario B: Ground Station Outage: Assessing network resilience and re-assignment.

The objective of scenario B is to analyze the effects of regional VDL Mode 2 network resilience and degradation in the face of a critical infrastructural failure [2][3]. In this scenario, there is a total shutdown at GS3 (Girona) such that the capacity of the node starts from 90 messages/minute to 0 messages/minute. The implementation of this model within the spreadsheet requires the capacity cell of GS3 to be set to zero and then run the Excel solver program to redistribute the baseline load of 339 messages/minute among other functional nodes, GS1 (Barcelona) – up to 180 msg/min and GS2 (Palma) – up to 110 msg/min. Any load in messages that exceeds the physical capacity of the network is automatically allocated to the overflow node where each message has a heavy penalty of 100.

The structural workspace is altered to represent a total loss without modifying the fundamental structure of the optimization process itself. This is accomplished in the following manner:

- Modification of Capacity Threshold: The main modification made differentiating this example from the basic model is in the Ground Station Capacity Monitoring block. The capacity threshold of GS3 (Girona) is altered by manual override from the basic level of 90 messages/minute to a zero capacity threshold of 0 messages/minute. The capacity thresholds of GS1 and GS2 (180 and 110 msg/min respectively) did not change. In order to avoid any infactibity issues that may arise as a result of closing down one of the ground stations, the additional overflow row (as a route) is introduced along with standard rows assigning messages to specific ground stations. It should be noted that the overflow channel serves as a buffer with an infinite capacity threshold (equals 9999 msg/min) but has a very high price in the multi-criteria cost matrix.

- To facilitate optimal dynamic control of the network failure by the optimization engine, an essential architectural revision is introduced to the core allocation configuration of the Binary Decision Variable and Network Solution Matrices. Specifically, a new routing variable, the OVERFLOW column, is introduced alongside the conventional ground station assignment columns (GS1, GS2, and GS3), as can be seen in figure 17. As a result, the dimensionality of each of the

15 modeled flights is increased to four possible binary choices {GS1, GS2, GS3, OVERFLOW}. In this revised setup, the underlying Linear Programming problem preserves the strict binary restriction that obligates each flight to be associated with only one routing column, implying the requirement of the row sum of all the decision variables associated with any aircraft to be 1 [24]. With GS3 capacity set to zero, this architectural modification facilitates Solver's application of the binary solution matrix to route the traffic from the faulty ground station and automatically allocate the unsolvable portion of the telemetry load into the overflow column.

Binary Decision Variables and Network Solution Matrix					
Decision variables and solution					
Aircraft	GS1	GS2	GS3	OVERFLOW	Suma
A1	1	0	0	0	1
A2	1	0	0	0	1
A3	0	1	0	0	1
A4	1	0	0	0	1
A5	1	0	0	0	1
A6	1	0	0	0	1
A7	0	0	0	1	1
A8	1	0	0	0	1
A9	0	0	0	1	1
A10	0	1	0	0	1
A11	0	1	0	0	1
A12	0	1	0	0	1
A13	1	0	0	0	1
A14	1	0	0	0	1
A15	0	1	0	0	1
Suma	473,3263487	473,3263487	473,3263487	473,3263487	

Figure 17 Binary DecisionVariables and Network Solution Matrix // Source: Own elaborated on Excel

- Expansion of Binary Decision Constraint: The process of incorporating the emergency routing path as part of the optimization process required an extension of the range of the binary decision variables as part of the Solver constraints. In particular, the constraint involving the use of binary values for routing decisions is changed from its initial value that focused on the physical ground stations alone to one that included the new "overflow" column, as shown in figure 18. Technically, this means that the Excel Solver will treat the overflow as a true binary value (0 or 1) for each of the fifteen flight scenarios.

Binary Decision Variables and Network Solution Matrix					
Decision variables and solution					
Aircraft	GS1	GS2	GS3	OVERFLOW	Suma
A1	1	0	0	0	1
A2	1	0	0	0	1
A3	0	1	0	0	1
A4	1	0	0	0	1
A5	1	0	0	0	1
A6	1	0	0	0	1
A7	0	0	0	1	1
A8	1	0	0	0	1
A9	0	0	0	1	1
A10	0	1	0	0	1
A11	0	1	0	0	1
A12	0	1	0	0	1
A13	1	0	0	0	1
A14	1	0	0	0	1
A15	0	1	0	0	1

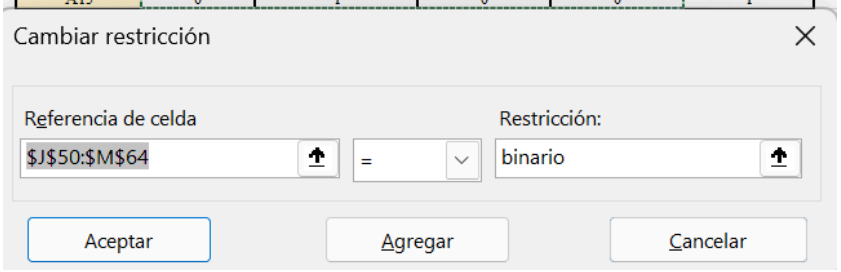


Figure 18 Binary restriction on Decision Variables Matrix // Source: Own elaborated on Excel

The solution results in Scenario B demonstrate the effect of a disruption in the infrastructure on the VDL Mode 2 network capacity. By imposing the maximum operational capacity of GS3 (Girona) at 0 messages/minute, the Excel Solver is compelled to re-allocate the initial amount of 339 messages/minute of the fleet through the other remaining available nodes. In such a scenario, GS1 (Barcelona) becomes fully saturated, with a total capacity of 180 messages/minute (100%), whereas GS2 (Palma) handles a load of 94 messages/minute out of its total capacity of 110 messages/minute, leaving 16 open positions. As it can be seen, the physical limitations of the network do not allow further re-assignment and optimization; therefore, the remaining 65 messages/minute are directed straight into the OVERFLOW channel, thus indicating that 19.17% of all regional air space traffic will experience the loss of the primary data link. The high overflow rate stems mostly from the operational cost matrix, which does not allow an efficient routing of the planes flying in the northern sector due to their line-of-sight (LoS) restriction/path attenuation compared with Palma.

5.4. Managerial Implications: Cost-benefit analysis of optimization vs. infrastructure expansion

The data derived from Scenarios A and B are extremely valuable for decision making by the relevant stakeholders in the management of the air space, networks, and airline operations. This section will provide a cost-benefit analysis for comparing immediate optimization of software with capital investment in infrastructure (CAPEX).

5.4.1. The Operational and Financial Boundaries of Software Optimization

In the short term, it is demonstrated that the developed multi-criteria mathematical model performs extremely well as a cheap yet effective tactical approach. Through the intelligent application of routing within the spreadsheet, the network will be able to endure an additional 12% traffic surge without any need for physical assets, thus fully exploiting its existing capabilities.

However, as evidenced by this paper's analysis, software optimization inevitably hits an absolute physical barrier when saturation occurs in the infrastructure. Beyond the 12% traffic expansion threshold, or in the case of failure in a single node, where 19.17% of the traffic will be rerouted through the emergency channel (Scenario B), no amount of mathematical calculations will have a say against the laws of physics and geography. Purely relying on software at such stressful times would result in the following risks:

- AOC/ATC Communication Disconnect: Shunting 65 messages per minute to overflow channels suggests that an extremely hazardous operating situation exists where there is packet loss, synchronization issues [3][9], and the necessity of falling back on traditional VHF voice communications frequencies [1][5].

- Overload of Voice Frequency Communications Channels: Falling back to voice communications significantly burdens pilots and air traffic controllers and raises the danger of operating errors.

5.4.2. Strategic Infrastructure Expansion (CAPEX vs. OPEX)

In order to accommodate industry trend towards expanding aircraft fleets and ensuring network reliability [19], there is no other choice but to move away from tactical software-based routing and focus on strategic CAPEX infrastructure growth. In this regard, the analysis offers evidence supporting two potential routes of CAPEX investments:

1. Improving Hardware Infrastructure at Major Hub Nodes: An upgrade of transceivers as well as increasing frequency slot throughput capacity for GS1 (Barcelona) past the 180 msg/min restriction would enable the node to accommodate the surge of peripheral traffic without overload.

2. Adding Fourth Geographically Diverse Ground Station Node: Construction or lease of additional VDL2 ground station in the northern coastal region would

help to mitigate LoS-related challenges highlighted during the outage of Girona (GS3) [16].

The conclusion for Network Planning is that although software-optimized solutions should always remain in use to reduce OPEX [17] and even handle normal loads, it cannot be seen as an alternative to development. Airspace sustainability calls for balanced design whereby software-optimized solutions take care of the tactical variability, while physical infrastructure expansion takes care of future needs.

6. Conclusions and Future Work

6.1. Summary of Findings

The current study has thoroughly covered the problems of congestion and operational inefficiencies present in today's aviation telecommunication networks, concentrating on VDL Mode 2 (VHF Data Link Mode 2) protocol [3] in the Barcelona FIR & TMA area. By shifting away from analog communication (VHF Voice) that relied on the "party line" concept and towards digital technology of packet switching, it has been proved with the help of mathematical calculations that optimization of existing infrastructure can be regarded as a viable alternative to network expansion (CAPEX)[1][3][5].

The primary results obtained as a consequence of executing the MILP model with Simplex LP algorithm are presented below:

- Multicriteria Normalization Effectiveness: Incorporating different criteria such as Geometric Propagation Distance, Packet Error Rate (PER) of D8PSK mode [8][9], and communication services price indicators provided by service providers (CSP, SITA and ARINC) [12][13] into a nondimensional matrix with scaling between 0 and 1 by applying min-max normalization has successfully resolved the issue related to the elimination of the bias due to the difference in magnitudes of the values included in the optimization process and provided a balanced perspective regarding both technical resilience and economic cost.

- Bottleneck Problem Resolution Using Load Criteria: It is shown that the method of allocation based only on the criterion of "the strongest signal" leads to local overload and violates the principle of operational safety [2]. Introducing the number of messages per minute as a multiplier in the operational cost matrix has allowed solving the problem and distributing the load of airspace terminals among peripheral radio stations and regional infrastructures (such as GS3 -

Girona / LEGE) before achieving saturation at the central node (GS1 - Barcelona / LEBL).

- Operational Safety Assurances: By integrating the Operational Priority Index as the denominator in the multi-objective cost function, we created the mathematical "protection override." In the scenario of simulated emergency situations (for example, aircraft A15 with Priority 3), the system significantly minimized the value of the objective function coefficient (resistance) of that particular row, which caused a completely autonomous decision-making process to optimize such that its crucial safety links (CPDLC and ADS-C) were protected [1][3] in spite of any economical or geographical costs.

- Strict Compliance with Physical Constraints: By introducing geometric visibility gates using the spherical radio horizon equation of ($LoS = 1.23 \times \sqrt{ALTft}$), we created a failsafe filter, which automatically ruled out all dissipative decision variables.

In conclusion, the current research has managed to design and implement a simplified assignment model in order to optimize the communication channels between aircraft and VDL2 ground stations under a congested situation. Using linear programming optimization, this model has proven the great potential of using assignment optimization in achieving an even network load, reducing channel congestion and focusing on emergency flights. However, it is crucial to identify the major limitations that are associated with this particular approach. Namely, the created model functions as a simplified assignment approach based on the static picture of air traffic, using assumed nominal capacities and implemented via Excel Solver software. Therefore, while this research provides important information about the potential of mathematical optimization in aeronautical telecommunications networks, it should not be regarded as the confirmation of its applicability to the real-life functioning of the VDL2 network.

6.2. Achievement of Objectives

Methodology for achieving the objectives of this thesis has successfully been achieved in full accordance with the objectives set at the beginning of the project. This is evidenced by:

- The Identification of Operational Limitations (Goal Attained): The physical limitations involved in the implementation of the VDL2 CSMA communication protocol [3][10] as well as the noise sensitivity of the D8PSK phase modulation have been effectively captured and used to set the maximum messages per

minute limits on the processing of LEBL (180 msg/min), LEPA (110 msg/min), and LEGE (90 msg/min).

- Mathematical Modeling Framework (Goal Attained): The objective function for minimizing network friction (Z = 310.688) has been established under strict constraints.

- Accessibility of Validation (Achieved): In the case of the assignment problem studied in this paper, the mathematical model and the corresponding problem have been solved through accessible management software. The particular piece of software used in this research is Microsoft Excel with the use of the Simplex LP Solver. It has proven that the particular type of assignment problem can be solved effectively by the accessible management tools.

- Analysis of Sensitivity and Resilience (Accomplished): The matrix nature of the problem allowed to conduct stress tests on dynamic changes in network, such as sudden increase of load on sectors by 20% and complete outages of ground stations caused by infrastructural failures.

- Recommendations for Strategic Management Decisions (Accomplished): This allows to provide the basis for ANSPs' decisions about optimizing the available capacity of their networks using load [2] balancing and delay major capital expenditures on physical equipment purchases.

6.3. Recommendations for Future Research

Although there is success achieved with the application of the linear model, the ever-changing and dynamic nature of digital air traffic control presents opportunities for many scientific expansions. In terms of future work, the following suggestions are made:

1. Transition to Stochastic and Dynamic Optimizing Algorithms: At the moment, the algorithm works with a synchronous snapshot of the airspace at the fixed point in time. It is necessary to take into account continuous four-dimensional flight trajectories (4D-trajectories)[14], built from the predictive state vectors, thus turning the static assignment matrix into a dynamic, multistage optimizing model taking into account the time factor and continuous handovers.

2. Integrating Petri Net Models into MAC Protocol Simulation: Due to the underlying CSMA MAC protocol, the probability of packet collisions increases non-linearly with channel load. Thus, the development of an innovative hybrid

approach utilizing Linear Programming along with Petri Net simulation modeling could help mathematically precisely monitor GSC queues and automatically initiate packet retransmission due to CRC-based integrity errors [9].

3. Scaling Using Metaheuristic Algorithms and Cloud Computing: During the continent-wide scenario with hundreds of flights and dozens of roaming stations, the amount of possible search space in a binary decision problem becomes enormous. In such a situation, GA, PSO, and other metaheuristics, performed using cloud computing technologies, could be considered to obtain near-optimal solutions within milliseconds [15].

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Annexes

Optimization problem

Aircraft Flight Profiles and Telemetry Data						
Aircraft	Callsign	Alt (ft)	Dist (nmi)	Line of sight (LoS)	Average message/min	Priority
A1	WZZ6674	8600	6,5	114,07	30	1
A2	IBE06VY	35975	13,4	233,30	10	1
A3	ANE53GX	19300	14,4	170,88	22	2
A4	VLG75CT	2175	17,7	57,36	35	1
A5	RAM960U	2125	18,3	56,70	35	1
A6	DLH0TU	4525	20,2	82,74	35	1
A7	RYR1FR	3250	21,9	70,12	35	1
A8	VLG1438	29000	24,1	209,46	15	1
A9	VLG7CH	6650	25,5	100,30	30	1
A10	VLG9DC	11500	282	131,90	22	1
A11	TAP1036	5050	29,6	87,41	30	2
A12	VJT569	33000	30,3	223,44	10	2
A13	AEA1684	38975	31,6	242,83	10	1
A14	WZZ1919	34975	33,5	230,03	10	1
A15	EJU16VW	37000	34,3	236,60	10	3

Raw VHF Radio Link Metrics and CSP Tariffs									
Aircraft	GS1_dist (LEBL)	GS2_dist (LEPA)	GS3_dist (LEGE)	GS1_PER	GS2_PER	GS3_PER	GS1_price	GS2_price	GS3_price
A1	35	190	95	0,5	2,5	1,5	1	1,5	1,2
A2	120	240	65	1,5	3	0,8	1,1	1,4	1
A3	84	160	110	1	2	1,4	1,1	1,3	1,2
A4	12	210	105	0,2	3,5	1,8	1	1,6	1,3
A5	18	205	102	0,3	3,5	1,8	1	1,5	1,2
A6	25	215	80	0,4	3,5	1,3	1	1,6	1,2
A7	42	185	120	0,6	2,4	1,9	1,1	1,4	1,3
A8	140	290	45	1,9	3,8	0,5	1,3	1,7	1
A9	55	175	135	0,8	2,2	2	1,1	1,4	1,3
A10	70	150	150	1	2	2	1,2	1,3	1,3
A11	60	230	75	0,9	3,2	1,1	1,1	1,5	1,1
A12	195	90	210	2,6	0,7	2,8	1,5	1,8	1,7
A13	115	260	50	1,5	3,5	0,6	1,2	1,6	1
A14	160	310	35	2,2	3,9	0,4	1,3	1,7	1
A15	90	140	165	1,2	1,8	2,3	1,1	1,3	1,4

MAX	310	3,9	1,8
	DIST	PER	PRICE

Stations capacity (message/min)		
GS1	GS2	GS3
180	110	90

Scaled and Normalized Dimensionless Metrics Matrix									
Normalization									
Aircraft	GS1_dist	GS2_dist	GS3_dist	GS1_PER	GS2_PER	GS3_PER	GS1_price	GS2_price	GS3_price
A1	0,113	0,613	0,306	0,128	0,641	0,385	0,556	0,833	0,667
A2	0,387	0,774	0,210	0,385	0,769	0,205	0,611	0,778	0,556
A3	0,271	0,516	0,355	0,256	0,513	0,359	0,611	0,722	0,667
A4	0,039	0,677	0,339	0,051	0,897	0,462	0,556	0,889	0,722
A5	0,058	0,661	0,329	0,077	0,897	0,462	0,556	0,833	0,667
A6	0,081	0,694	0,258	0,103	0,897	0,333	0,556	0,889	0,667
A7	0,135	0,597	0,387	0,154	0,615	0,487	0,611	0,778	0,722
A8	0,452	0,935	0,145	0,487	0,974	0,128	0,722	0,944	0,556
A9	0,177	0,565	0,435	0,205	0,564	0,513	0,611	0,778	0,722
A10	0,226	0,484	0,484	0,256	0,513	0,513	0,667	0,722	0,722
A11	0,194	0,742	0,242	0,231	0,821	0,282	0,611	0,833	0,611
A12	0,629	0,290	0,677	0,667	0,179	0,718	0,833	1,000	0,944
A13	0,371	0,839	0,161	0,385	0,897	0,154	0,667	0,889	0,556
A14	0,516	1,000	0,113	0,564	1,000	0,103	0,722	0,944	0,556
A15	0,290	0,452	0,532	0,308	0,462	0,590	0,611	0,722	0,778

Multi-Criteria Operational Routing Cost Matrix			
Costs			
Aircraft	GS1	GS2	GS3
A1	23,90	62,62	40,73
A2	13,83	23,21	9,70
A3	12,52	19,26	15,19
A4	22,59	86,23	53,29
A5	24,17	83,72	51,00
A6	25,86	86,80	44,03
A7	31,52	69,65	55,88
A8	24,92	42,81	12,43
A9	29,81	57,19	50,12
A10	25,28	37,82	37,82
A11	15,53	35,94	17,03
A12	10,65	7,35	11,70
A13	14,22	26,25	8,71
A14	18,02	29,44	7,71
A15	4,03	5,45	6,33

Binary Decision Variables and Network Solution Matrix				
Decision variables and solution				
Aircraft	GS1	GS2	GS3	Suma
A1	1	0	0	1
A2	0	0	1	1
A3	0	1	0	1
A4	1	0	0	1
A5	1	0	0	1
A6	1	0	0	1
A7	1	0	0	1
A8	0	0	1	1
A9	0	1	0	1
A10	0	1	0	1
A11	0	0	1	1
A12	0	1	0	1
A13	0	0	1	1
A14	0	0	1	1
A15	0	1	0	1
Suma	310,6875287	310,6875287	310,6875287	

Ground Station Channel Congestion and Capacity Monitoring				
Total loads on ground stations				
	GS1	GS2	GS3	TOTAL NETWORK
TOTAL LOAD	170	94	75	339
CAPACITY	180	110	90	380

Global Network Target Optimization Value (Objective Function)	
Minimized total cost	310,688

Scenario A

Aircraft Flight Profiles and Telemetry Data							
Aircraft	Callsign	Alt (ft)	Dist (nmi)	Line of sight (LoS)	Average message/min	Stressed messages	Priority
A1	WZZ6674	8600	6,5	114,07	30	30	1
A2	IBE06VY	35975	13,4	233,30	10	10	1
A3	ANE53GX	19300	14,4	170,88	22	22	2
A4	VLG75CT	2175	17,7	57,36	35	35	1
A5	RAM960U	2125	18,3	56,70	35	35	1
A6	DLH0TU	4525	20,2	82,74	35	35	1
A7	RYR1FR	3250	21,9	70,12	35	35	1
A8	VLG1438	29000	24,1	209,46	15	15	1
A9	VLG7CH	6650	25,5	100,30	30	30	1
A10	VLG9DC	11500	282	131,90	22	22	1
A11	TAP1036	5050	29,6	87,41	30	30	2
A12	VJT569	33000	30,3	223,44	10	10	2
A13	AEA1684	38975	31,6	242,83	10	10	1
A14	WZZ1919	34975	33,5	230,03	10	10	1
A15	EJU16VW	37000	34,3	236,60	10	10	3

Ground Station Channel Congestion and Capacity Monitoring				
Total loads on ground stations				
	GS1	GS2	GS3	TOTAL NETWORK
TOTAL LOAD	170	94	75	339
CAPACITY	180	110	90	380

Traffic Incrementation
0,00%

	Minimized cost	GS1	GS2	GS3
0%	310,688	170	94	75
5%	336,69	178,5	93,45	84
10%	338,118	176	108,9	88
12%	346,898	179,68	110,0000002	90,000000003
14%	346,898	182,876564	111,9522784	91,63115783
15%	346,896	184,480744	112,934316	92,43493991
20%	346,896	192,501646	117,8445036	96,45385034
25%	346,896	200,522548	122,7546913	100,4727608
30%	346,896	208,54345	127,6648789	104,4916712

Scenario B

Multi-Criteria Operational Routing Cost Matrix				
Costs				
Aircraft	GS1	GS2	GS3	OVERFLOW
A1	23,90	62,62	40,73	100
A2	13,83	23,21	9,70	100
A3	12,52	19,26	15,19	100
A4	22,59	86,23	53,29	100
A5	24,17	83,72	51,00	100
A6	25,86	86,80	44,03	100
A7	31,52	69,65	55,88	100
A8	24,92	42,81	12,43	100
A9	29,81	57,19	50,12	100
A10	25,28	37,82	37,82	100
A11	15,53	35,94	17,03	100
A12	10,65	7,35	11,70	100
A13	14,22	26,25	8,71	100
A14	18,02	29,44	7,71	100
A15	4,03	5,45	6,33	100

Binary Decision Variables and Network Solution Matrix					
Decision variables and solution					
Aircraft	GS1	GS2	GS3	OVERFLOW	Suma
A1	1	0	0	0	1
A2	1	0	0	0	1
A3	0	1	0	0	1
A4	1	0	0	0	1
A5	1	0	0	0	1
A6	1	0	0	0	1
A7	0	0	0	1	1
A8	1	0	0	0	1
A9	0	0	0	1	1
A10	0	1	0	0	1
A11	0	1	0	0	1
A12	0	1	0	0	1
A13	1	0	0	0	1
A14	1	0	0	0	1
A15	0	1	0	0	1
Suma	473,3263487	473,3263487	473,3263487	473,3263487	

Ground Station Channel Congestion and Capacity Monitoring					
Total loads on ground stations					
	GS1	GS2	GS3	OVERFLOW	TOTAL NETWORK
TOTAL LOAD	180	94	0	65	339
CAPACITY	180	110	0	9999	290