# Dynamic Frequency Assignment for Mobile Users in Multibeam Satellite Constellations

by

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# Abstract

The unprecedented levels of flexibility and scalability of the next generation of communication satellite systems call for new resource management algorithms that adapt to dynamic environments. The upcoming landscape of satellite communication services will be defined by an increased number of unique users, a large portion of which will correspond to mobile users such as planes or ships. The additional challenge introduced by these users is addressing the spatiotemporal uncertainty that comes in the form of delays, changes in their trajectory, or both. Given that mobile users will constitute an important segment of the market, satellite operators prioritize leveraging modern digital payloads to develop flexible resource allocation strategies that are robust against dynamic user bases.

One of the key problems in this context is how to manage the frequency spectrum efficiently. While numerous solutions address dynamic frequency assignment scenarios, the additional layer of complexity presented by mobile users has not been sufficiently studied, and it is unclear whether novel frequency assignment algorithms can address spatiotemporal uncertainty. Specifically, we argue that unexpected changes in the position of users introduce new restrictions into the frequency assignment, which previous algorithms in the literature might not be able to meet, especially if decisions need to be made in real-time and at scale.

To address this gap, we propose a dynamic frequency management algorithm based on integer linear programming that assigns resources in scenarios with both fixed and mobile users, accounting for the spatiotemporal uncertainty of the latter. Our method includes both long-term planning and real-time operation, a synergy that has not been sufficiently explored for satellite communications and proves to be critical when operating under uncertainty. To fulfill the problem's scope, we propose different strategies that extend a state-of-the-art frequency management algorithm. These strategies are divided into proactive strategies, which stem from robust optimization practices, and reactive strategies, which exploit a high degree of real-time control.

To assess the performance of our algorithm and determine which strategies work better under which context, we simulate operational use cases of non-geostationary constellations with different levels of uncertainty. The results identify that the framework and the strategies are able leverage the capabilities of satellite systems to allocate resources efficiently. We find that the studied strategies present several tradeoffs when addressing spatiotemporal uncertainty.

**Keywords**: Satellite Communications, Dynamic Frequency Assignment, Resource Allocation, Dynamic Resource Management, Mobile Users, Uncertainty, Satellite Constellations, Spectrum Management, Integer Linear Programming

# Resum

Els nivells de flexibilitat i escalabilitat mai vistos de la propera generació de sistemes de comunicació per satèl·lit exigeixen nous algorismes de gestió de recursos que s'adaptin a contextos dinàmics. El futur entorn dels serveis de comunicació per satèl·lit estarà definit per un nombre més gran d'usuaris, una gran part dels quals correspondrà a usuaris mòbils com avions o vaixells. El repte addicional que introdueixen aquests usuaris és abordar la incertesa espai-temporal que es presenta en forma de retards, canvis en la seva trajectòria, o tots dos. Atès que els usuaris mòbils constituiran un segment important del mercat, els operadors de satèl·lits prioritzen l'aprofitament dels avançats sistemes digitals per desenvolupar estratègies flexibles d'assignació de recursos que siguin robustes davant de les bases d'usuaris dinàmiques.

Un dels problemes clau en aquest context és com gestionar l'espectre de freqüències de manera eficient. Mentre que nombroses solucions aborden escenaris d'assignació de dinàmica freqüències, el nivell addicional de complexitat que presenten els usuaris mòbils no ha estat prou estudiat, i no és clar si els nous algorismes d'assignació de freqüències poden abordar la incertesa espai-temporal. Concretament, sostenim que els canvis inesperats en la posició dels usuaris introdueixen noves restriccions en l'assignació de freqüències que els algoritmes la literatura podrien no ser capaços de complir, especialment si les decisions s'han de prendre en temps real i a escala.

Per solucionar aquesta limitació, proposem un algorisme de gestió dinàmica de freqüències basat en programació lineal entera que assigna recursos a escenaris amb usuaris tant fixos com mòbils, tenint en compte la incertesa espai-temporal d'aquests últims. El nostre mètode inclou tant la planificació a llarg termini com l'operació en temps real, una sinergia que no ha estat prou explorada per a les comunicacions per satèl·lit i que és crítica quan s'opera sota incertesa. Per complir l'abast del problema, proposem diferents estratègies que amplien un algorisme de gestió de freqüències de l'estat de l'art. Aquestes estratègies es divideixen en estratègies proactives, que deriven de pràctiques d'optimització robustes, i estratègies reactives, que exploten un alt grau de control en temps real.

Per avaluar el rendiment del nostre algorisme i determinar quines estratègies funcionen millor en cada context, simulem casos d'ús en constel·lacions no geoestacionàries amb diferents nivells d'incertesa. Els resultats identifiquen que el el nostre algorisme i les estratègies són capaços d'aprofitar les capacitats dels sistemes de satèl·lits per assignar recursos de manera eficient. Descobrim que les estratègies estudiades presenten diversos avantatges i desavantatges en abordar la incertesa espai-temporal.

**Paraules clau**: Comunicacions per satèl·lit, assignació dinàmica de freqüències, assignació de recursos, gestió dinàmica de recursos, usuaris mòbils, incertesa, constel·lacions de satèl·lits, gestió de l'espectre, programació lineal entera

# Resumen

Los niveles de flexibilidad y escalabilidad nunca vistos de la próxima generación de sistemas de comunicación por satélite exigen nuevos algoritmos de gestión de recursos que se adapten a contextos dinámicos. El futuro entorno de los servicios de comunicación por satélite estará definido por un mayor número de usuarios, una gran parte de los cuales corresponderá a usuarios móviles como aviones o barcos. El reto adicional que introducen estos usuarios es abordar la incertidumbre espacio-temporal que se presenta en forma de retrasos, cambios en su trayectoria, o ambos. Dado que los usuarios móviles constituirán un segmento importante del mercado, los operadores de satélites dan prioridad al aprovechamiento de los avanzadas sistemas digitales para desarrollar estrategias flexibles de asignación de recursos que sean robustas frente a las bases de usuarios dinámicas.

Uno de los problemas clave en este contexto es cómo gestionar el espectro de frecuencias de forma eficiente. Mientras que numerosas soluciones abordan escenarios de asignación dinámica de frecuencias, el nivel adicional de complejidad que presentan los usuarios móviles no ha sido suficientemente estudiado, y no está claro si los nuevos algoritmos de asignación de frecuencias pueden abordar la incertidumbre espacio-temporal. En concreto, sostenemos que los cambios inesperados en la posición de los usuarios introducen nuevas restricciones en la asignación de frecuencias que los algoritmos la literatura podrían no ser capaces de cumplir, especialmente si las decisiones deben tomarse en tiempo real y a escala.

Para solventar esta limitación, proponemos un algoritmo de gestión dinámica de frecuencias basado en la programación lineal entera que asigna recursos en escenarios con usuarios tanto fijos como móviles, teniendo en cuenta la incertidumbre espacio-temporal de estos últimos. Nuestro método incluye tanto la planificación a largo plazo como la operación en tiempo real, una sinergia que no ha sido suficientemente explorada para las comunicaciones por satélite y que resulta ser crítica cuando se opera bajo incertidumbre. Para cumplir con el alcance del problema, proponemos diferentes estrategias que amplían un algoritmo de gestión de frecuencias del estado del arte.

Estas estrategias se dividen en estrategias proactivas, que se derivan de prácticas de optimización robustas, y estrategias reactivas, que explotan un alto grado de control en tiempo real.

Para evaluar el rendimiento de nuestro algoritmo y determinar qué estrategias funcionan mejor en cada contexto, simulamos casos de uso operativo de constelaciones no geoestacionarias con diferentes niveles de incertidumbre. Los resultados identifican que el marco y las estrategias son capaces de aprovechar las capacidades de los sistemas de satélites para asignar recursos de forma eficiente. Descubrimos que las estrategias estudiadas presentan varias ventajas y desventajas al abordar la incertidumbre espacio-temporal.

**Palabras clave**: Comunicaciones por satélite, asignación dinámica de frecuencias, asignación de recursos, gestión dinámica de recursos, usuarios móviles, incertidumbre, constelaciones de satélites, gestión del espectro, programación lineal entera

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# Chapter 1

# Introduction

## 1.1 Motivation

Over the past few years, satellite communication has emerged as one of the leading markets in a growing space economy thanks to its myriad of applications across industries, such as media broadcast, extended broadband coverage, support of 5G technologies, integration of wired and unwired communication systems, or defense and security operations. Motivated by these new opportunities, both established satellite operators, such as Intelsat, Viasat, and SES, as well as newer contestants, such as SpaceX or Amazon, are taking advantage of recent technological advances, reduced launch costs and improved manufacturing processes to develop satellite constellations and compete in a new and challenging satellite communications landscape.

The first challenge that satellite operators will face is operating in a dynamic and uncertain environment, defined by the complex user demand characteristics. To meet the population's need to be connected "anytime, anywhere" and provide connectivity where ground infrastructure is unreliable or completely unavailable, satellite operators must develop operational policies that tolerate unpredicted temporal and spatial changes in demand. These changes come not only from seasonal and diurnal variations, such as daily peak hours on different continents, but also from the location changes over time of users that require mobile connectivity, such as aircraft, ships, and ground vehicles. These mobile users are becoming an important segment of the market. Therefore, providing continuous coverage along their travel routes will be crucial for success in a highly competitive market.

In the airline industry, having in-flight connectivity is becoming an essential component of the passenger experience, and airlines have already begun to provide their aircraft with the necessary technologies. The number of antennas installed onboard airplanes presented a 19.3% increase year-over-year to 10,000 units by the end of 2021 and will continue to grow. By the end of the decade, the number of installed antennas is expected to exceed the 40,000 unit mark. The demand for aeronautical applications is expected to reach 1,000 Gbps, with an annual revenue opportunity of $3.8 billion for satellite operators [2]. In 2020, the market of maritime mobile users was composed of approximately 70,000 broadband-enabled vessels, and the retail revenue was at 2.2 billion dollars. The number of vessels with broadband connectivity is projected to grow to more than 140,000 by 2030, with an expected capacity demand of 1,000 Gbps and an annual revenue opportunity of $3.4 billion [3]. Government and military end-users also present a clear increased need for mobile connectivity and improved use-cases, requiring fast and reliable response times. They are also set to be an important part of the market, with an expected demand increase from 52 Gbps in 2020 to over 1,000 Gbps by the end of the decade [4].

Unlike fixed users, mobile users move between satellite coverage areas and contribute to significant demand changes throughout the day, from periods where connectivity is not required to localized demand beaks due to, for example, a large number of aircraft departing during a short time window. In the case of aeronautical and maritime users, their demand is concentrated on populated traffic routes, contributing to uneven distributions of traffic density.

The second challenge encountered by satellite operators is managing the increased flexibility and degrees of freedom of new satellite systems. Traditional satellites were usually in geostationary orbit (GEO) and used wide beams to cover large regions spanning thousands of kilometers, spreading the available radio frequency and power resources. The next-generation satellite systems are populating non-geostationary orbits (NGSO) and are equipped with spot beam technologies to cover particular service areas that span a few hundred kilometers. These narrower spot beams have higher directivity and, therefore, higher transmit and receive gain, enabling the use of smaller user equipment and high-order modulation schemes to achieve high data rates. They also have the ability to steer beams, reuse spectrum, and redistribute power among beams based on commands sent to the operating satellites. Leveraging these added capabilities, including reallocating resources in real-time, is crucial to increase system efficiency, improve service quality for current and future users, and operate in new use cases.

Finally, the third challenge of the new satellite communications landscape is the dimensionality of the new satellite systems, which adds yet another level of complexity. Satellite operators are deploying constellations with thousands of satellites, e.g., SpaceX's Starlink with 4408 satellites [5, 6], and thousands of beams, e.g., as SES' O3b mPower with up to 50k beams [7].

Dynamic and uncertain user demand patterns, including mobile connectivity, together with the increased flexibility and the dimensionality of the upcoming constellations, make traditional and static man-centered resource allocation, which relies on conservative operational margins, an infeasible option for satellite operators if they want to be competitive in this new landscape. New Dynamic Resource Management (DRM) tools must be developed to optimize and control constellation resources to overcome these new challenges and achieve high system utilization.

Multiple research lines have started to focus on developing algorithms, ranging from classical optimization techniques to artificial intelligence methods, that can replace current human decision-making processes. Although solutions can be found that address resource allocation under uncertainty in user demand, the additional layer of complexity and uncertainty presented by mobile users with high-throughput needs has not been sufficiently studied. It is unclear whether novel algorithms can address this problem, especially when presented at scale. In order to make progress toward satisfying the increased demand for mobile connectivity, this Thesis tries to close this research gap by proposing an algorithmic solution to solve an instance of the DRM problem in the context of multibeam satellite constellations.

## 1.2 General objectives

The main goal of this Thesis is to contribute to the development of Dynamic Resource Management tools for the upcoming satellite communications systems by focusing on efficient and dynamic spectrum management, a very limited, complex to manage, and worth exploiting resources. This work presents a dynamic frequency assignment solution that enables operation under the dynamic demand patterns and uncertainty added by mobile users.

## 1.3 Literature review

This section first provides an overview of the new landscape of mobile satellite communications and outlines the changes in demand needs, antenna technologies, regulations, and interference concerns compared to previous solutions. Secondly, it overviews frequency and bandwidth assignment solutions in satellite communications.

### 1.3.1 Mobile communications

The ever-growing user demand for mobile global broadband communications has fueled the development of a new type of satellite terminal, known as Earth stations in motion (ESIM). These new terminals use small antennas with tracking capabilities and advanced modulation and coding schemes that enable high data-rate communications from airplanes, maritime vehicles, or land vehicles. Although different satellite terminals have been onboard these vehicles since the end of the 1970s, when Inmarsat was established, they operated using low-frequency bands (L/S-band) and provided narrowband services with low data rates. Technology advances adopted by satellite designers and terminal manufacturers have allowed mobile connectivity to support high-speed communications using higher frequency bands (Ku/Ka-band). These new satellite systems present aditional technical and operational challenges compared to previous low-throughput mobile terminals and fixed high-throughput counterparts. They need to have reduced sizes to operate from a moving vehicle, airplane, or maritime vessel and provide improved pointing accuracy to maintain service quality and avoid interference with other applications [8]. The emergence of these new types of user terminals highlights the importance of rethinking satellite services, from more flexible regulations to more efficient resource management strategies.

Some works in the literature provide a broad overview and solutions to meet mobile connectivity requirements. Chini et al. [9] present a survey on satellite communication services for mobile users overviewing different research issues, standardization requirements, and operational systems. McLain et al. [10, 11] shows the difference between aeronautical traffic compared to fixed applications and provides insight on satellite design and resource management to address the challenges of the broadband aeronautical market. Focusing also on broadband aeronautical connectivity, Dinc et al. [12] propose new architectures and business models and recognize the potential of NGSO constellations to meet the latency and data demand for IFC. More generally, McLain and King [13] examine the prospects for GEO satellites and LEO constellations to provide mobile broadband connectivity, focusing on their risk, cost, and the possibility of using existing mobile terminals.

Significant improvements in antenna technologies offer new opportunities for mobile connectivity through a smaller size, weight, and power [14]. Alazab et al. [15] and Murthy [16] present solutions to characterize antenna pointing accuracy and polarization alignment for vehicle-mounted terminals. Rahmat-Samii and Densmore [17] offers a comprehensive survey of antenna technology trends and challenges, including those for aeronautical, maritime, and land mobile applications, while McLain and Panthi focus on broadband services in aviation. Lesur et al. [18], and Abdel-Wahab et al. [19] present phased-array antenna solutions for Ka-Band mobile connectivity applications.

Global regulatory organizations have recognized the industry's need to meet the growing demand for mobile satellite connectivity. The 2015 World Radiocommunication Conference (WRC-15) adopted radio regulations for mobile satellite terminals to use Ka-band communications with GSO satellites. During WRC-19, the frequency allowed to be used by ESIMs in the Ka-band was expanded but still limited to GSO satellites. Although using Ka-band with NGSO satellites has already been allowed by national spectrum regulatory organizations, it will be addressed internationally during WRC-23 [20, 21, 22].

Expanding the spectrum allocated to mobile broadband services involves sharing frequency with other applications, which requires protecting other operators from unacceptable interference. To that end, recent works study how to share this frequency with other communication systems for the following years. Oh and Kang [23], Menanor et al. [24], and Weerackdoy and Cuevas [25] study the interference effects of mobile land terminals and fixed service stations for terrestrial services. Similarly, Oh and Park [26] studies interference between maritime ESIMs and terrestrial services. Panthi and Amodio. [27] focus on aeronautical broadband service to study the impact of sharing frequency bands with current terrestrial services and recommend interference mitigation approaches. More generally, Kim et al. [28] present a general model for the coexistence of cellular networks with land, maritime and aeronautical ESIMs, to assess adjacent channel interference. In addition to interference considerations, Cuevas and Weerackody [29, 8] provide insight into the technical and operational characteristics and regulatory challenges that need to be addressed to provide service to mobile users.

### 1.3.2 Frequency assigment

Dynamic Resource Management (DRM) aims at optimizing satellite resources, i.e., those elements and decisions that can be controlled in a satellite system. The literature study and problem representation offered by Guerster et al. [30] identifies four primary resources that need to be allocated in flexible high-throughput satellite systems: beamforming and pointing, bandwidth, central frequency, and power assigned to each beam. This literature review focuses on frequency and bandwidth allocation.

Initially, the frequency assignment problem in satellite communications was defined as the rearrangement of frequencies of one set of carriers that minimizes the largest and total interference given another set of carriers with a fixed frequency allocation. These works assumed GSO satellites and fixed terminal positions. Mizuike and Ito [31] explore cochannel interference minimization between two systems by assigning frequency bands to carriers using a depth-first binary-branching algorithm. The author divides the frequency spectrum into discrete segments, describing the allocation of each carrier with a collection of spectrum segments, and proves that the problem is NP-complete when carriers need to occupy adjacent frequency segments.

Moving from classical optimization to neural network approaches, Funabiki and Nishikawa [32] present a Gradual Neural Network approach to improve the solution of this complex combinatorial optimization problem that simultaneously requires constraint satisfaction and goal function optimization. Wang et al. [33] propose a Noisy Chaotic Neural Network that improves the computational time requirements required by previously proposed approaches by simplifying the problem formulation. The author also separates the optimization objectives from the constraints, although, in this case, this is achieved by mapping the interference associated with a specific frequency assignment to the neuron's bias. In later work, Want et al. [34] propose a Competitive Hopfield Neural Network, which is enhanced by introducing stochastic dynamics that help avoid local minima, a multi-start mechanism that improves search dynamics, and a weighting coefficient setting strategy that allows to satisfy the problem constraints and improve the objective function simultaneously. Their results show that their approach is better than or competitive with the other presented neural network approach and heuristic algorithms, such as simulated annealing. The authors argue that their general optimization algorithm framework can also be applied to other practical optimization problems.

Including metaheuristic methods, Salcedo et al. [35, 36] achieve improved results by combining a Hopfield Neural Network, which manages the problem's constraints, with simulated annealing and a genetic algorithm, respectively, to improve the solution obtained from the network. The proposed approach achieves better scalability due to the separate management of constraint satisfaction and goal function. Salman et al. [37] present different approaches inspired by Differential Evolution algorithms, some of which use embedded heuristics. Comparing their performance to other algorithms, they demonstrate that the algorithms based on Differential Evolution are robust and able to find comparable and even better solutions with lower computational times. Contrary to previous approaches, Wang and Cai [38] reformulate the frequency assignment problem as a multiobjective optimization problem to explore the trade-offs between minimizing the larget and total interference. Their presented multiobjective evolutionary algorithm also outperforms state-of-the-art single-objective approaches. Houssin et al. [39] study the frequency assignment problem from the point of view of reusing frequency in a given service area and using traditional spot beam coverage. The authors propose integer linear programming and greedy allocation algorithms that involve cumulative interference constraints, i.e., the total interference that each user can tolerate. By considering the link budget for each user, their approach aims to maximize the number of users the system can serve. The frequency reuse approach outperforms traditional spot beam coverage in the scenarios tested.

Other works focus on optimizing the bandwidth assigned to each beam instead of its central frequency. Park et al. [40, 41] propose a dynamic bandwidth allocation scheme and explore the trade-off between total allocated capacity and fairness among beams, as well as a selective active beam allocation scheme that overcomes the degradation of total system capacity. By proposing an optimal bandwidth allocation algorithm for multi-spot beams, Want et al. [42] include fairness in their study and explore the trade-off with system total capacity. Li et al. [43] adopts a game theory model for the optimization of spectrum resources, in which the optimal allocations are obtained in a computing-efficient manner by fixing Bayesian equilibrium.

Su et al. [44] introduce an original formulation based on a differential equation to model system bandwidth dynamics and a Stackelberg game. In their approach, the controllers regulate the bandwidth for each satellite, which controls their bandwidth requests based on real-time requirements and the bandwidth price. Breaking from the continuous bandwidth allocation, Want et al. [45] propose a game-theoretical approach to solve the bandwidth assignment problem for discontinuous frequency bands. In addition to considering the individual bandwidth requirements and total available bandwidth, their approach includes user prioritization.

Some frequency assignment algorithms have also been tested for NGSO constellations. Pachler et al. [46] propose a heuristic frequency and bandwidth assignment algorithm and apply it to a LEO constellation use case. Testing their solution in a MEO use case, Garau et al. [47], the authors implement an algorithm based on Integer Linear Programming that can prioritize different operational requirements, such as minimizing power consumption, and achieve improved results compared to a heuristic approach. Their algorithm can assign frequency and spectrum in high-dimensional scenarios with fixed users, setting a distance threshold for interference mitigation. Pachler [48] uses a similar approach to characterize the importance of the frequency assignment in MEO use cases while also considering the allocation of the other satellite resources.

Focusing on dynamic bandwidth allocation, Liu et al. [49] present a dynamic bandwidth allocation algorithm based on bee colony optimization that encompasses information exchange beyond the physical layer. Their method can tolerate different quality of service requirements on the application layers and include several considerations regarding modulation order, coding efficiency, transmission rate, and user priority. Kawamoto et al. [50] flexibly allocate frequency resources accounting for inter-beam interference, which is mitigated using two polarizations. They also demonstrate the ability of their model to allocate frequency resources under state changes around the system, presented as varying request rates for the different beams and groups of beams. With a focus shift towards the deployment characteristics and requirements of radio resource management techniques, Ortiz-Gomez et al. [51] analyze and compare different machine learning algorithms for power and bandwidth allocation using a GEO satellite with a reduced number of beams.

Some works consider mobile users and GEO satellite constellations, but given their static nature, they model these users as changes in the total demand in fixed beams. Using actual demand data from aircraft, Abe et al. [52] present a frequency and bandwidth allocation approach based on predictive control and spare optimization. The authors model the demand based on aircraft size and test their solution in a scenario with a low number of beams. Abdu et al. [53] and Honnaiah et al. [54] propose adaptive resource management algorithms and test them using data from aeronautical and maritime users according to the traffic simulator developed by Al-Hraishawi et al. [55]. Similarly, their solutions are only in scenarios with a reduced number of beams.

## 1.4 Specific objectives

While some works consider dynamic bandwidth allocation in the presence of mobile users, it is limited to GSO satellites and scenarios with a reduced number of static beams. The current state-of-the-art DRM approaches fail to address frequency and bandwidth assignment problems in the presence of mobile users for NGSO satellite constellations. Given that mobile users will constitute an important segment of the market, this Thesis presents a framework based on mixed-integer programming to allocate frequency and bandwidth to user bases that include mobile users. The framework can generate long-term frequency and bandwidth assignment plans that include uncertainty considerations and leverage new satellite systems' reallocation capacities to exploit the synergy between long-term and short-term resource allocation.

## 1.5 Overview

The remainder of this Thesis is organized as follows: Chapter 2 presents an overview of satellite communications systems and the concepts involved in satellite communications; Chapter 3 formulates the frequency assignment problem from NGSO constellations under the presence of mobile users and uncertainty; Section 4 describes the methodology followed to address this challenges, including the considerations taken before and during operations as well as strategies to overcome uncertainty; Chapter 5 presents the user distributions and scenarios that have been used to evaluate the framework and the results for different use cases; and finally Chapter 6 summarizes the work carried out in this Thesis, outlines its conclusions, and proposed future research directions.

# Chapter 2

# Background

This chapter covers the theoretical background of satellite communication systems and provides the reader with the general knowledge to understand the work of this Thesis. It describes the main concepts regarding the configuration of satellite systems, satellite antennas, radiated and transmitted power, and noise characteristics and their implications in a satellite communications link. For further information on satellite communication systems, the reader is referred to [1].

## 2.1 General Configuration

The satellite communications system consists of three different entities:

- The *space segment* consists of the satellites orbiting the Earth organized into a constellation.
- The *control segment* includes the ground facilities and stations required to monitor and control the satellites, equipped with tracking, telemetry, and command (TTC) capabilities to manage the traffic and resources onboard the satellites.
- The *ground segment* contains the rest of the earth stations, namely gateways to terrestrial networks, user stations such as VSATs or handsets, and service stations connected to service providers.

The space segment is connected to earth entities using communications links, radio or optical modulated carriers between transmitting and receiving equipment. These links can be grouped depending on the segment of the transmitting and receiving end:

- the *uplinks* from earth stations to satellites;
- the *downlinks* from satellites to earth stations;
- the *intersatellite links* between satellites.

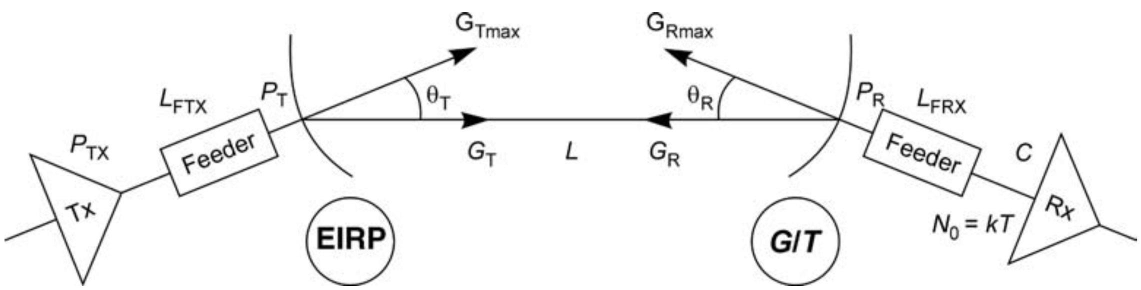



Figure 2-1: Configuration of a communications link [1].

The transmitting end of the communication link consists of a transmitter connected to an antenna using a feeder. The performance of the antenna is measured by its *effective isotropic radiated power* (EIRP), defined as:

$$EIRP = P_T G_T \quad \text{(W)} \tag{2.1}$$

where $G_T$ is the radiated power and $G_T$ is the gain in the direction of the receiver. Similarly, the receiving end consists of an antenna connected to a receiver using a feeder. The overall performance of the link is given by the ratio of the power of the modulated carrier $C$ to the noise power spectral density $N_0$ at the receiver input.

## 2.2 Antenna parameters

### 2.2.1 Gain

The gain of an antenna in a given direction is defined as the ratio of the power radiated (or received) to the power radiated (or received) by an isotropic antenna fed with the same power. The maximum gain, achieved in the direction of maximum radiation, has a value given by:

$$G_{\max} = (4\pi/\lambda^2)A_{eff} \tag{2.2}$$

where $\lambda$ is the wavelength of the electromagnetic wave and $A_{eff}$ is the effective aperture area of the antenna. For an antenna with efficiency $\eta$, $A_{eff} = \eta A$, and a circular reflector of diameter $D$, $A = \pi D^2/4$. The efficiency of an antenna accounts for several factors, including the illumination law, spill-over loss, surface impairments, and ohmic and impedance mismatch losses.

### 2.2.2 Radiation pattern

The radiation pattern specifies the variations in the gain in different directions. Antennas with a circular aperture or reflector have a radiation pattern with rotational symmetry, which can be represented within a plane in either polar coordinate or Cartesian coordinate form, as shown in Fig. 2-2.

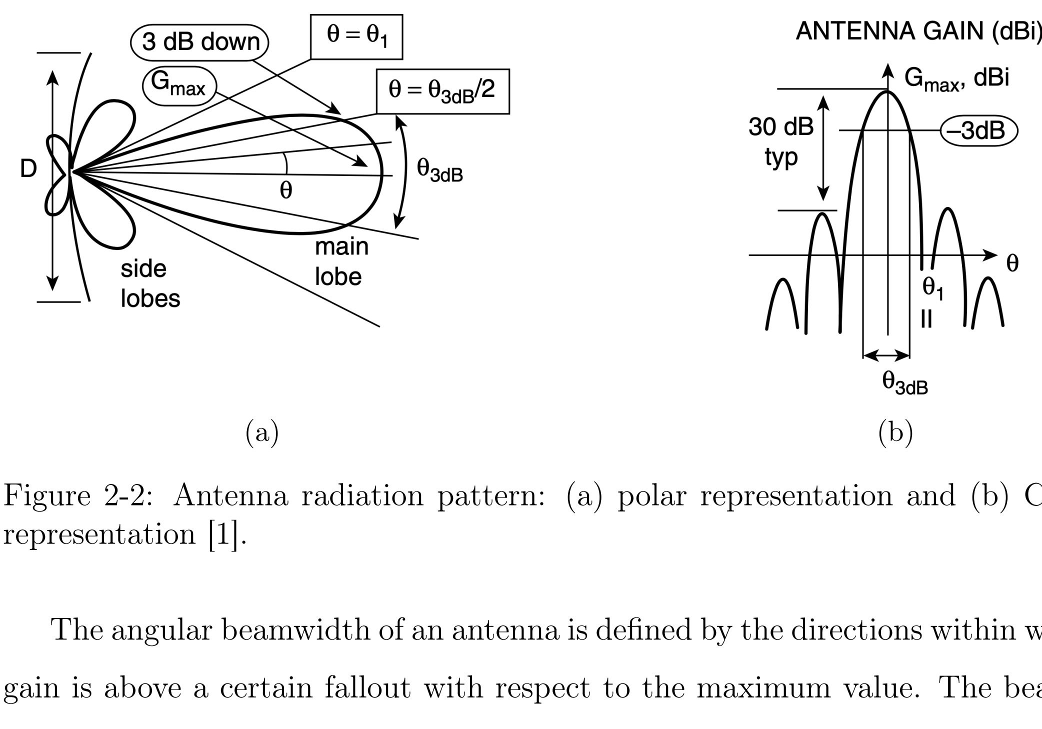



Figure 2-2: Antenna radiation pattern: (a) polar representation and (b) Cartesian representation [1].

The angular beamwidth of an antenna is defined by the directions within which the gain is above a certain fallout with respect to the maximum value. The beamwidth for a fallout of 3dB $\theta_{3\text{ dB}}$ is often used, as it indicates the directions for which the gain falls to approximately half its maximum value. This beamwidth is related to the ratio ($\lambda/D$) by a coefficient that depends on illumination law, although a typical value of 70°is used, leading to the expression:

$$\theta_{3\text{ dB}} = 70(\lambda/D) \quad \text{(degrees)} \tag{2.3}$$

For directions close to that of maximum radiation ($|\theta| < \theta_{3\text{ dB}}/2$), the gain in dBi is given by:

$$G(\theta)_{\text{dBi}} = G(\theta)_{\text{max, dBi}} - 12(\theta/\theta_{3\text{ dB}})^2 \quad \text{(dBi)} \tag{2.4}$$

By combining equations (2.2) and (2.3) assuming an antenna with cirular aperture, it can be seen that the maximum gain depends on the 3 dB beamwidth but not on the wavelength:

$$G_{\text{max}} = \eta(\pi D/\lambda)^2 = \eta(\pi 70/\theta_{3\text{ dB}})^2 \tag{2.5}$$

### 2.2.3 Polarization

Electromagnetic waves consist of an electric field component and a magnetic field component, both orthogonal and perpendicular to the direction of probation. The two components vary in magnitude and direction at the wave's frequency, and, by convention, the variation of the electric component defines the polarization of the wave, as depicted in Fig. 2-3. Three parameters characterize the polarization of a wave:

- The *direction of rotation* with respect to the direction of propagation: right-hand (clockwise) or left-hand (counter-clockwise).
- The *axial ratio* $AR$, i.e., the ratio between the maximum and minimum magnitude of the electric field. The polzarization is called circular for unit axial ratios, linear for infinite axial rartios, and elliptical otherwise.
- The *inclination* $\tau$ of the ellipse.

Two waves are said to have orthogonal polarizations if their electric fields describe identical ellipses in opposite directions. Antennas can neither transmit nor receive waives in the polarization orthogonal to their design polarization, allowing them to establish two links at the same frequency between the exact two locations using two orthogonal polarizations. In practice, however, the imperfections of the antennas and the possible depolarization of the waves might lead to undesirable mutual interference between the two links.

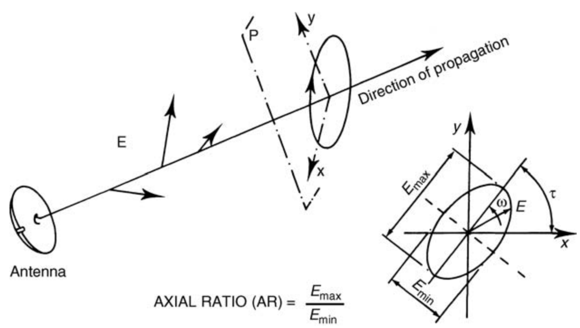



Figure 2-3: Characterisation of the polarisation of an electromagnetic wave [1].

## 2.3 Radiated power

Two standard metrics are used to describe the power radiated by an antenna. The first one is the Effective Isotropic Radiated Power (EIRP), which is the hypothetical power that an isotropic antenna would have to radiate to provide the same signal strength as the considered antenna in its direction of highest gain.

The power radiated per unit solid angle by an isotropic antenna fed from a radio-frequency source of power $P_T$ is given by:

$$P_T/(4\pi) \quad (\mathrm{W\,sr^{-1}}) \tag{2.6}$$

In the direction where the value of transmission gain is $G_T$, an antenna radiates a power per unit solid angle equal to:

$$P_T G_T/(4\pi) \quad (\mathrm{W\,sr^{-1}}) \tag{2.7}$$

The product $P_T G_T$ is the EIRP and is expressed in Watts.

The second metric is the power flux density, which characterizes the amount of power flow through a unit area. A surface of area $A$ situated at a distance $R$ from a transmitting antenna subtends a solid angle of $A/R^2$ at the transmitting antenna. From Expression 2.7, the received power is:

$$P_R = (P_T G_T/(4\pi))(A/R^2) = \Phi A \quad \text{(W)} \tag{2.8}$$

where the magnitude $\Phi = P_T G_T / 4\pi R^2$ is called the power flux density and is expressed in $\mathrm{W\,m^{-2}}$.

## 2.4 Received signal power

A receiving antenna with effective aperture area $A_{R,\text{eff}}$ that is located at a distance $R$ from a transmitting antenna receives power equal to:

$$P_R = \Phi A_{R,\text{eff}} = (P_T G_T/(4\pi R^2))A_{R,\text{eff}} \tag{2.9}$$

Expressing the effective area of an antenna as a function of its receiving gain according to (2.2) yields an expression for the received power:

$$P_R = (P_T G_T/(4\pi R^2))(\lambda^2/4\pi)G_R = (P_T G_T)(\lambda/4\pi R)^2 G_R = (P_T G_T)(1/L_{FS})G_R \quad \text{(W)} \tag{2.10}$$

where $L_{FS}$ is the *free space loss* and represents the ratio of the received and transmitted powers in a link between two isotropic antennas.

In addition to free space losses, satellite communication systems might experience additional losses. Atmospheric constituents, such as gaseous components in the troposphere and water in the ionosphere, contribute to additional signal attenuation, usually denoted by $L_A$. The feeder loss between the transmitter and the antenna on the transmitting end, $L_{FTX}$, and between the antenna and the receiver on the receiving end, $L_{FRX}$ also need to be taken into account.

Imperfect alignment of the transmitting and receiving antennas can also cause depointing losses due to the fallout of antenna gain with respect to the maximum gain on transmission and reception. The value of these losses is given $L_T = 12(\theta_T/\theta_{3\text{ dB}}$ for transmission and $L_R = 12(\theta_R/\theta_{3\text{ dB}}$ for reception, where $\theta_T$ and $\theta_R$ are the angles of transmission and reception, respectively.

Finally, if the receiving antenna is not correctly oriented with the polarisation of the transmitted wave, it can lead to polarization mismatch losses, denoted by $L_{POL}$.

The signal power at the receiver input, considering the possible loss sources, is given by:

$$P_{RX} = (P_{TX}G_{T\max}/L_T L_{FTX})(1/L_{FS}L_A)(G_{R\max}/L_R L_{FRX}L_{POL}) \quad (\text{W}) \tag{2.11}$$

## 2.5 Noise

Noise consists of all unwanted contributions, whose power is added to the wanted carrier power and reduces the ability to reproduce the desired information correctly. Noise might originate from natural radiation sources within the antenna reception or components in the receiving equipment. Carriers from other transmitters also contribute to the noise in the received signal. This noise is described as interference.

Power contributions in the bandwidth $B$ of the wanted modulated carrier are considered harmful noise. White noise is modeled with a constant spectral density $N_0$ (W/Hz) and is one of the most popular noise models. The noise power $N$ (W) captured by a receiver with a noise bandwidth $B_N$ is given by:

$$N = N_0 B_N \quad (\text{W}) \tag{2.12}$$

Although natural noise sources have nonconstant power spectral density, white noise is proven convenient for representing observed noise.

The noise temperature is a common way of expressing the level of available noise power introduced by a source or component. The noise temperature of a two-port noise source delivering an available noise power spectral density $N_0$ is given by:

$$T = N_0/k \quad \text{(K)} \tag{2.13}$$

where $k$ is Boltzmann's constant $1.379 \times 10^{-23} = 228.6$ (dBW/Hz K), $T$ represents the thermodynamic temperature of a resistance that delivers the same available noise power as the source under consideration. The available noise power is defined as the power delivered by the source to a device, the impedance of which matches that of the source.

## 2.6 Link performance

The link performance is commonly evaluated as the ratio of the received carrier power, $C$, to the noise power spectral density, $N_0$, and is quoted as the $C/N_0$ ratio, which is expressed in hertz. Therefore, with the characterization of the received power and noise, the $C/N_0$ ratio allows to measure the individual performance of a link:

$$C/N_0 = \frac{(P_{TX} G_{T\max}/L_T L_{FTX})(1/L_{FS} L_A)(G_{R\max}/L_R L_{FRX} L_{POL})}{kT} \tag{2.14}$$

It is common to group the terms in the above expression as follows in order to differentiate the contribution from the different parts of the communication link:

$$C/N_0 = (EIRP)(1/L)(G/T)(1/k) \tag{2.15}$$

This way, we can separately examine three essential factors: $EIRP$, which characterizes the transmitting equipment; $1/L$, which characterizes the transmission medium; and $G/T$, which is the composite receiving gain/noise temperature, also called *figure of merit*, and characterizes the receiving equipment.

### 2.6.1 Multibeam and monobeam coverage

It can be seen from the previous section that the quality of the link depends directly on the gain of the satellite antenna, which acts as a receiver in the uplink and as a transmitter in the downlink. More specifically, the link quality depends on the angular beamwidth of the antenna, as observed in Equation 2.5, which expresses the dependency of the maximum antenna gain on the 3 dB beamwidth.

A satellite with a single beam antenna can provide coverage to an area in different ways. It may use a wide beam with high beam width to cover a large surface, providing connectivity over a broad area and establishing long-distance links within the same beam at the expense of reduced link performance. Alternatively, the satellite may provide coverage over a much smaller area using a narrower beam, achieving high antenna gain and link performance. However, the satellite will not be able to service terminals within the covered surface. Therefore, with single-beam coverage, it is necessary to choose between either extended coverage that provides service with reduced quality to dispersed earth stations or reduced coverage that provides a better service to geographically concentrated earth stations.

Nonetheless, there exists the possibility of using multi-beam coverage to reconcile these two alternatives. In this case, extended coverage is achieved by using multiple narrow beams, each beam providing an antenna gain that increases as the beamwidth decreases. With multi-beam coverage, the link performance increases with the number of beams, limited by the antenna technology and operational complexity. A representation of single-beam and multi-beam coverage can be found in Figure 2-4.

Using multiple narrow beams to cover a large area provides significant advantages compared to using a single beam. In the uplink from earth stations to satellites, the higher receiver gain on the satellite allows to reduce the size and therefore cost of ground antennas while maintaining the same link performance. Furthermore, if the terminal size of the ground segment is retained, the increased link performance can be transferred into an increase in capacity. Moreover, multi-beam coverage allows reusing the same frequency band several times to increase the total network capacity without

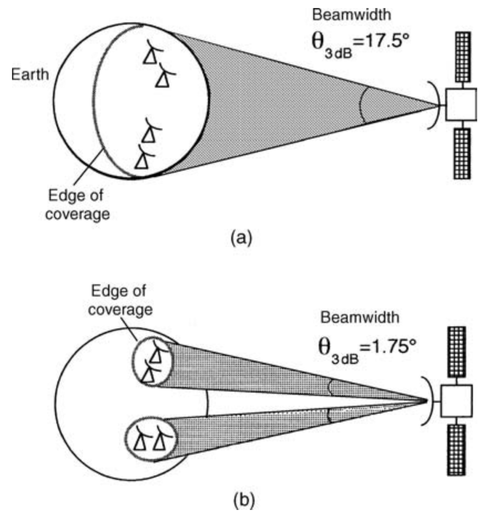



Figure 2-4: (a) Single-beam coverage and (b) multi-beam coverage [1]

increasing the allocated bandwidth. In this case, the isolation resulting from antenna directivity is exploited to use the same frequency band in separate beam coverages. Figure 2-5 shows how frequency can be reused using orthogonal polarization and angular separation of the beams.

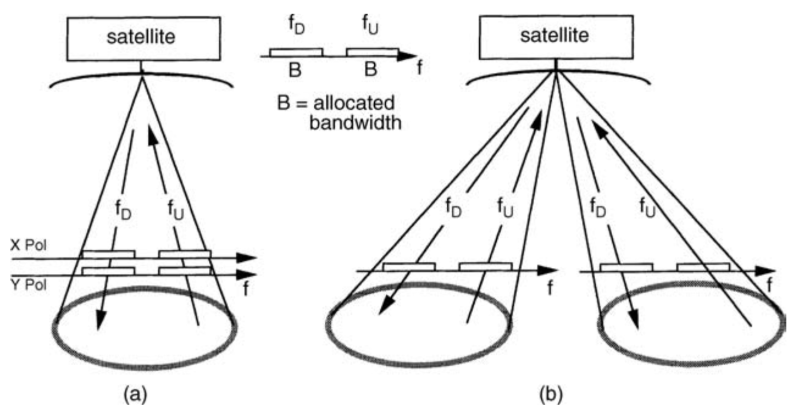
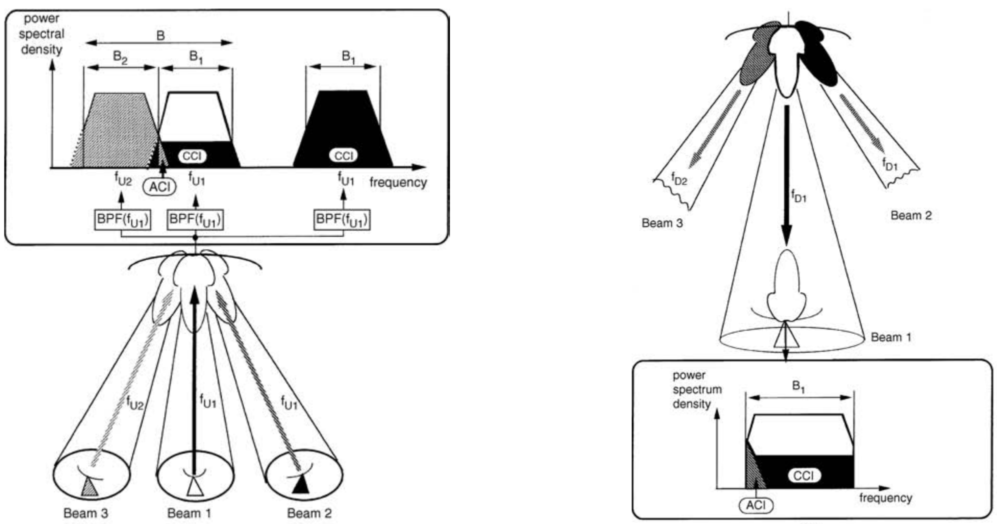



Figure 2-5: Frequency re-use with two beams by (a) orthogonal polarisation and (b) angular separation of the beams in a multibeam satellite system [1].

One of the main disadvantages of using multi-beam coverage is the interference generated within the satellite system, also called *self-interference*. On the downlink, a ground terminal might receive interfering signals transmitted over the same band to other ground terminals if it is in the side lobe of their beams. This noise is called *co-channel interference*. Moreover, due to imperfect filtering, a ground terminal might also receive interfering signals from beams using adjacent frequency bands. This noise is called *adjacent channel interference*. Both types of interference are illustrated in Figure 2-6 for uplink and downlink.

Another disadvantage of using multi-beam coverage is interconnecting different coverage areas, which adds complexity to the satellite payload, which is already much more complex than that used for single-beam coverage. Despite these disadvantages, multi-beam satellite systems are the most used systems thanks to their reducing in the size and cost of the earth segment and increasing the system capacity using frequency reuse mechanisms without the need to increase the allocated bandwidth.




(a) (b)

Figure 2-6: Self-interference between beams in a multibeam satellite system: (a) uplink and (b) downlink [1].

## 2.7 Overall link performance

As described in the previous sections, other disturbances, such as co-channel or adjacent channel interference, affect the performance of the communications link. Additionally, when non-linear amplifiers are used, the output is not only the amplified carriers but also the intermodulation products. This interference also needs to be taken into account when computing the overall link performance, or carrier-to-noise-plus-interference-ratio, which is expressed as:

$$\frac{C}{N_0 + I} = \left( \frac{1}{C/N_0} + \frac{1}{CABI} + \frac{1}{CASI} + \frac{1}{CXPI} + \frac{1}{C3IM} \right)^{-1} \quad \text{(Hz)} \tag{2.16}$$

where $CABI$ is the Carrier to Adjacent Beam Interference, $CASI$ is the Carrier to Adjacent Satellites Interference, $CXPI$ is the carrier to cross Polarization Interference, and $C3IM$ is the carrier to third-order Inter-Modulation products interference.

The bit-energy-to-noise-plus-in-terference ratio $E_b/(N+I)$ is defined from the carrier to-noise-plus-interference-ratio as:

$$\frac{E_b}{N + I} = \frac{C}{N_0 + I} \frac{BW}{R_b} \tag{2.17}$$

where $BW$ is the allocated bandwidth and $R_b$ is the resulting data rate. At the same time, the achieved data rate can be computed as:

$$R_b = \frac{BW}{1 + \alpha_r} \Gamma \left( \frac{E_b}{N + I} \right) \tag{2.18}$$

where $\alpha_r$ is the roll-off factor and $\Gamma$ is a parametric function that represents the spectral efficiency of the modulation and coding scheme (MODCOD), which expresses the amount of information that can be transmitted per unit of bandwidth in bps/Hz and depends on the bit-energy-to-noise-plus-interference ratio $E_b/(N+I)$ itself. The MODCOD schemes are defined by a spectral efficiency and a quality threshold, which refers to the minimum quality of the link required to apply that MODCOD scheme with a bit error rate (BER).

# Chapter 3

# Problem formulation

In this chapter, we formulate the frequency assignment problem for fixed and mobile users under operational uncertainty in NGSO constellations. This chapter is organized as follows: Section 3.1 provides a general description of the frequency assignment problem, highlighting the considerations introduced by mobile users; Section 3.2 provides a more detailed description of the problem, expands on the assumptions, and formulates the constraints and objective; and Section 3.3 defines the metrics used to evaluate the frequency assignment solutions.

## 3.1 General problem description

The frequency assignment problem involves assigning a central frequency, bandwidth, and polarization to the beams connecting fixed and mobile users to gateways to satisfy their demands. The expectations between the satellite providers and the users are defined in contracts called Service Level Agreements, which include the available data rate from the gateway to the user (forward data rate) and from the user to the gateway (return data rate), as well as other considerations regarding the service, such as performance and availability, i.e., where the service will be available.

As mobile users change location over time, beam coverage changes from that of fixed users. One solution is providing coverage using multiple fixed beams, in which case the frequency assigned to the user and the bandwidth allocated to each of the beams it traverses–and therefore possible constraints associated with it–will change over time. Another approach is to provide coverage using steerable beams that follow the users throughout their trajectory. In this case, the frequency and bandwidth assigned to the user can be kept unchanged as long as the time-dependent interference is considered. Finally, more complex hybrid approaches can also be explored.

A user can be connected to a gateway if both of them are within a satellite's covered area. Unlike fixed users, mobile users will need to change the gateway they are connected to as they change position. Threfore, having enough capacity in the gateways along mobile users' trajectories is crucial to ensuring that service can be provided.

Since spectrum is a highly demanded and regulated resource, the assigned frequency and bandwidth must respect the regulatory constraints, including frequency landing rights, which are permissions to use certain frequencies over a specific area. These regulations can especially constrain the frequency assignment for mobile users as they need to be provided service over different territories.

Frequency assignment needs to be carried out for both uplink connections from Earth to space and downlink connections from space to Earth. Uplink connections tend to have larger power and frequency availability since the transmission system is not power constrained, and the interference tends to be lower. However, the uplink connection can present additional challenges for mobile users as the terminals might cause interference with existing terrestrial applications. Nonetheless, the downlink connection tends to be more restricted since it relies on the limited power available onboard the satellite and must deal with high interference, especially over areas with high demand. For mobile users, there is the additional challenge of time-dependant and uncertain interference considerations.

As mentioned, satellites route data from users to gateways and vice-versa. This routing introduces a coupling between the uplink and downlink connections. Satellites with a bent-pipe architecture present a stronger coupling, as the bandwidth of the uplink and downlink carriers cannot be changed onboard the satellite. On the other hand, satellites with onboard processing capabilities can change the bandwidth between the two links. The satellite architecture needs to be considered when solving the frequency assignment problem.

The above considerations regarding mobile users have a strong uncertainty component. For example, even though the departure time and destination of an airplane might be known, it can suffer delays or trajectory deviations, which might involve flying over a country with different spectrum landing rights, causing interference with other users, or requiring capacity from an already saturated gateway. More complex mobile communication use cases, where the users are not required to provide information about when and where they will need connectivity, have an even stronger impact on how to solve the frequency assignment. Therefore, providing service to mobile users requires allocating resources without accurate a priori knowledge of their position, i.e., frequency assignment needs to be carried out under spatiotemporal uncertainty.

## 3.2 Specific problem description

In this Thesis, we pose the frequency assignment as an optimization problem, using a formulation similar to those used in [56, 46, 48, 47]. We consider a single plane constellation with $N_S$ multibeam satellites that connect multiple fixed and mobile users to gateways on Earth, as depicted in Figure 3-1.

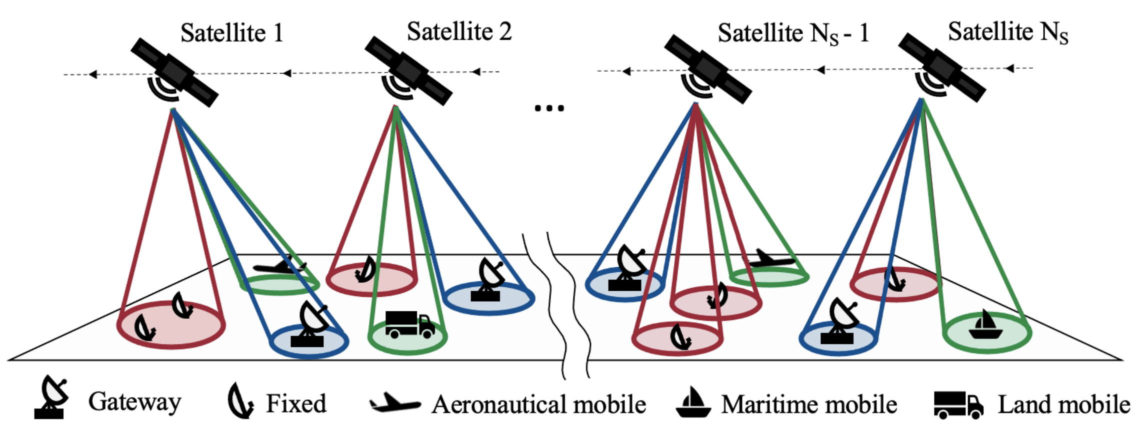



Figure 3-1: Constellation with $N_S$ satellites in single orbital plane connecting fixed and mobile users to gateways.

### 3.2.1 User and gateway beams

The users are already grouped in to a set of user beams $\mathcal{B}_u$:

$$\mathcal{B}_u = \{B_{u_i} = (\phi_{u_i}(t), \lambda_{u_i}(t), t^s_{u_i}, t^e_{u_i}, d_{u_i}, \mathcal{U}_i)\} \ \forall i \in \{1, ..., N_{B_u}\} \tag{3.1}$$

where

| | |
|---|---|
| $B_{u_i}$ | = user beam $i$ |
| $\phi_{u_i}(t), \lambda_{u_i}(t)$ | = latitude, longitude of user beam $i$ at time $t$ |
| $t^s_{u_i}, t^e_{u_i}$ | = start, end service times of user beam $i$ |
| $d_{u_i}$ | = demand of user beam $i$ |
| $\mathcal{U}_i$ | = set of users covered by user beam $i$ |

We consider that multiple fixed users can be grouped under a single fixed user beam. In contrast, each mobile user is provided service by a beam that follows them throughout their trajectory. Therefore, for user beams serving fixed users, $\phi_{u_i}(t) = \phi_{u_i}$, $\lambda_{u_i}(t) = \lambda_{u_i}$, and $|\mathcal{U}_i| \geq 1$.

The traffic from the user beams is routed to the gateways using a known set of fixed gateway beams $\mathcal{B}_g$:

$$\mathcal{B}_g = \{B_{g_i} = (\phi_{g_i}, \lambda_{g_i}, t^s_{g_i}, t^e_{g_i}, d_{g_i}, g_{g_i}, b_u)\} \ \forall i \in \{1, ..., N_{B_g}\} \tag{3.2}$$

where

| | |
|---|---|
| $B_{g_i}$ | = gateway beam $i$ |
| $\phi_{g_i}, \lambda_{g_i}$ | = latitude, longitude of gateway beam $i$ |
| $t^s_{g_i}, t^e_{g_i}$ | = start, end service times of gateway beam $i$ |
| $d_{g_i}$ | = demand of gateway beam $i$ |
| $g_i$ | = gateway covered by gateway beam $i$ |
| $b_u$ | = user beam associated with gateway beam $i$ |

Gateway beams transmit data from a single user beam to a gateway and are centered at the gateway position. One gateway can have multiple gateway beams associated with it, i.e., it can receive data from various user beams. Each gateway

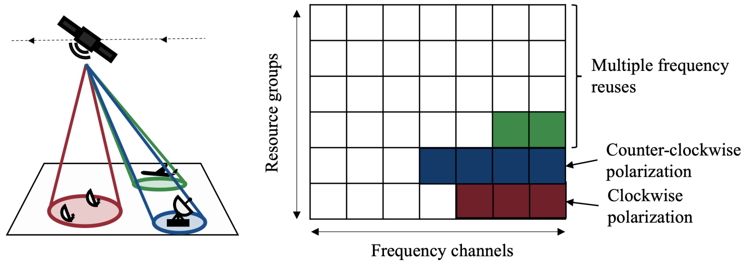



Figure 3-2: Frequency assignment representation in the form of a grid with $N_r \cdot N_p$ rows (resource groups) and $N_{ch}$ columns (frequency channels). In this example, $N_r = 3$, $N_p = 2$, and $N_{ch} = 7$. The coloring indicates the frequency assignemnt of each of the beams.

beam is mapped to only one user beam from which data is routed. However, a user beam can be associated with multiple gateways beams. This is the case for user beams providing service to mobile users, as their traffic will be routed to different gateways throughout their trajectories. In that case, the service times of the gateway beams associated with a satellite beam will not overlap. The gateway beam used depends on the position of the user beam, as both must be within the covered area by a satellite. Considering this, the number of gateway beams can be larger than the number of user beams $N_{B_g} \geq N_{B_u}$.

The satellite that establishes the connection between the user beams and the gateway beams is also known depending on its orbital position with respect to the user and the gateway. $\mathcal{B}$ is the set that includes both user and gateway beams, with a total of $N_B = N_{B_u} + N_{B_g}$ beams:

$$\mathcal{B} = \mathcal{B}_u \cup \mathcal{B}_g = \{B_i\} \; \forall i \in \{1, ..., N_B\} \tag{3.3}$$

### 3.2.2 Frequency plan and constraints

We assume that all satellites are identical and have access to the same part of the spectrum, which is divided into $N_{ch}$ frequency channels. Each satellite has $N_r$ frequency reuses and $N_p$ polarizations. Specific frequency reuse and polarization combinations are also referred to as resource groups. Figure 3-2 introduces a representation of the frequency plan decision space in the form of a grid with $N_r \cdot N_p$ rows (resource groups) and $N_{ch}$ columns (frequency channels).

The objective of the problem is to find a frequency assignment $\mathcal{A}$ for each of the beams:

$$\mathcal{A} = \{a_i = (f_i, b_i, g_i, p_i, e_i)\} \ \forall i \in \{1, ..., N_{b_u} + N_{b_g}\} \tag{3.4}$$

where

$f_i$ = initial frequency of beam $i$

$b_i$ = number of channels of beam $i$

$g_i$ = reuse group of beam $i$

$p_i$ = polarization of beam $i$

$e_i$ = active flag of beam $i$

The active flag allows deactivating beams for which a feasible frequency assignment cannot be found, as well as all other beams associated with it. For example, if the user beam cannot be successfully assigned frequency resources, the gateway beams associated with it can be deactivated.

For each beam, we can define the minimum $b_{min,i}$ and the maximum $b_{max,i}$ number of frequency channels, such as those necessary to meet its demand given the highest and lowest spectral efficiency values of the system, respectively. If $b_i < b_{min,i}$ the demand of the beam will not be met, and if $b_i > b_{max,i}$ unnecessary bandwidth would be assigned to that beam, as its demand can be met with fewer frequency channels. The frequency assignment variables are defined as:

$$\begin{aligned}
&0 \leq f_i \ \forall i \\
&f_i + b_i \leq N_{ch} \ \forall i \\
&b_{min,i} \leq b_i \leq b_{max,i} \ \forall i \\
&0 \leq g_i \leq N_r \ \forall i \\
&0 \leq p_i \leq N_p \ \forall i \\
&f_i, b_i, g_i, p_i \in \mathbb{Z} \ \forall i
\end{aligned} \tag{3.5}$$

Frequency assignment is subject to two main constraints: interference and frequency reuse constraints, encoded using the binary variables $\alpha_{ij}$ and $\beta_{ij}$, respectively. The reuse constraint ensures that any two beams that are assigned to the same satellite at some point $\beta_{ij} = 1$ ($\beta_{ij} = 0$ otherwise) do not use the same frequency channel and resource group. This constraint ensures that we are not simultaneously assigning the same resources to two beams, capturing the handover considerations from the dynamics of NGSO constellations and those derived from the movement of mobile beams. Therefore, to compute this constraint we need to take into account the start and end service time, the location change of mobile beams, and the gateway beam they use depending on their position.

The interference constraint ensures that two beams assigned to the same satellite and geographically close do not interfere with each other. The interference constrain calculation is based on the angular separation $\gamma_{ij}(t)$ between beams $i$ and $j$. This angular separation depends on the position of the beams at time $t$ and takes the minimum value, i.e., the worst case, of a satellite pass. This way, although this minimum angular separation changes over time, the interference constraint between beams does not depend on the position of the satellites. Two beams are considered to be located geographically close enough to interfere and thus have an interference constraint $\alpha = 1$, if $\gamma_{ij}(t) < \alpha_{min}\ \forall t$, where $\alpha_{min}$ represents a minimum angular separation angle, for example, twice the beamwidth.

Given these interference and frequency reuse considerations, the following logical restrictions can be forced on frequency assignment.

$$\begin{aligned}&e_i = 0 \text{ or } e_j = 0 \text{ or } e_i = 0 \text{ or } \beta_{ij} = 0 \text{ or } g_i \neq r_j \text{ or } p_i \neq p_j \\ &\text{or } f_i + b_i \leq f_j \text{ or } f_j + b_j \leq f_i\end{aligned} \tag{3.6}$$

$$\begin{aligned}&e_i = 0 \text{ or } e_j = 0 \text{ or } e_i = 0 \text{ or } \beta_{ij} = 0 \text{ or } \alpha_{ij} = 0 \text{ or } p_i \neq p_j \\ &\text{or } f_i + b_i \leq f_j \text{ or } f_j + b_j \leq f_i\end{aligned} \tag{3.7}$$

Equation 3.6 ensures that if two active beams are assigned to the same satellite at some point have either different reuse groups, polarization, or non-overlapping frequency channels. Equation 3.7 ensures that if two active beams are assigned to the same satellite and are geographically close at some point have either different polarization or non-overlapping frequency channels. Notice that the beams cannot have different reuse groups and the same polarization in this case. For a more detailed formulation of the constraints, the reader is referred to [47].

Although we focus on the downlink frequency assignment, this formulation can be used for both the downlink and uplink, assuming satellite architectures with onboard processing capabilities. In that case, beams in opposite directions do not have interference or reuse constraints. The formulation can also be adapted to satellites with bent-pìpe architecture by imposing the bandwidth assigned to user beams to equal that assigned to their associated gateway beams.

### 3.2.3 Objective function

We have presented the decision variables and constraints that must be considered to design a valid frequency. To prioritize different feasible different frequency plans, we use the objective function with activation variables presented by Garau et al. [47], as it allows us to encode different operator preferences. The frequency assignment problem can be formulated as:

$$\begin{aligned} \max_{\mathcal{A}} \quad & \sum_{i=1}^{N_B} \left( w_{1,i} b_i - |w_{2,i}| g_i - |w_{3,i}| f_i - |w_{4,i}| P_i(f_i, b_i) + |w_{5,i}| e_i \right) \\ \text{s.t.} \quad & \text{Equation 3.6} \\ & \text{Equation 3.7} \\ & \text{Equation 3.5} \end{aligned} \tag{3.8}$$

where $w_{1,i}$, $w_{2,i}$, $w_{3,i}$, $w_{4,i}$, $w_{5,i}$ are weighting parameters for beam $i$, with $w_{k,i} \in \mathbb{R}$, and allow to target maximization or minimization of allocated bandwidth, frequency reuse minimization, spectrum prioritization, power minimization and beam activation, respectively. While satellites are constrained by the maximum available power, this is not encoded as a hard constraint. Instead, it is included in the objective function, as frequency plans with lower power consumption are inherently more attractive. Further considerations regarding the power consumption calculation for each beam can be found in [47]. It is important to highlight that temporal dependency, such as how long a beam stays active and consumes power, can be included in the weighting coefficients of the objective function.

### 3.2.4 Uncertainty in the frequency assignment

The information known about the position of mobile users depends on the use case can change over time. For example, a satellite operator might have information about a flight departure time, origin, and destination several days in advance and can plan accordingly. Before the flight departs, it might also have access to the exact route that the aircraft will follow, which might include considerations to minimize flight time while avoiding bad weather and restricted airspace and maintaining traffic separation. There can also be unexpected route changes only known at the time that the airplane is being provided service. Other users offer different information patterns. For example, a land mobile user might request service in a specific location without prior notice. In that case, the start and end service times and user position are hard to be predicted a priori.

Therefore, the frequency assignment needs to be carried out taking into account that the position and start and end service times of mobile users, and thus that of their user beams, are not accurately known a priori. In the case of a user beam covering an airplane, a delay in the flight departure will change the service start and end times, $t_u^s$ and $t_u^e$, and consequently, the start and end times of the gateway beams associated with it, $t_{g_i}^s$ and $t_{g_i}^e$. Both delays and trajectory modifications will change the position of the user beam at a particular time $\phi_u(t)$ and $\lambda_u(t)$. These changes have implications for that beam's interference and frequency reuse constraints. Its minimum angular separation with other beams might be lower than expected, and thus they might no longer be able to use the same frequency. The beam might also be assigned to the same satellite as other beams that need to use the same resources.

Both of these cases result in an invalid frequency allocation and need to be accounted for when solving the frequency assignment problem for mobile users.

## 3.3 System metrics

Different metrics have been used in the literature to quantify the efficiency of resource allocation in satellite communications. Guerster [56] offers an overview of the most common metrics and the works in which are used. In this Thesis, we consider total power consumption and the number of served users.

Total power consumption is used to quantify the efficiency of the frequency allocation. We define the total power consumption as the sum of the required power, which has two different contributions: the power required to serve the demand of each beam according to the link budget and the necessary power to perform frequency reuses. Since the frequency assignment is time-dependent, the metric becomes the average total power consumption $P$ of the constellation:

$$P = \frac{1}{T} \int_0^T \sum_{i=1}^{N_B} P_i(f_i, b_i)\, dt + \epsilon|\mathcal{R}| \tag{3.9}$$

$$\mathcal{G} = \bigcup_i \{g_i\} \tag{3.10}$$

where

$T$ = length of the considered time period

$P_i$ = power consumptiton of beam $i$

$\epsilon$ = power consumption per active reuse group $g_i$

$\mathcal{G}$ = set of frequency reuses assigned to at least one beam

The power contribution of having active reuse groups highly depends on the characteristics of the satellite payload and can be modeled using the parameter $\epsilon$. In this work, this power contribution is not considered to be time-dependent.

On the other hand, the unmet demand quantifies the user satisfaction and is defined as the sum of demand that cannot be met. Since the unmet demand is also time-dependent, the metric becomes the average unment demand $UD$:

$$UD = \frac{1}{T} \int_0^T \sum_{i=1}^{N_B} \max(d_i - r_i, 0) \, dt \tag{3.11}$$

where $r_i$ is actual data-rate offered by beam $i$.

To quantify the utilization of the available spectrum, some results will also refer to the spectrum utilization $S$, which can be computed as:

$$S = \frac{1}{T} \int_0^T \sum_{i=1}^{N_B} b_i \, dt \tag{3.12}$$

Although metrics that include the quality of service or fairness have also been used, using the unmet demand metric emphasizes the importance of guaranteeingn service to the maximum number of users. The metric mentioned above are usally normalized against the estimated consteallation power, average aggregated demand, and total spectrum resources, respectively.

It is important to highlight that the selected optimization function encodes power consumption $P$ consideration through $w_{2,i}$ and $w_{4,i}$, as well as unmet demand $UD$ considerations through $w_{5,i}$, which focuses on activating as many beams as possible. Setting a lower limit on $b_i$ ensures that the demand of that beam is met if it is activated. This confirms the suitability of the selected optimization objective function and constraints according to widely used system metrics for resource allocation in satellite systems.

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# Chapter 4

# Methodology

This chapter presents a framework for dynamic frequency assignment in multibeam satellite constellations. The framework is based on mixed-integer linear programming and allows generating feasible frequency assignments when operating in the presence of mobile users and the uncertainty they introduce. Section 4.1 overviews the frequency plan optimization framework extended in this work, and Section 4.2 details the changes of the new framework and how it is intended to operate.

## 4.1 Optimization framework

The framework presented in this work is an extension of the frequency plan optimization framework presented by Garau et al. [47]. Their framework includes frequency reuse mechanisms to optimize frequency and bandwidth assignment in constellations with thousands of beams while respecting interference and reuse constraints. Their framework also allows encoding multiple operator goals, such as maximizing bandwidth, minimizing the number of frequency reuses, and minimizing total power consumption.

The authors linearize the non-linear formulation presented in the previous chapter using auxiliary variables, which allows using a commercial linear integer solver. The authors also propose an iteration-based optimization method that allows changing the allocation of a few beams at a time while the rest are left fixed. This enables operation in high-dimensional use cases and introduces the flexibility to configure the algorithm depending on the scenario and computing time constraints. In order to deal with different solutions with the same power consumption, the framework includes spectrum prioritization terms in the objective function.

In addition, Garau et al. propose an alternative formulation where the frequency assignment decision for each beam is encoded as binary variables, enhancing the framework's scalability. The authors leverage the fact that the frequency assignment of most of the beams is not changed during an iteration to select and rank the best assignments for the beams that need to be changed, significantly reducing the search space of the problem and improving run times. With these improvements, the number of variables increases linearly with the number of changes and selected assignments per iteration, while the number of constraints increases quadratically.

It is essential to highlight that the way the framework is implemented allows having a feasible frequency assignment and improving it according to the available computing power and time. For cases that are not time-sensitive, the framework can be configured to better explore the search space and generate better frequency plans. If that is not the case, the framework's configuration can be modified to make a reduced number of changes in real-time.

## 4.2 Dynamic frequency assignment

Ideally, given the high-dimensionality and complexity of the frequency allocation problem in multibeam satellite constellations, satellite operators would develop a frequency plan before operations, i.e., long before service is provided to the users, where all the resources (beam placement, routing, frequency, bandwidth, and power) can be considered simultaneously without computing time constraints. During operations, i.e., when users need to be served, the satellites would only need to execute this precomputed optimal plan without deviating from it.

However, the uncertainty in the position of mobile users makes this an unrealist solution. The capability of allocating frequency resources during operations, when more accurate information about the operational environment is known, proves to be crucial to providing feasible frequency assignments.

This importance of generating efficient frequency plans before operations and reallocating resources in real-time is emphasized in Guerster et al. [30], and Garau et al. [57]. We understand this need and include both long-term planning and real-time control in the proposed dynamic frequency assignment framework.

### 4.2.1 Uncertainty-aware strategies

Performing frequency reallocations is highly limited by computing time and operational constraints, e.g., changing the frequency assignment of a beam involves sending commands to the satellites and coordinating with the user terminal. Therefore, during operations, it is only possible to refine an already existing frequency plan by modifying a subset of the decision variables. Due to this limitation, there exists the possibility of not being able to find a feasible allocation. To mitigate these unwanted situations, we propose the usage of frequency allocation **strategies**, defined as changes in how the frequency assignment is performed to account for uncertainty.

These strategies can be divided into two main divided into two approaches.

- The first approach encompasses what are called **proactive strategies**, which stem from robust optimization practices. They consist in generating a more conservative frequency assignment before operations, such that possible uncertainty and contingencies are captured. This way, the number of changes to be performed during operation due to uncertainty in the position of mobile users–and therefore, the risk of not meeting their demand needs– is lowered. A frequency assignment with these characteristics can be obtained using **conservative constraint calculations**, e.g., having a larger interference threshold.

- The second approach includes what can be classified as **reactive strategies**, which exploit a high degree of real-time control. These strategies rely on including operational margin in the frequency plan generated before operations to reallocate frequency resources in real-time if necessary. Such frequency assignment can be obtained by explicitly **reserving resources**, e.g., not assigning part of the available spectrum.

However, these two approaches limit the system's capacity and the frequency assignment's efficiency. The limited system capacity comes from the increased number of constraints for proactive strategies and the explicitly limited capacity for reactive strategies. This can result in a higher number beams with unallocated frequency resources, which increases the unmet demand, and a less efficient frequency assignment, which increases the power consumption. These strategies and their performance can highly differ depending on the type of user. For instance, a maritime customer with slow mobility dynamics that follows a known travel route will require different uncertainty considerations than a customer that requires global coverage demand at unexpected locations without prior notice.

Since it is unclear whether current frequency assignment algorithms can address the additional layer of complexity presented by mobile users and operate under the added uncertainty, we propose solving this problem by using a frequency assignment framework that exploits the synergy of long-term and short-term frequency assignment, together with a way to introduce protection against uncertainty through proactive and reactive strategies.

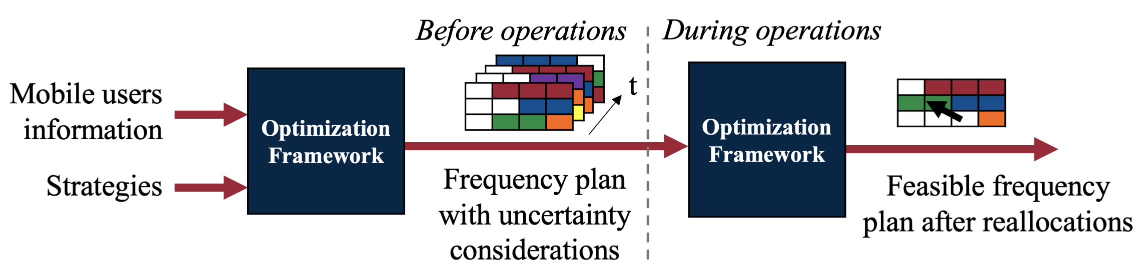


Figure 4-1: Dynamic frequency assignment framework.

### 4.2.2 Framework model

The architecture of the proposed dynamic frequency assignment framework for multibeam satellite constellations is depicted in Figure 4-1. As observed, the frequency assignment is divided into two domains: before operations and during operations.

- Before operations, the optimization framework takes as input information about mobile users, e.g., the area where they need to operate or their expected position at different times, as well as uncertainty-aware strategies. These strategies adjust how conservative the long-term frequency is and the number of reserved resources that can be needed for real-time control.
- During operations, when more accurate information about the user position is known, the framework refines, if necessary, the frequency plan obtained before operations by reallocating frequency resources.

This extended framework allows encoding a wide range of information regarding the expected position of mobile users. Moreover, it allows to flexibly introduce and combine uncertainty-aware strategies to overcome the challenges introduced by the spatiotemporal uncertainty introduced by mobile users.

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# Chapter 5

# Results

This chapter first presents the constellation model and user distributions used to assess the framework's performance. Finally, it describes the three cases that have been used to test the proposed framework and the results that have been obtained.

## 5.1 Operator assets

In this work, the chosen constellation is similar to O3b mPower, which consists of 10 satellites in an equatorial circular orbit at an altitude of 8,062 km [58]. The number of satellites is assumed to be $N_S = 7$ without loss of generality to mitigate the effect of other resource allocation decisions that are out of this thesis's scope, such as routing between beams and satellites. The satellite payload capabilities, such as the number of polarization, frequency reuses, and frequency channels, are assumed based on estimates of the constellation capacity and are specified in each experiment. The position and antenna characteristics of the gateways are provided by SES S.A. based on realistic configurations.

## 5.2 User distribution

The demand and mobility patterns of satellite communications users require complex modeling. In addition, the information provided by the users to the operator and the time it is provided can vary on a contract basis. In this work, we have divided the user distribution into fixed, maritime, and land mobile users to capture a wide range of possible user characteristics. The user distributions are described later in this section.

### 5.2.1 Demands and terminal characteristics

The data rates offered by the satellite operator have been modeled using three different tiers of increasing information rates that capture the necessities of different market segments. The first tier goes from 50-100 Mbps with 10 Mbps increment, the second from 100 to 250 Mbps with 30 Mbps increments, and the third from 250 to 500 Mbps with 50 Mbps increments.

Three different terminal sizes and characteristics have been considered based on data provided by SES SA. Each terminal model includes the antenna type (e.g., parabolic), dimension, $EIRP$, $G/T$, and $G$. The different terminals sizes are assigned to one of the tiers to avoid discrepancies between the capabilities of the user terminal and the demand to be met. This way, we avoid having combinations of demand and terminal characteristics that might be unrealistic, such as assigning large demands to a small terminal with low gain.

Based on data from industry reports and traffic simulation models [55], the ratio between the four types of users has been estimated such that fixed users, aeronautical mobile, maritime mobile, and land mobile account for approximately 75%, 10%, 10%, and 5% of the average capacity demand throughout the day.

### 5.2.2 Fixed users

Fixed users are always active, meaning that they always have demand requirements, do not change position over time, and their location is known. The fixed user distribution is generated based on data from the Gridded Population of the World v4 dataset [59] published by the NASA Socioeconomic Data and Applications Center, SEDAC. The location of each user is sampled from a 0.2-degree resolution grid that contains information about the population in it. The sampling is performed such that the probability of a user being in a cell is proportional to its population. The exact position of each user is selected randomly from the cell area using uniform sampling. Figure 5-1 shows a sample of 20k users obtained using this mechanism.

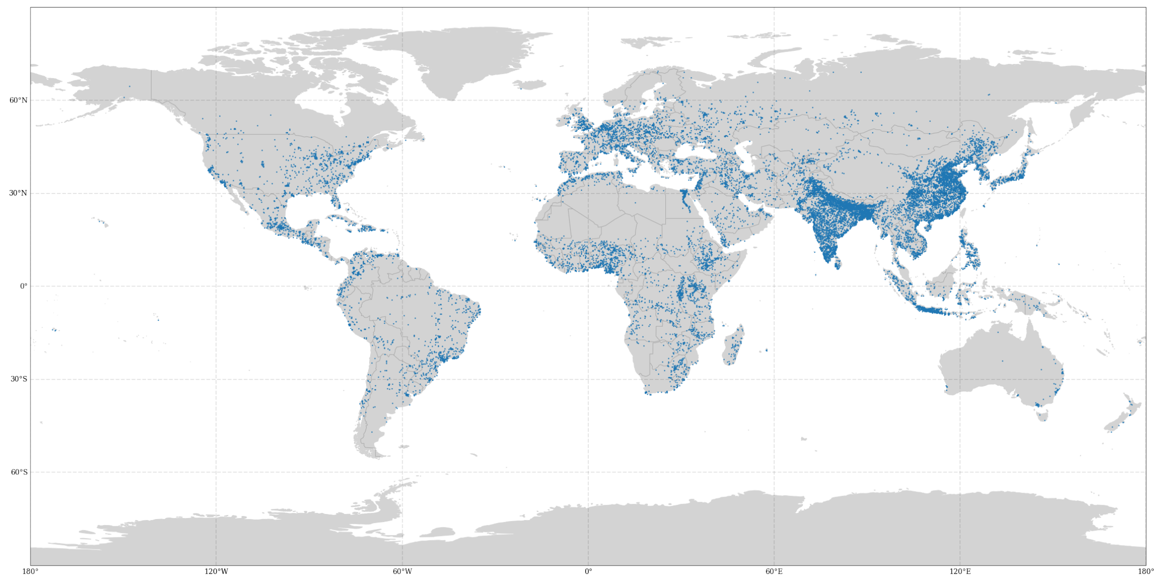


Figure 5-1: Fixed users distribution.

### 5.2.3 Aerial mobile users

The aerial mobility user distribution is based on an open-source dataset containing over 67663 routes between 3321 airports and 548 airlines across the globe [60]. Figure 5-2 shows the aerial routes considered in this study. Aeronautical mobile users present fast mobility patterns and relatively short active times of the order of hours. They intend to model commercial aviation customers. We assume that the source and destination airports and the scheduled departure times are known.

For this type of user, we introduce uncertainty in their position by analyzing actual flight tracks from the Eurocontrol R&D Dataset [61], which includes timestamped airplane positions for nearly 750k flights over 30 days. Figure 5-3 shows a sample of over 20k flight trajectories recorded during one day and four flights with the exact origin and destination airport but different trajectories. We use this dataset

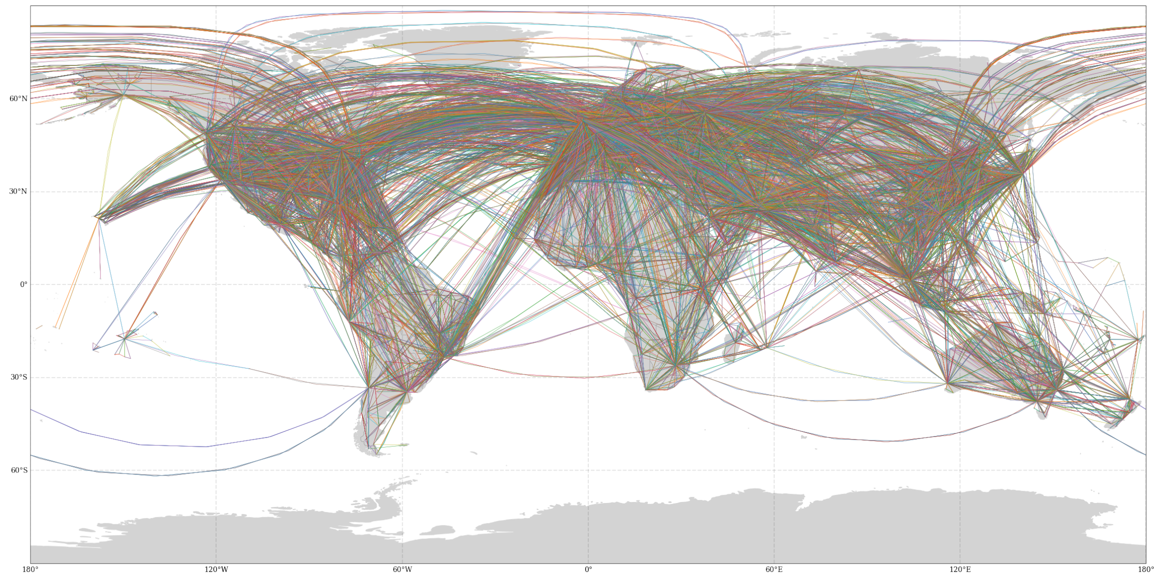


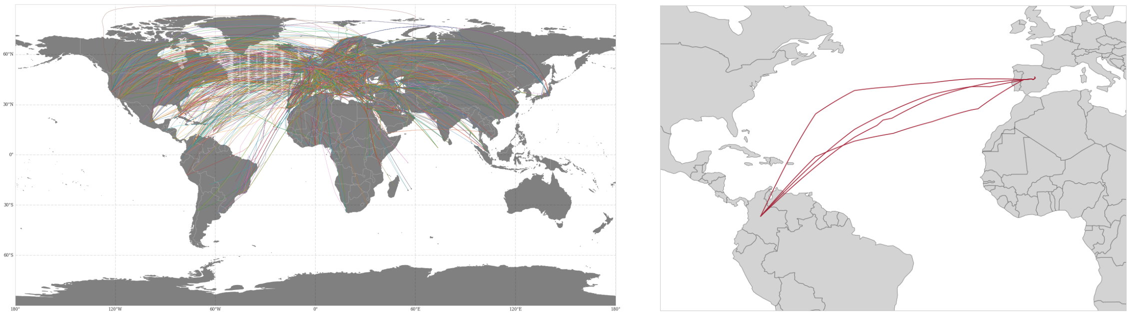

Figure 5-2: Aerial mobility users distribution.

to characterize the delays and deviations of aeronautical mobile users. The trajectory deviations are characterized by computing the distance of the actual trajectory to the geodesic between the source and destination locations. During the modeling, we consider how this distance changes throughout the trajectory (the deviation is smaller towards the start and end points). These deviations are normalized against the trajectory length, and together with the flight delay, we generate three groups representing low, medium, and high uncertainty. With this procedure, we create synthetic delays and trajectory deviations of different magnitude for global airplane routes given the start and end locations and the scheduled departure time.

### 5.2.4 Maritime mobile users

Maritime mobile users present long service times of the order of days. They contribute to long-term geographical demand changes, and their position is assumed to be known in advance with relatively high accuracy, as they have slow speeds and follow pre-specified routes. They intend to model cargo ships, cruises, and large vessels.

The maritime mobile user distribution is obtained from an open-source dataset that contains over 45k maritime routes spanning the globe [62]. The routes have been identified from Automatic identification system (AIS) data, a tracking system that



(a) (b)

Figure 5-3: Flight tracks extracted from the Eurocontrol dataset: (a) flights during one day and (b) sample of four flights with the same origin and destination but different trajectories.

uses transceivers on ships to send their position, course, and speed to other nearby vessels, satellites, and terrestrial antennas. Figure 5-4 shows the maritime routes considered in this study.

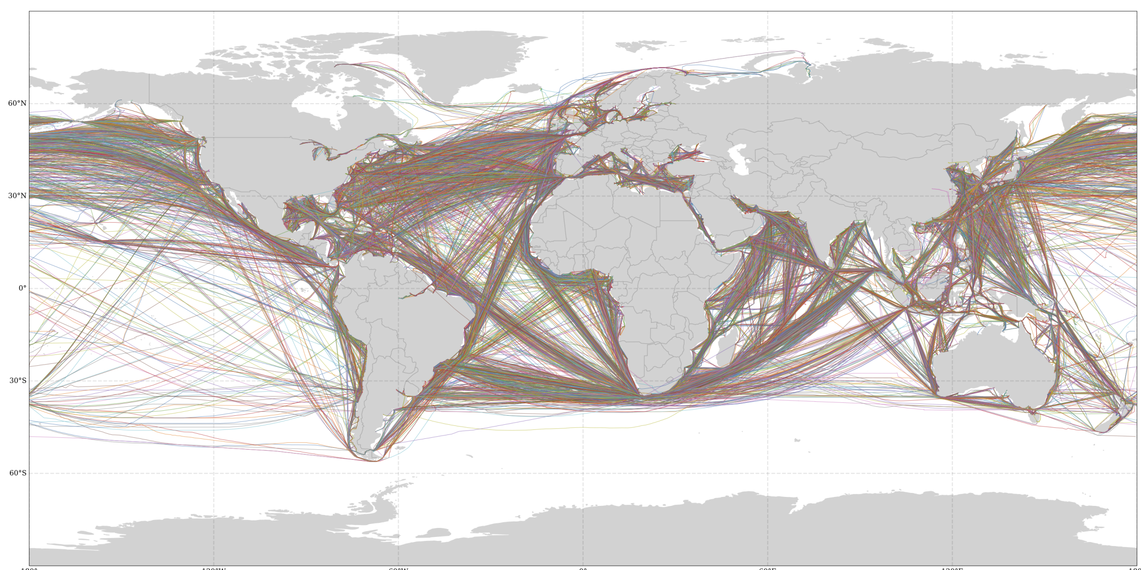



Figure 5-4: Maritime mobility users distribution.

### 5.2.5 Land mobile users

Land mobility mobile users present short service times of a few hours. They intend to model ground vehicles such as trains, trucks, or RVs. Their location and service times are not known in advance.

The distribution of land mobility users is synthetically generated to simulate ground mobility patterns worldwide. The trajectories of these users have been modeled as consecutive travels in different directions. Figure 5-5 shows a sample of land mobility patterns.

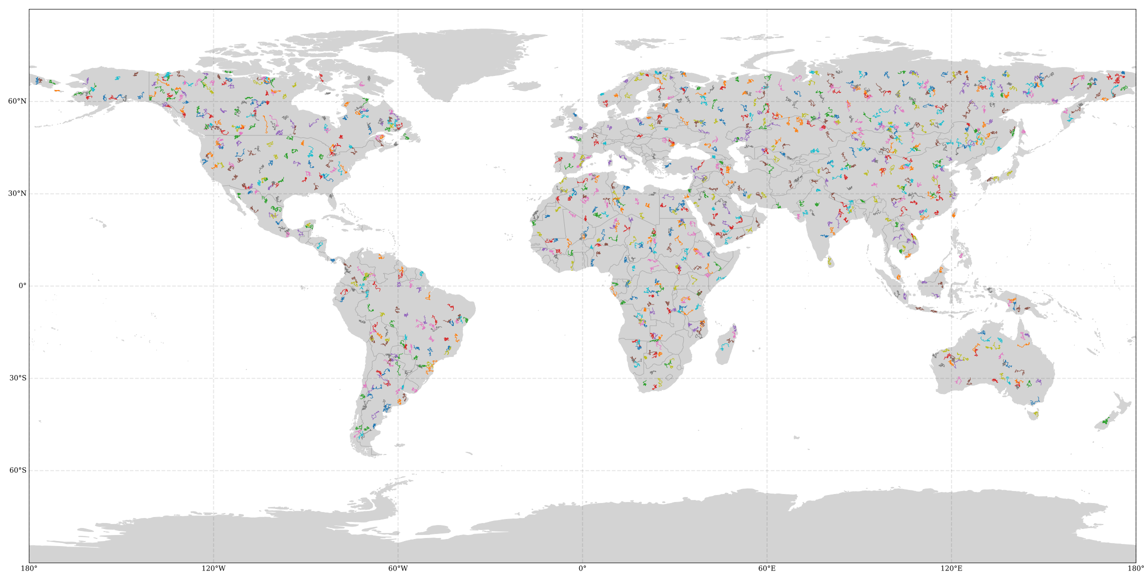



Figure 5-5: Land mobility users distribution.

## 5.3 Other resource allocation decisions

This presented frequency assignment framework has several inputs: beam placement information, data rate information, routing information, and a warm start frequency plan.

Beam placement is computed by grouping fixed users into the minimum number of beams through edge clique cover, proposed by Pachler et al. [46]. The optimality criterium of this method is minimizing the number of beams. The data rate of each beam is assumed to be the aggregate peak demand of the covered users.

User demand is routed to the closest gateway without considering the gateways' fill rates. This approach is based on reducing the Euclidian distance between user and gateway, which reduces power consumption. The satellites that will make the connection between a user beam and a gateway beam are decided by taking into account the minimum elevation angle of the terminals. The implementation details are provided in [56].

To speed up the computation, a warm start frequency plan is obtained with the heuristic algorithm proposed in [46], which has also been modified to account for mobile users.

## 5.4 Validation

To validate the generated frequency plans, we ensure that beams do not occupy the same resource on the same satellite at any time. We also verify that the beams that hold an interference restriction do not use the same frequencies and the same polarization. Moreover, we confirm that if a user beam is active, all the associated gateway beams are also active. If all this holds, we consider the frequency assignment to be valid.

## 5.5 Experiments

This work presents three different experiments to progressively assess the functionality, flexibility, and scalability of the framework:

- Frequency assignment with no uncertainty in low-dimensional scenarios.
- Frequency assignment with uncertainty in low-dimensional scenarios.
- Frequency assignment with uncertainty in high-dimensional scenarios.

The experiment characteristics and results are detailed in the following sections.

## 5.6 Frequency assignment with no uncertainty in low-dimensional scenarios

This first analysis evaluates the framework's capabilities to generate long-term frequency assignments using the information known a priori about the users, specifically regarding their trajectories or possible future locations. The goal of these experiments is to verify that our algorithm can generate a valid frequency plan that captures the movement of users over time and the changes that this involves in the interference and handover constraints.

We use a user distribution concentrated at a specific region of the globe, along a longitude span similar to that covered by one satellite, as shown in Figure 5-6. The idea behind using these reduced scenarios is that we can reach high satellite utilization as they go over that area without the computational requirements of optimizing for a global user basis. Moreover, users that are never geographically close to a particular region have a limited impact on the frequency allocation of that area as they will not add new interference or handover constraints. This analysis might also be interesting for satellite operators when targeting location-specific operation policies, such as acquiring more spectrum permissions or accepting new users.

This experiment's constellation capacity, shown in Table 5.1, is down-scaled from the estimated constellation capacity to make it compatible with the size of the user distribution. The capacity demand of the users is set to be lower than that of a single satellite, allowing the framework to focus on minimizing the system's overall power consumption and maximizing the number of users that can be served under feasible conditions. We perform 100 Monte Carlo Simulation runs with 60 fixed, 225 aerial, 8 maritime, 20 terrestrial users.

The unmet demand and power consumption results for the 100 simulation runs are shown in Table 5.2. The results show that the framework can generate a frequency plan prior to operations based on precise information about mobile users, capture the mobility considerations and successfully meet the user demand. Figure 5-7 shows the frequency plan of single resource group for the user distribution shown in Figure 5-6.

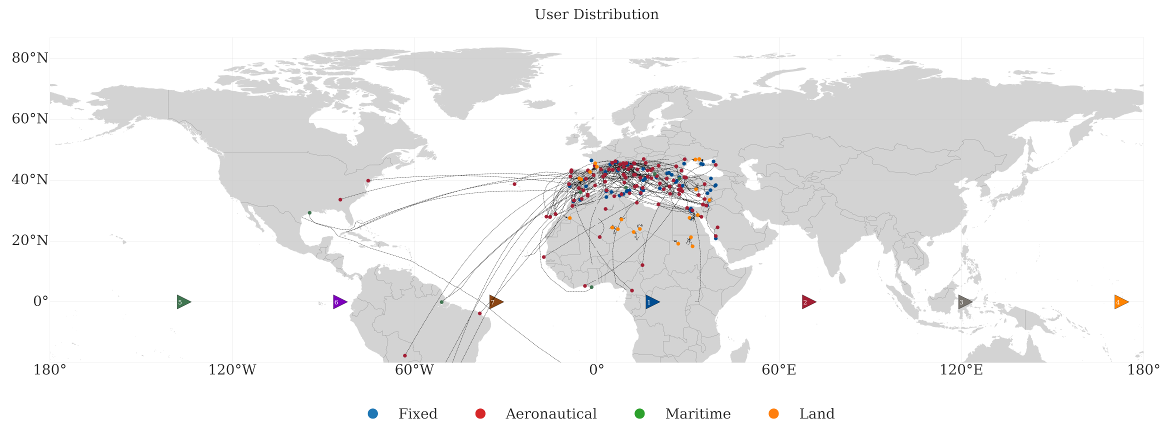



Figure 5-6: Sample user distribution with 60 fixed users, 225 aerial users, 8 maritime users, and 20 land users, colored according to the legend, which are provided service using 284 forward and 511 return beams (795 in total). The plot shows the initial position and trajectories of the users that the constellation needs to provide service throughout a 24-hour period. All the users are shown in this plot, although they will require service at different times. The satellite are depicted as triangles situated over the equator.

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Number of satellites | $N_s$ | - | 7 |
| Number of frequency channels | $N_{ch}$ | - | 80 |
| Number of frequency reuses | $N_r$ | - | 8 |
| Number of polarizations | $N_p$ | - | 2 |
| Bandwith per frequency channel | $BW_{ch}$ | MHz | 15 |

Table 5.1: Constellation parameters for reduced scenarios. The values are downscaled from the estimated constellation capacity based on the criteria of the author.

| Configuration | Normalized $UD$ | Normalized $P$ | Normalized $S$ |
|---|---|---|---|
| Baseline (no uncertainty) | 0.000 (0.000) | 0.111 (0.007) | 0.067 (0.005) |

Table 5.2: Results of frequency assignment with no uncertainty in reduced scenarios, showing the normalized unmet demand, normalized power consumption and normalized spectrum utilization.

This frequency plan informs of the frequency that each beam can use over time and does not include information about which satellite is powering it. Therefore, there can be overlapping assignments (indicated by a darker coloring) between beams that do not have a reuse constraint. As an example, at $t = 15$h, two gateway beams use the frequency channel 80, but are assigned to satellites 3 and 5. However, since the beams are distributed over a small longitude span, most beams are assigned to the same satellite at some point and therefore cannot use the same resources, i.e., their frequency assignments do not overlap. Figure 5-8 shows the frequency assignment of the same resource group from the satellite point of view, where allocations do not overlap. Appendix A contains the frequency assignments for the rest of the satellites.

Figure Fig. 5-10 shows the frequency assignment from the gateway perspective. It can be observed that the assignments corresponding to fixed users (in blue) do not change over time and always use the same frequency channels. Since mobile users do not require service at all times and need to be routed to other gateways as they change location, frequency resources can be shared among multiple users to increase resource utilization efficiency. There are unused frequency channels due to interference constraints with other beams.

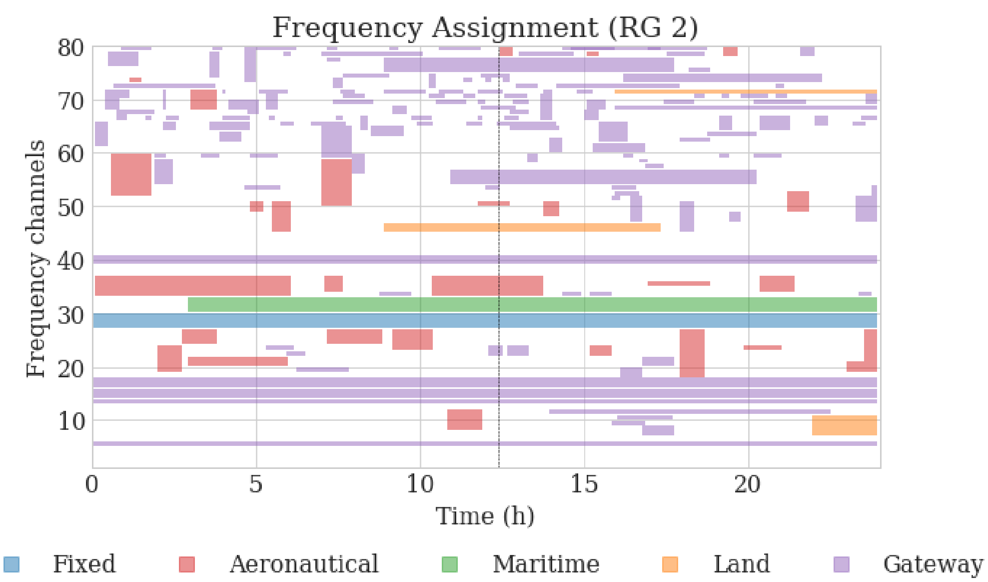
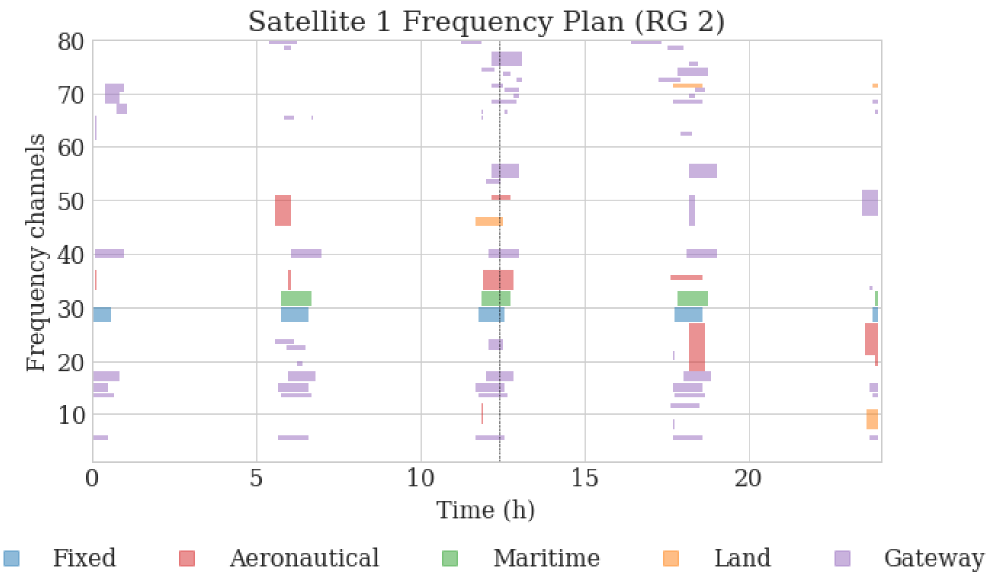
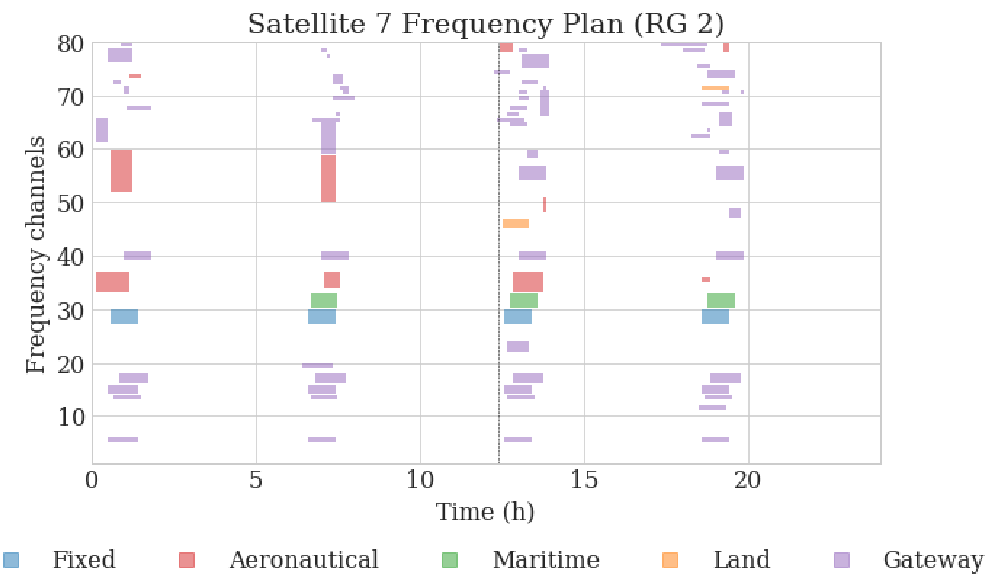



Figure 5-7: Time-dependent frequency plan showing the beams assigned to the resource group 2.




(a)




(b)

Figure 5-8: Resource group 2 frequency assignment over time for satellites 1 (a) and 7 (b). The dashed vertical line indicates a simulation time of 12 hours and 20 minutes, for which the user position and the constellation frequency assignment is plotted in Figure 5-9.

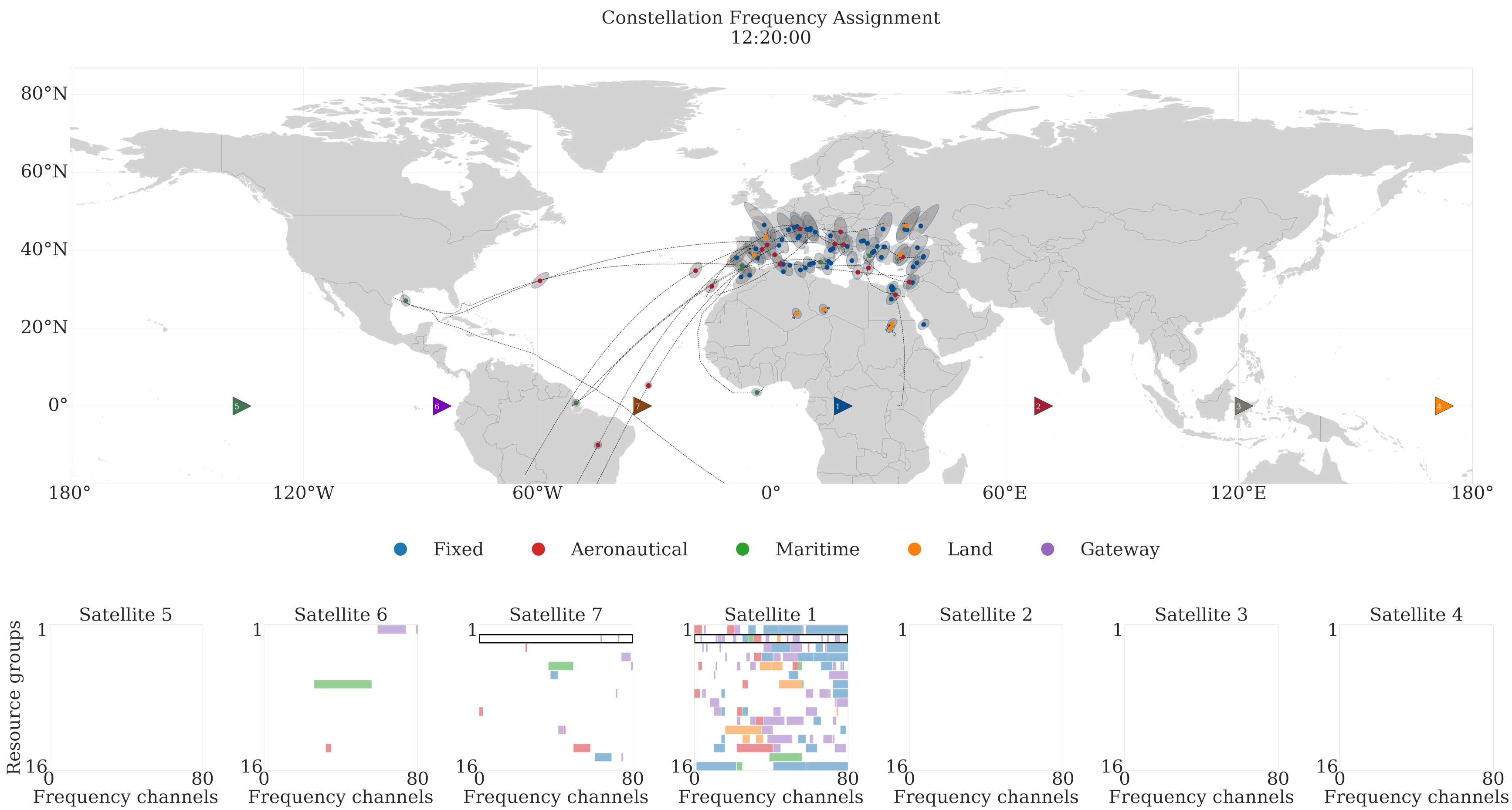



Figure 5-9: Constellation frequency assignment at a specific time. The upper part of the figure shows the users' position along their trajectories at a simulation time of 12 hours and 20 minutes. The shaded area around the users is the beam footprint, which is colored according to the satellite that powers it. Resource group 2 of satellites 1 and 7 is highlighted.

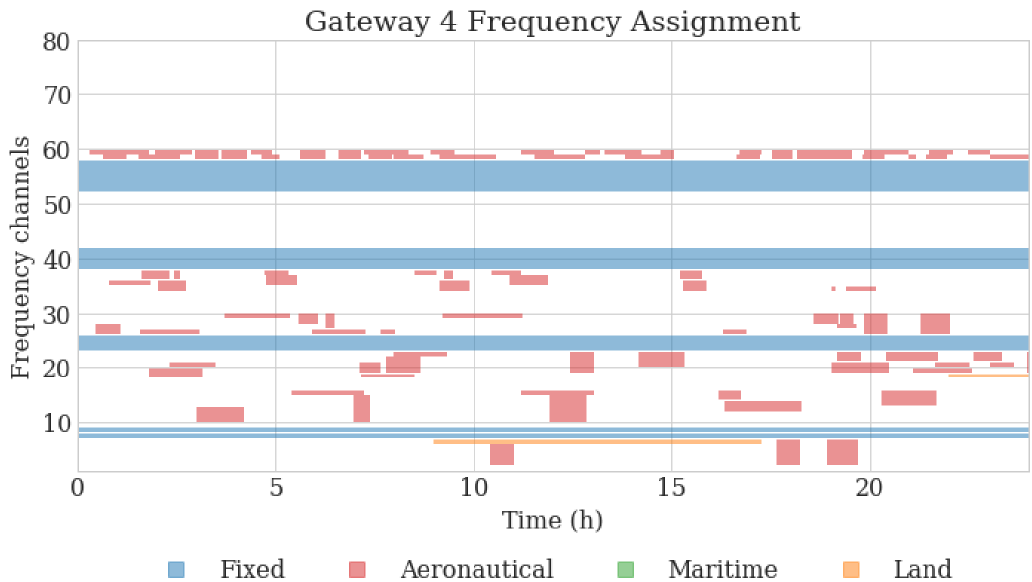



Figure 5-10: Frequency assignment over time (one polarization) for one of the gateways.

## 5.7 Frequency assignment with uncertainty in low-dimensional scenarios

This second analysis evaluates the framework's capabilities to generate long-term frequency assignments when the information about mobile users' trajectories or possible future locations. Therefore, in this experiment, it needs to operate under uncertainty.

The constellation parameters and user bases are the same as in the previous experiment. However, now we assume that the delays and deviations of aeronautical mobile users, which are modeled using actual flight data, are not known. We also assume that we do not have any a priori information about land mobile users, i.e., they will start service at unexpected times and locations. We also differentiate three use cases with low, medium, and high uncertainty based on the magnitude of the deviations and delays of aeronautical mobile users.

To assess the performance of our framework under uncertainty, we first generate a frequency plan based on the information known before operations. As explained, this information can vary depending on the user type and their contract with the satellite operator. We assume that we have the following information:

- the position of fixed users,
- accurate trajectories and service start time of maritime mobile users,
- start and end locations and service start time of aeronautical mobile users,
- no information about land mobile users

To allocate frequency resources to aeronautical users before operations, we assume they follow the shortest path between the start and endpoints. Since we assume that no information is known about land mobile users before operations, they are not included in the frequency assignment plan.

During operations, we assume that accurate information about the mobile users' positions is known during a two-hour interval before the actual service start time. That is, mobile users are assumed to provide the satellite operator their accurate planned locations as soon as two hours before they require to be provided service and as late as the actual requested service start time. This would include use cases ranging from an airline company providing flight routes two hours before departure, a period during which reallocations could be performed, to a ground vehicle requiring service as soon as possible, where the time to react is much lower. Although further changes in the user trajectories could be included in the simulations, we assume that we accurately know where they will be after this update.

After this information is known, interference and reuse constraints concerning that user and the beams associated with it are recomputed. If the frequency assignment of the beams (including user and gateway beams) is not invalidated due to unexpected constraints, we do not need to reallocate, and we can rely on the frequency plan computed before operations. Otherwise, the framework tries to perform reallocations using reserved resources, if any. These reserved resources can be shared with other users or be explicitly reserved for them. During these reallocations, the number of frequency channels assigned to the beams is allowed to vary. This way, the bandwidth assigned to the beam can be reduced to find a feasible allocation at the expense of higher power consumption. The frequency assignment of other beams is not modified.

If the frequency assignment remains unfeasible after this reallocation attempt, we consider that we cannot provide service to the user, and all the beams associated with it are deactivated. Because of this last step, the results obtained in this experiment are considered worst-case scenarios. This is a consequence of modeling the interference as a hard binary constraint. In practice, the data rate offered to the users would be temporarily reduced.

### 5.7.1 Improving performance using strategies

We are interested in verifying that our framework can use different strategies to operate under uncertainty. To demonstrate the framework's flexibility to encode these considerations, we propose an initial set of strategies that can be further studied and optimized to achieve better results. In this section, we comment on the effects of using the following two strategies:

**Reserving spectrum** Reserving spectrum falls under the category of reactive strategies since it leverages a higher degree of real-time control. In this case, we reserve 10% of the available frequency channels when generating the frequency allocation before operation. The risk of being unable to provide service is reduced by having a reserved pool of spectrum resources that can be used in case an assignment violates a new constraint.

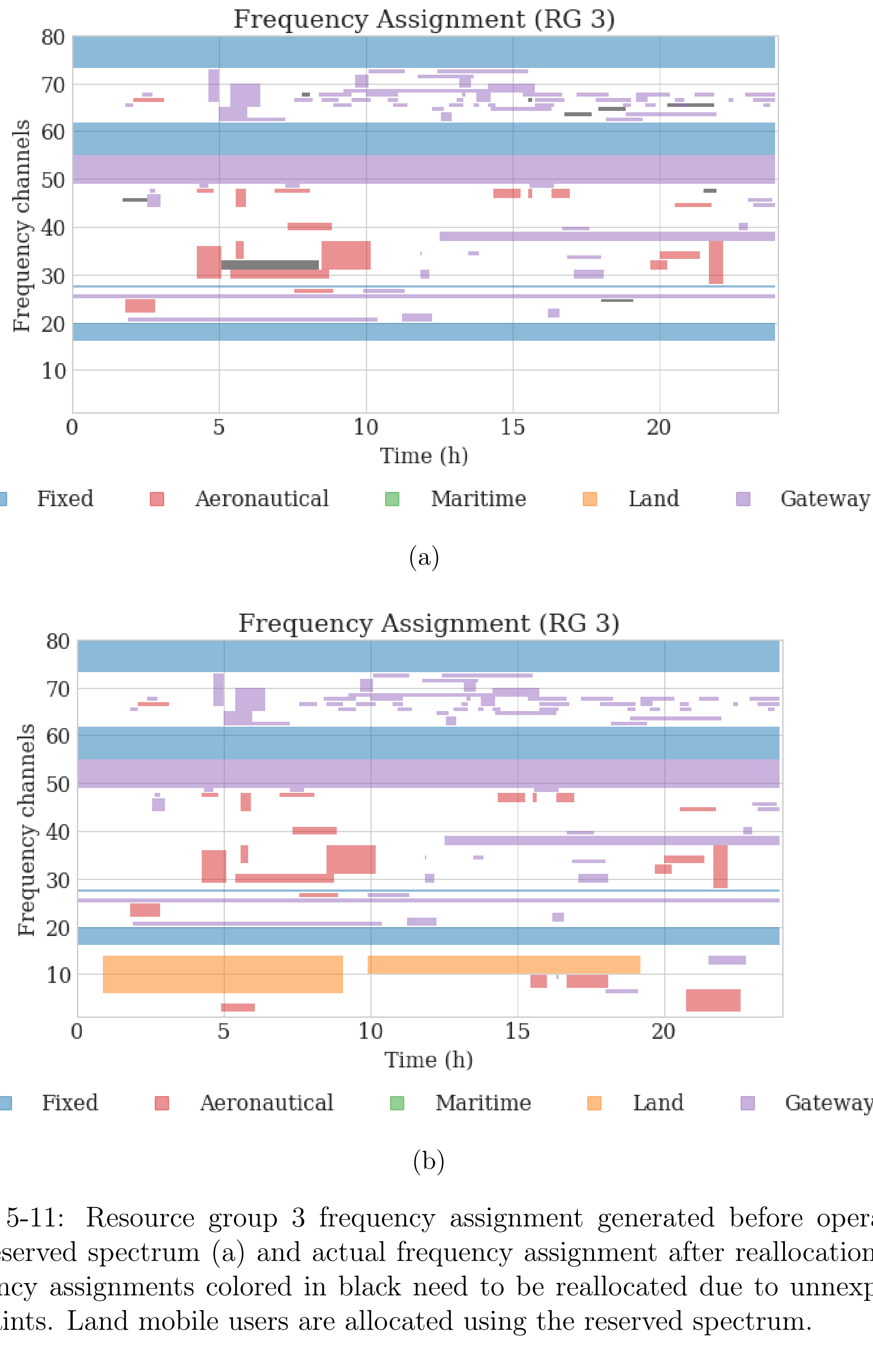
**Including temporal and interference buffers** This strategy falls under the category of proactive strategies since it is based on conservative constraint calculations and a robust allocation. In this case, the constraints are computed assuming that the departure time of aeronautical mobile users can be delayed. This value can be selected based on a statistical study of flight delays. Moreover, a larger interference threshold is used to compute the interference constraints. This allows capturing interference constraints that might arise from deviations in the position of aeronautical mobile users. As an initial approximation, we use the $50^{\text{th}}$ flight delay percentile for the temporal buffer and a 30% increase in the interference threshold.

For comparison purposes, we also compute frequency assignment (1) without reserving resources nor being conservative when computing the constraints (2) assuming the user information is accurately known a priori. The rest of the strategies and implementation details can be found in Appendix B. We perform 20 Monte Carlo Simulation runs for each of the strategies and configurations and the 3 levels (low, medium, high) of trajectory deviations and delays of aeronautical mobile users, resulting in a total of 600 runs.

Figure 5-11 shows the frequency assignment of one resource group over time, where the reallocations and frequency assignment of new users using reserved spectrum can be observed. Figure Fig. 5-12 shows the frequency assignment of the same resource group from the point of view of a satellite.

The normalized unmet demand and power consumption results for these experiments are summarized in Table 5.3. The results show that our framework can successfully encode uncertainty considerations and operate in under the presence of mobile users and uncertainty, meeting 100% of the demand in scenarios with low spatiotemporal uncertainty, i.e., with land mobile users that start service at unexpected locations and times and aeronautical mobile users that suffer small delays and trajectory deviations. In scenarios with high uncertainty, our framework allows meeting 99.9% of the demand. These results are achieved by reserving part of the spectrum and using it to make reallocations during operations. It can be observed that using strategies successfully results in lower unmet demand at the expense of increased power consumption due to a less efficient frequency assignment. It is also important to highlight that strategies involving reserving spectrum achieve lower unmet demand because the framework is able to allocate land mobile users, which are not included in the frequency plan generated before operations.

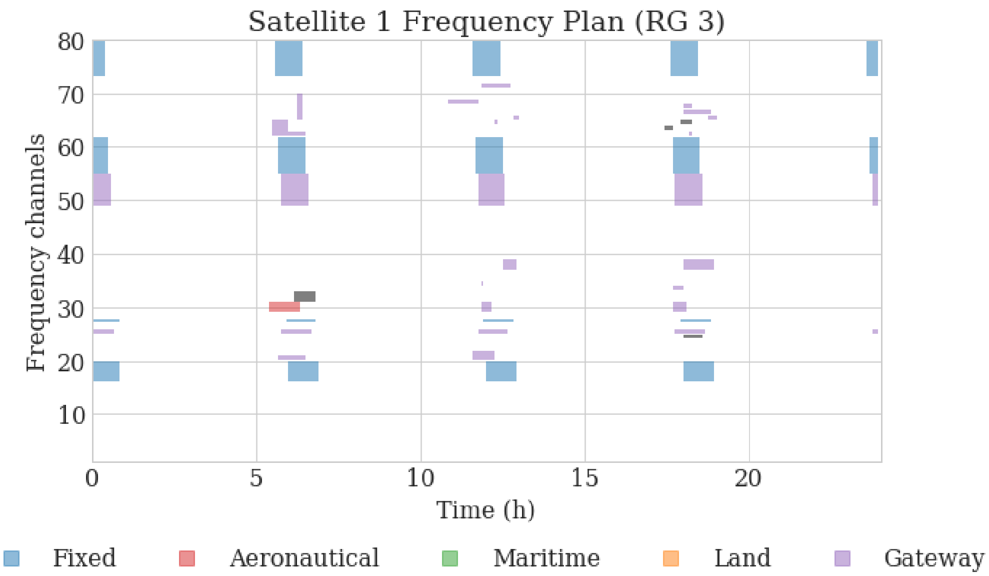
We observe that the unmet demand is higher with high uncertainty due to the increased number of unexpected constraints that invalidate the frequency assignment. Compared to not using any additional uncertainty considerations, being conservative when computing the constraints allows reducing the unmet demand by 40% by using only 3% more power. In contrast, by reserving spectrum and performing more reallo-



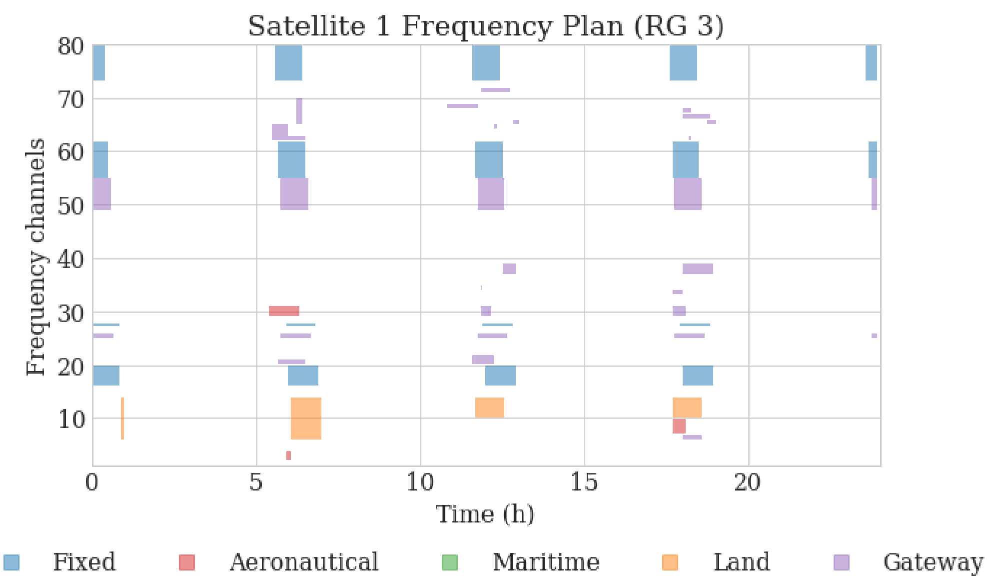

(a)

(b)

Figure 5-11: Resource group 3 frequency assignment generated before operations with reserved spectrum (a) and actual frequency assignment after reallocations (b). Frequency assignments colored in black need to be reallocated due to unexpected constraints. Land mobile users are allocated using the reserved spectrum.




(a)




(b)

Figure 5-12: Frequency assignment generated before operations with reserved spectrum (a) and actual frequency assignment after reallocations (b) for one satellite. Frequency assignments colored in black become infeasible due to unexpected constraints. Land mobile users are allocated using the reserved spectrum.

| Strategy | Normalized $UD$ | Normalized $P$ |
|---|---|---|
| **Low uncertainty** | | |
| No additional considerations | 0.008 (0.004) | **0.109 (0.008)** |
| Reserved spectrum | **0.000 (0.000)** | 0.117 (0.010) |
| Temporal + Interference buffers | 0.005 (0.004) | 0.112 (0.009) |
| Baseline (no uncertainty) | 0.000 (0.000) | 0.110 (0.008) |
| **High uncertainty** | | |
| No additional considerations | 0.015 (0.006) | **0.108 (0.007)** |
| Reserved spectrum | **0.002 (0.007)** | 0.116 (0.009) |
| Temporal + Interference buffers | 0.009 (0.005) | 0.111 (0.008) |
| Baseline (no uncertainty) | 0.000 (0.000) | 0.109 (0.008) |

Table 5.3: Results of frequency assignment with uncertainty in reduced scenarios, showing the normalized unmet demand and normalized power consumption.

cations, a further reduction in unmet demand can be achieved. In the case with low uncertainty, all the demand is met by using 7% more power.

As shown in Table 5.4, by using a proactive strategy, the number of reallocations during operations is reduced by over 30%. Because of the added constraints, it achieves a 5% lower spectrum utilization than the base case but a 10% higher utilization than the reactive strategy, which explicitly limits the system's capacity.

| Strategy | Reallocations | Normalized $S$ |
|---|---|---|
| **Low uncertainty** | | |
| No additional considerations | 0.116 (0.016) | **0.069 (0.004)** |
| Reserved spectrum | 0.113 (0.013) | 0.059 (0.003) |
| Temporal + Interference buffers | **0.080 (0.018)** | 0.065 (0.003) |
| Baseline (no uncertainty) | 0.000 (0.000) | 0.068 (0.004) |
| **High uncertainty** | | |
| No additional considerations | 0.255 (0.021) | **0.067 (0.004)** |
| Reserved spectrum | 0.242 (0.016) | 0.057 (0.003) |
| Temporal + Interference buffers | **0.169 (0.028)** | 0.064 (0.004) |
| Baseline (no uncertainty) | 0.000 (0.000) | 0.067 (0.004) |

Table 5.4: Results of frequency assignment with uncertainty in reduced scenarios, showing the normalized number of reallocations and normalized spectrum utilization. The number of reallocations has been normalized against the number of beams associated with mobile users.

The overview of these results emphasizes the framework's capability to use strategies to capture uncertainty and improve its performance. We have also introduced the trade-offs they present in terms of unmet demand and power consumption, as well as other considerations such as the number of reallocations and spectrum utilization.

The performance of each strategy, or a combination of them, highly depends on the user base. For instance, for users with similar characteristics as the aeronautical mobile users modeled in this work (for which certain information is known before operations), reserving spectrum does not result in higher performance than having a more conservative constraint calculation. However, reserving spectrum turns out to be a good solution in scenarios with users for which we do not know a priori when they will start service (similar to land mobile users considered in this study) since they can be allocated part of those resources.

Optimizing strategies for a certain group of users can be done by studying their mobility dynamics. For example, for aeronautical mobile users, historical flight data between airports can be analyzed to characterize the delays and deviations of specific routes and compute the constraints accordingly. Optimizing strategies whose hyper-parameters do not depend on the users' locations, such as how much spectrum is reserved, becomes more complex. However, it can be done by performing experiments like the one presented in this section.

The framework also offers flexibility on how the strategies are defined. For example, in this case, we decided to reserve spectrum by not assigning part of it no any of the users. In practice, we can decide which users have access to those reserved resources, even establishing preferences based on user contracts.

These results show that the presented framework can operate under the uncertainty introduced by mobile users by encoding different uncertainty considerations in the form of strategies. These strategies can improve the framework's performance, but they depend on the user basis, requiring a specific study for each use case. Rather than characterize the framework performance for the presented user distribution, these results should be used to understand what trade-offs the different strategies can present, how they are related to the user characteristics, and what can be done to optimize them.

## 5.8 Frequency assignment with uncertainty in high-dimensional scenarios

In this last experiment, we test our framework in a high-dimensional scenario with a global user distribution, shown in Fig. 5-13. Table 5.5 presents the constellation parameters used in this experiment. Given the dimensionality of the scenario, we only perform 5 simulation runs for each of the strategies discussed in the previous section.

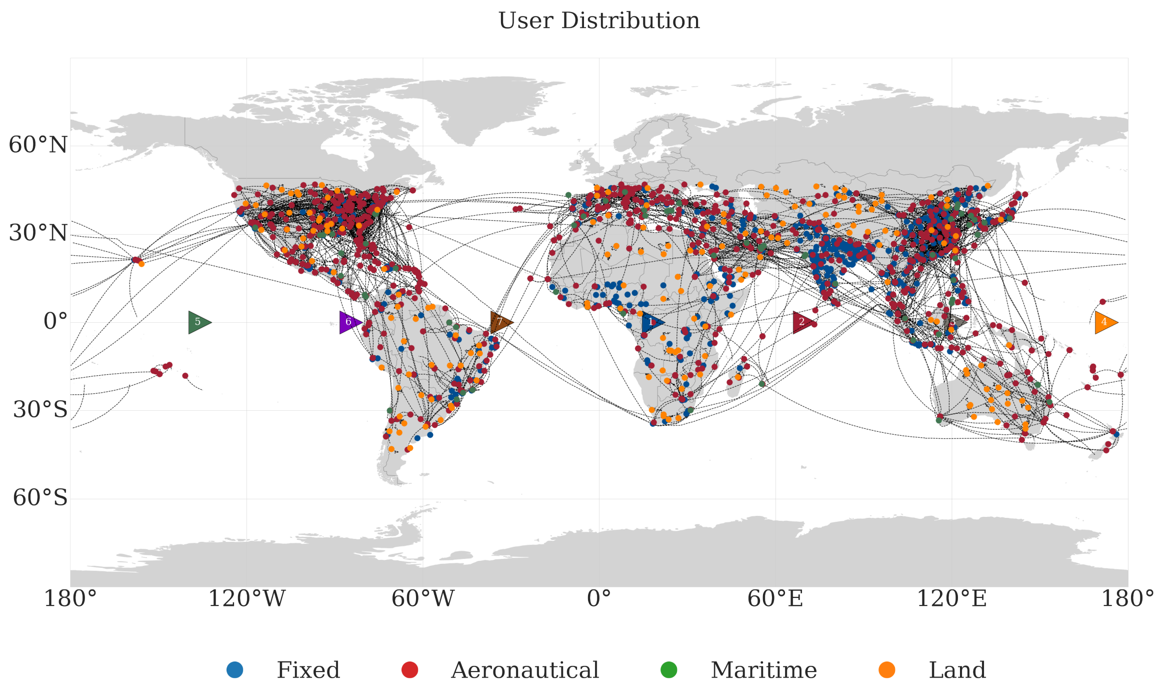



Figure 5-13: Sample user distribution with 530 fixed users, 2010 aerial users, 70 maritime users, and 180 land users, which are provided service using 2519 user and 3701 gateway beams (6220 in total).

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Number of satellites | $N_s$ | - | 7 |
| Number of frequency channels | $N_{ch}$ | - | 150 |
| Number of frequency reuses | $N_r$ | - | 12 |
| Number of polarizations | $N_p$ | - | 2 |
| Bandwith per frequency channel | $BW_{ch}$ | MHz | 15 |

Table 5.5: Constellation parameters for global scenarios. The values representative of the constellation actual capacity.

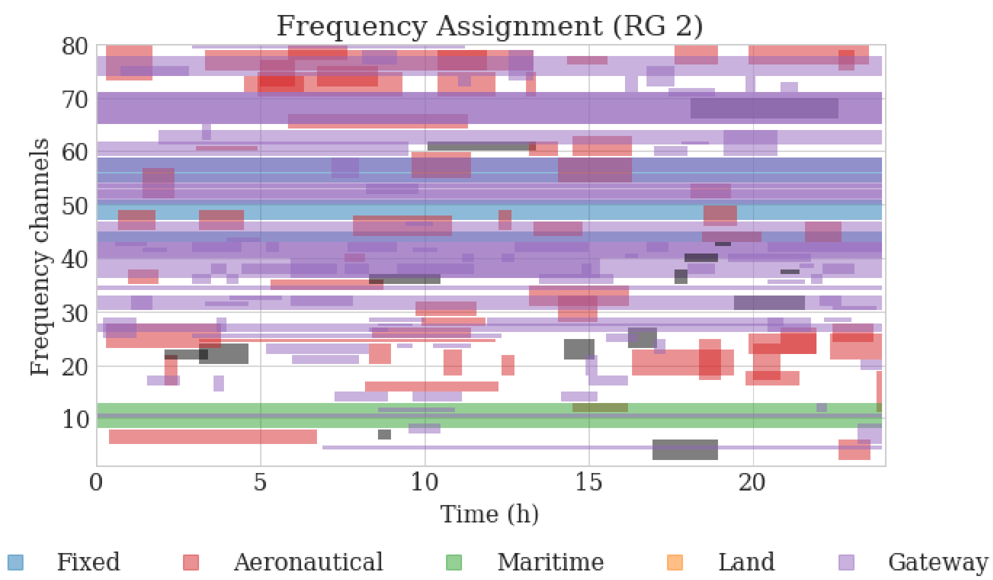
The normalized unmet demand and normalized power consumption are summarized in Table 5.6 and Table 5.7. With the selected strategies, we can serve 99.6% of the demand, using only 3% more power compared to a case with no uncertainty. Like the previous sections, Figure 5-14 shows the frequency assignment of one resource group over time, and Figure Fig. 5-15 shows the frequency assignment of the same resource group from the point of view of a satellite. The frequency assignment shown in the plot has been obtained including temporal and interference buffers. Given that the user distribution is not concentrated over one area, multiple users that are never assigned to the same satellite use the same spectrum resources. Moreover, it can be observed that the frequency assignment of one satellite is not limited to one area. These results show that the framework allows capturing mobility considerations and operating under uncertainty in high-dimensional use cases, leveraging the capabilities of modern satellite payloads in scenarios with thousands on beams.

| Strategy | Normalized $UD$ | Normalized $P$ |
|---|---|---|
| No strategy | 0.006 (0.002) | **0.424 (0.033)** |
| Reserved spectrum | 0.008 (0.006) | 0.460 (0.035) |
| Temporal + Interference buffers | **0.004 (0.001)** | 0.445 (0.036) |
| Baseline (no uncertainty) | 0.000 (0.000) | 0.432 (0.043) |

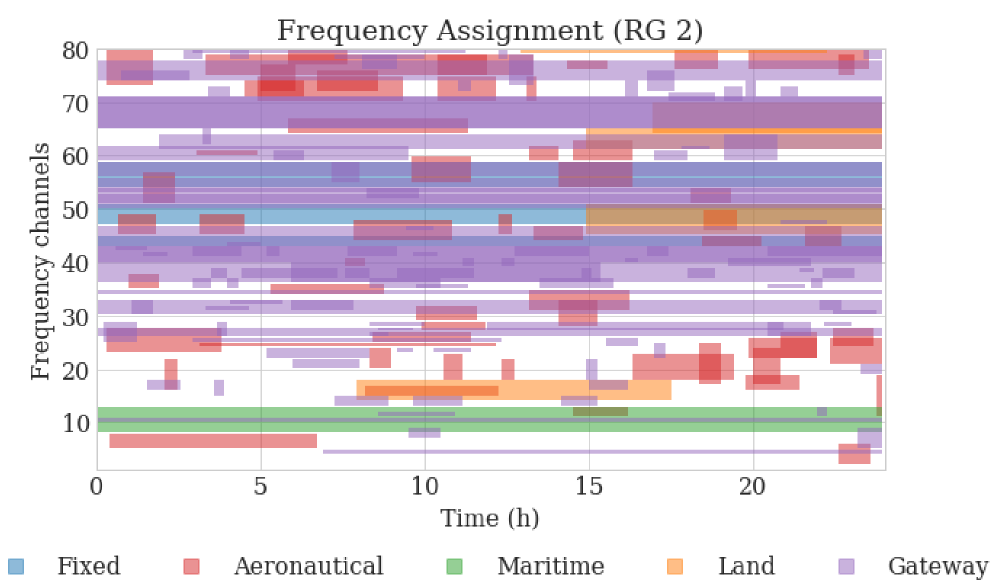
Table 5.6: Results of frequency assignment with uncertainty in high-dimensional scenarios, showing the normalized unmet demand and normalized power consumption.

| Strategy | Reallocations | Normalized $S$ |
|---|---|---|
| No strategy | 0.263 (0.005) | **0.198 (0.002)** |
| Reserved spectrum | 0.204 (0.004) | 0.187 (0.003) |
| Temporal + Interference buffers | **0.151 (0.006)** | 0.189 (0.002) |
| Baseline (no uncertainty) | 0.000 (0.000) | 0.188 (0.002) |

Table 5.7: Results of frequency assignment with uncertainty in high-dimensional scenarios, showing the normalized number of reallocations and normalized spectrum utilization. The number of reallocations has been normalized against the number of beams associated with mobile users.

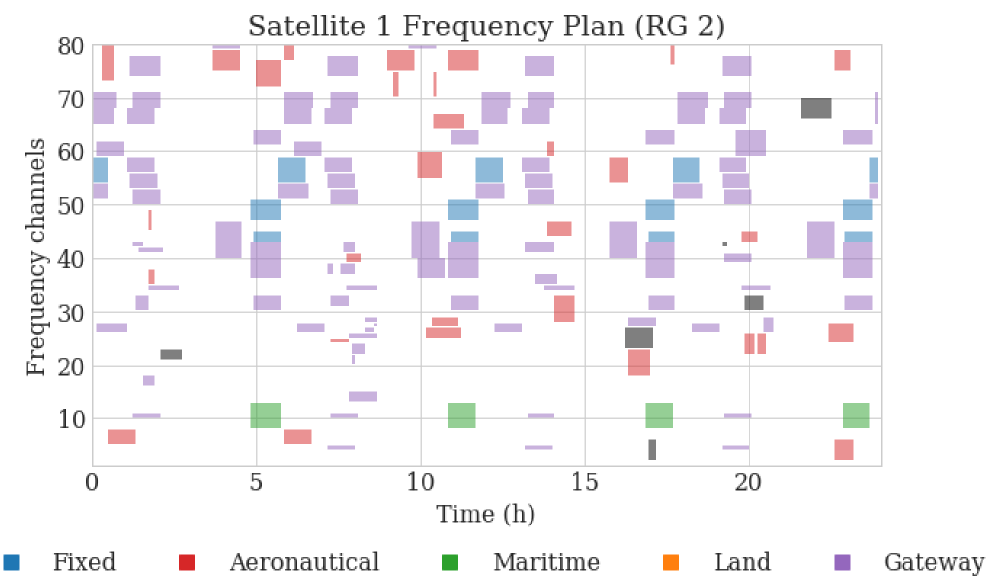



(a)

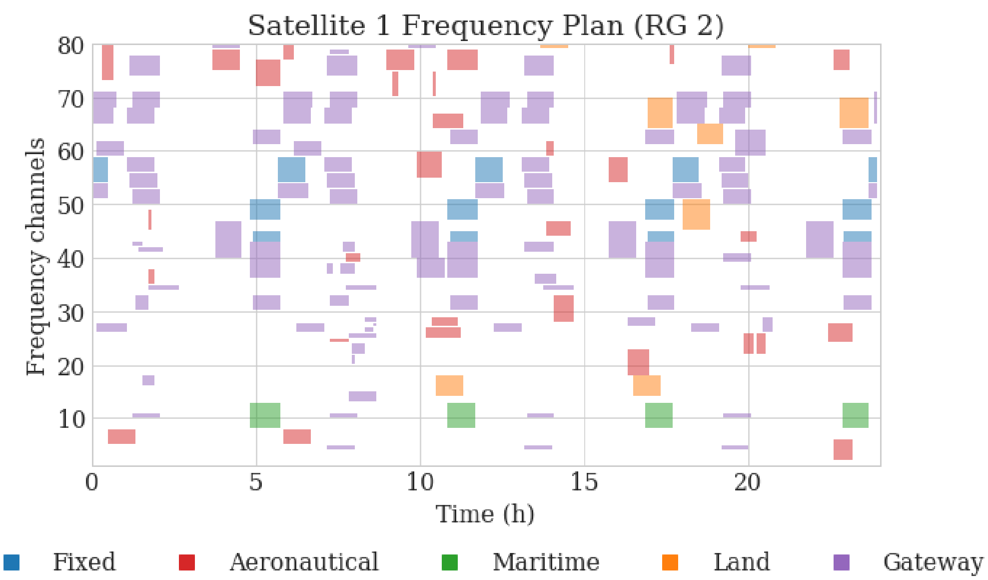



(b)

Figure 5-14: Resource group 2 frequency assignment generated before operations with temporal and interference buffers (a) and actual frequency assignment after reallocations (b) (only the first 80 frequency channels). Frequency assignments colored in black need to be reallocated due to unexpected constraints. Land mobile users are also allocated.




(a)




(b)

Figure 5-15: Resource group 2 frequency assignment generated before operations with temporal and interference buffers (a) and actual frequency assignment after reallocations (b) for one satellite (only the first 80 frequency channels).

# Chapter 6

# Conclusions

## 6.1 Thesis summary

In Chapter 1, we presented the challenges of the new satellite communications landscape and motivated the need to develop Dynamic Resource Management solutions explicitly involving the allocation of frequency resources. We reviewed the literature in the field to identify a research gap involving frequency assignment in multibeam satellite constellations to provide service to mobile users. Chapter 2 presented a general overview of satellite communications systems to provide the reader with the necessary background on the work of this thesis. In Chapter 3, we introduced the frequency assignment problem, highlighting the challenges introduced by mobile users, and formalized it as an optimization problem. In Chapter 4 we overviewed a frequency plan optimization framework and explained how it could be extended to operate under the uncertainty introduced by mobile users. Finally, in Chapter 5 we characterized the user distributions and models used in this work. We presented the results of the proposed dynamic frequency assignment framework in three cases: frequency plan design with and without uncertainty in reduced scenarios and frequency assignment with uncertainty in high-dimensional scenarios.

## 6.2 Conclusions and remarks

In this thesis, we have addressed the need to develop a frequency assignment optimization framework that solves the challenges of providing service to mobile users while accounting for the flexibility and dimensionality of the upcoming communication satellite systems. Our optimization framework leverages the synergy of long-term and short-term frequency assignment through strategies that allow efficiently handling frequency and bandwidth assignment under the uncertainty introduced by mobile users. The method extends an existing Integer Linear Programming framework to introduce temporal dependency and uncertainty considerations in the frequency assignment.

We have carried out three experiments to validate our method's functionality, flexibility, and scalability. The first experiment's results demonstrated the framework's ability to capture mobility and temporal considerations to solve the frequency assignment problem in simple scenarios efficiently. The second experiment shows that the framework allows designing frequency plans with different uncertainty considerations. These considerations, referred to as strategies, present different operational trade-offs that can be studied and optimized. Finally, the results from the third experiment prove that our framework can operate in a real-world scenario with over 6000 beams.

## 6.3 Future work

Based on the conclusions of this work, different directions of future research have been identified:

- Hybrid beam placement. While this work considers that all mobile users can be followed by steerable beams, having a hybrid solution where fixed beams can also service them might be a promising solution.

- Routing to gateways. We have considered that mobile users are always connected to the closest gateway, requiring satellites to frequently change the traffic routing. Avoiding this high number of changes will reduce not only the operational complexity but also the dimensionality of the problem.

- Extension to different algorithms. The algorithm used in this framework shows promising results and, given its flexibility, has room for improvement. However, trying other approaches both for long-term and short-term planning could result in interesting performance improvements.

- Incorporation of demand uncertainty. In this work, demand has been assumed to be fixed and known, which reduces the complexity of the problem but also the potential to simultaneously consider this uncertainty with that added by mobile users.

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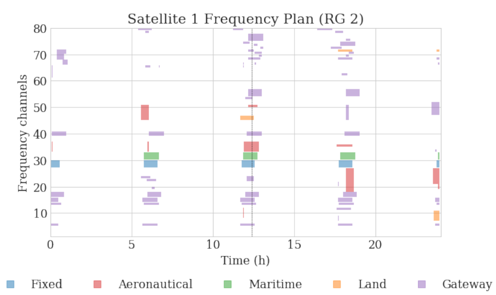
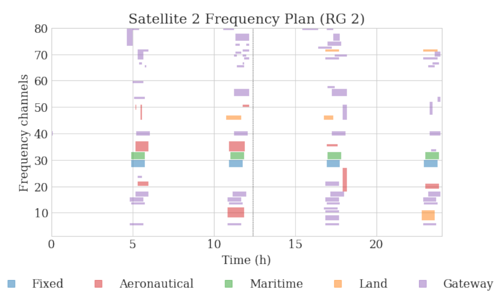
# Appendix A

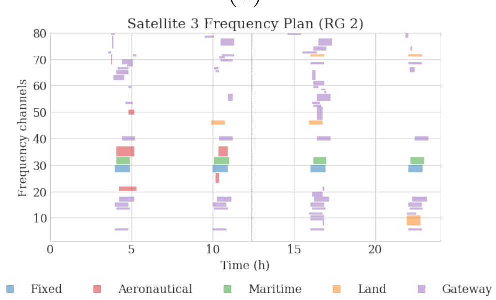
# Frequency assignment per satellite



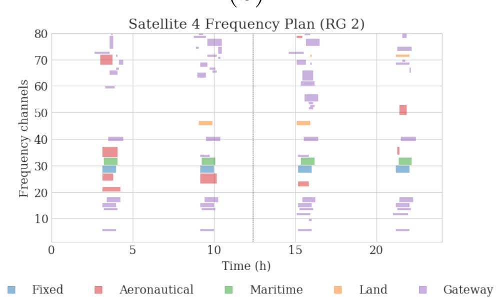

(a)




(b)

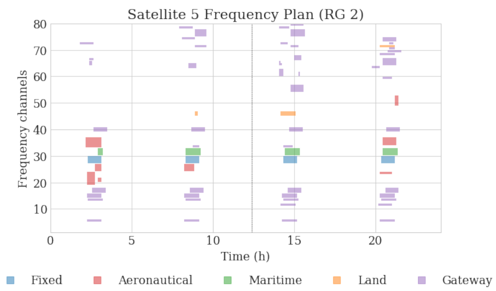



(c)

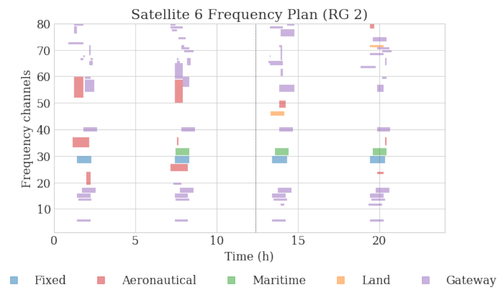



(d)

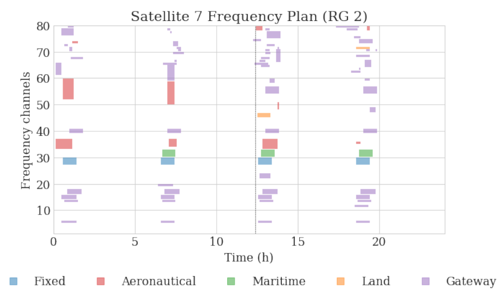
Figure A-1: Frequency assignments for a reduced scenario and no uncertainty (Satellites (1-4).




(a)




(b)




(c)

Figure A-2: Frequency assignments for a reduced scenario and no uncertainty (Satellites 5-7).

# Appendix B

# Strategies

**Reactive strategies** based on reserving resources and a higher degree of real-time control:

**A: Reserved bandwidth** $n_A \cdot b_{min,i}$ frequency channels are reserved adjacent to the ones used by each beam, thus $(n_A+1) \cdot b_{min,i} \leq b_i \leq b_{max,i} + n_A \cdot b_{min,i}$. Having adjacent reserved frequency at a per beam level lowers the risk of not being able to reallocate. Since the frequency channels are adjacent to the beam allocation, it does not increase the dimensionality of the problem. Only the case with $n_A = 1$ is tested.

**B: Reserved slots** $n_B \cdot b_{min,i}$ frequency channels are reserved in addition to the ones used by the beam, thus $n_B$ virtual assignments with $b_j = \cdot b_{min,i}$ are created. Breaking with the adjacency constraint further reduces the risk of not being able to reallocate at the expense of increasing the dimensionality of the problem. Only the case with $n_B = 1$ is tested.

**C: Reserved spectrum** $\lceil x_C \cdot N_{ch} \rceil$ frequency channels are reserved and left unallocated, thus $\lceil x_C \cdot N_{ch} \rceil \leq f_i$. The risk of not being able to provide service is reduced by having a reserved pool of spectrum resources that can be used in case an assignment violates a new constraint. The values $x_C = \{0.05, 0.10, 0.15\}$ are used.

**Proactive strategies** based on conservative constraint calculations and a robust allocation:

**D: Temporal buffer** The constraints are computed assuming that the departure time of aeronautical mobile users can be delayed up to $T_D$. Based on a statistical study of the flight delays, the values of the 50$^{\text{th}}$, 75$^{\text{th}}$, 95$^{\text{th}}$, and 99$^{\text{th}}$ percentiles are taken.

**E: Interference buffer** A smaller interference threshold $x_E \alpha_{min}$ is used to compute the interference constraints. Using a smaller interference threshold will result in capturing interference constraints that might arise from deviations in the position aeronautical mobile users. The values $x_E = \{1.15, 1.3, 1.45\}$ are used.

**Combinations** of different strategies:

**K1: Temp. buffer + Intrf. buffer** A combination of the values of $x_E$ and the 50$^{\text{th}}$, 75$^{\text{th}}$, and 95$^{\text{th}}$ delay percentile is used.

**L1: Temp. buffer + Intrf. buffer + Reserved spectrum** In this case, a combination of the values of $x_E$, the 50$^{\text{th}}$, 75$^{\text{th}}$, and 95$^{\text{th}}$ delay percentiles, and $x_C$ is used.

**Special cases** additional framework configurations

**G: No uncertainty** The frequency assignment is computed assuming that accurrate user information is known a priori and there is no uncertainty. This a theoretical and ideal case that is used as a reference, as there will be no unmet demand due to uncertainty.

**I: No strategy** The frequency assignment is computed using only the available information about the users and not using any additional uncertainty considerations.

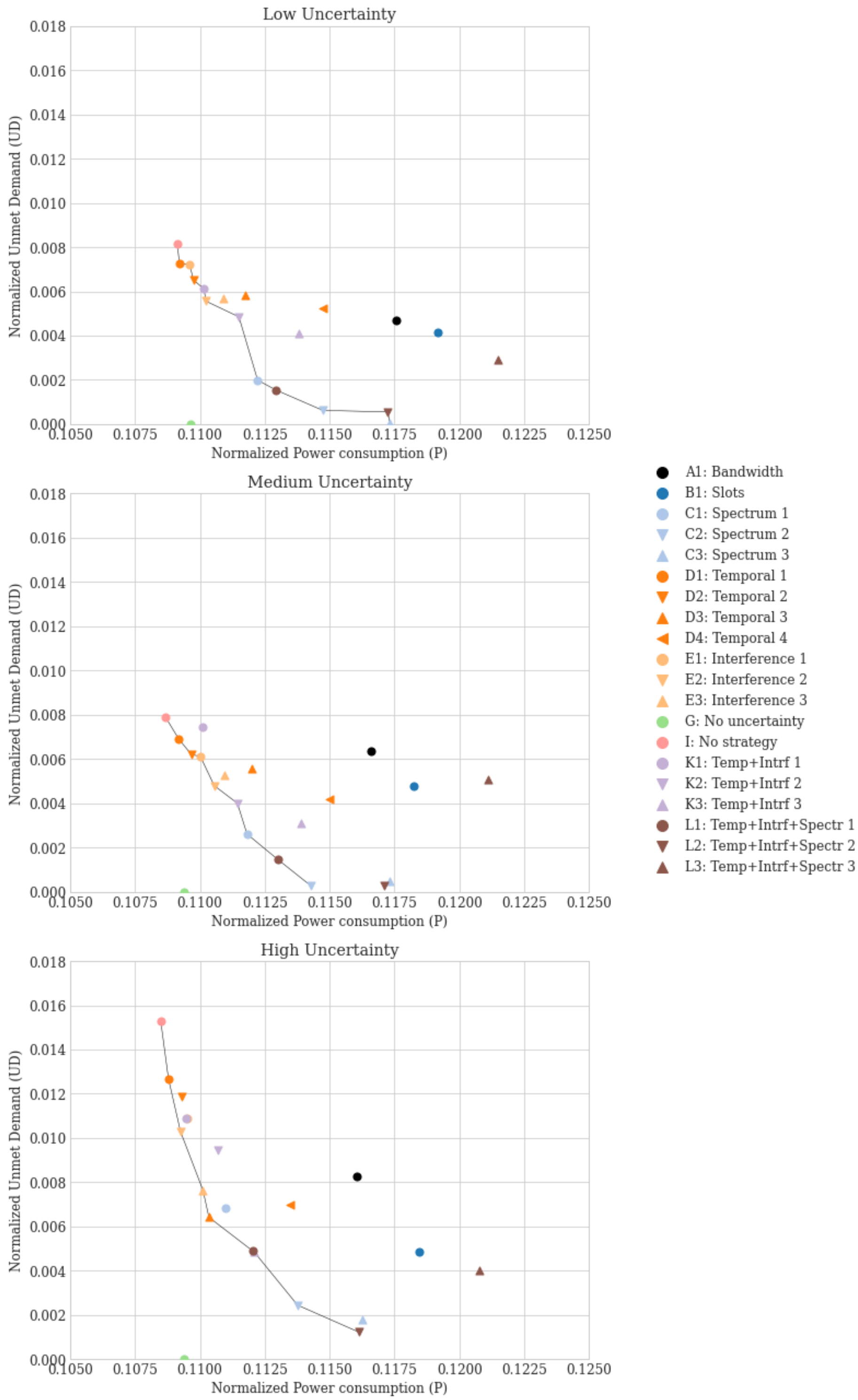



Figure B-1: Results of frequency assignment with uncertainty in low-dimensional scenarios, showing the normalized unmet demand and normalized power consumption for different strategies and uncertainty levels. The results are obtained from 20 Monte Carlo Simulation runs for each of the strategies and configurations, and for each level of trajectory deviations and delays of aeronautical mobile users.

| | Normalized Unmet Demand ($UD$) | | | Normalized Power Consumption ($P$) | | |
|---|---|---|---|---|---|---|
| Uncertainty | Low | Medium | High | Low | Medium | High |
| A1 | 0.005 (0.004) | 0.006 (0.007) | 0.008 (0.005) | 0.118 (0.011) | 0.117 (0.009) | 0.116 (0.009) |
| B1 | 0.004 (0.004) | 0.005 (0.004) | 0.005 (0.003) | 0.119 (0.011) | 0.118 (0.010) | 0.118 (0.010) |
| C1 | **0.002 (0.002)** | **0.003 (0.003)** | 0.007 (0.003) | **0.112 (0.009)** | **0.112 (0.008)** | 0.111 (0.008) |
| C2 | **0.001 (0.001)** | **0.000 (0.001)** | **0.002 (0.002)** | **0.115 (0.010)** | **0.114 (0.008)** | **0.114 (0.009)** |
| C3 | **0.000 (0.000)** | 0.000 (0.001) | 0.002 (0.007) | **0.117 (0.010)** | 0.117 (0.010) | 0.116 (0.009) |
| D1 | **0.007 (0.004)** | **0.007 (0.004)** | **0.013 (0.004)** | **0.109 (0.007)** | **0.109 (0.008)** | **0.109 (0.008)** |
| D2 | **0.007 (0.004)** | **0.006 (0.003)** | 0.012 (0.005) | **0.110 (0.008)** | **0.110 (0.008)** | 0.109 (0.007) |
| D3 | 0.006 (0.005) | 0.006 (0.004) | **0.006 (0.004)** | 0.112 (0.009) | 0.112 (0.009) | **0.110 (0.008)** |
| D4 | 0.005 (0.004) | 0.004 (0.004) | 0.007 (0.004) | 0.115 (0.009) | 0.115 (0.010) | 0.113 (0.009) |
| E1 | **0.007 (0.005)** | **0.006 (0.004)** | 0.011 (0.005) | **0.110 (0.008)** | **0.110 (0.008)** | 0.110 (0.008) |
| E2 | **0.006 (0.003)** | **0.005 (0.004)** | **0.010 (0.005)** | **0.110 (0.008)** | **0.111 (0.007)** | **0.109 (0.008)** |
| E3 | 0.006 (0.004) | 0.005 (0.003) | **0.008 (0.004)** | 0.111 (0.009) | 0.111 (0.008) | **0.110 (0.008)** |
| G | 0.000 (0.000) | 0.000 (0.000) | 0.000 (0.000) | 0.110 (0.008) | 0.109 (0.007) | 0.109 (0.008) |
| H | 0.053 (0.009) | 0.058 (0.010) | 0.079 (0.011) | 0.108 (0.008) | 0.107 (0.008) | 0.107 (0.007) |
| I | **0.008 (0.004)** | **0.008 (0.005)** | **0.015 (0.006)** | **0.109 (0.008)** | **0.109 (0.008)** | **0.108 (0.007)** |
| K1 | **0.006 (0.003)** | 0.007 (0.004) | 0.011 (0.004) | **0.110 (0.008)** | 0.110 (0.007) | 0.109 (0.008) |
| K2 | **0.005 (0.004)** | **0.004 (0.004)** | 0.009 (0.005) | **0.112 (0.009)** | **0.111 (0.008)** | 0.111 (0.008) |
| K3 | 0.004 (0.003) | 0.003 (0.003) | **0.005 (0.005)** | 0.114 (0.010) | 0.114 (0.009) | **0.112 (0.009)** |
| L1 | **0.002 (0.003)** | **0.001 (0.002)** | **0.005 (0.003)** | **0.113 (0.009)** | **0.113 (0.009)** | **0.112 (0.008)** |
| L2 | **0.001 (0.002)** | 0.000 (0.001) | **0.001 (0.003)** | **0.117 (0.011)** | 0.117 (0.010) | **0.116 (0.010)** |
| L3 | 0.003 (0.005) | 0.005 (0.010) | 0.004 (0.011) | 0.121 (0.012) | 0.121 (0.010) | 0.121 (0.010) |

Table B.1: Results of frequency assignment with uncertainty in low-dimensional scenarios, showing the normalized unmet demand and normalized power consumption for different strategies and uncertainty levels. The results are obtained from 20 Monte Carlo Simulation runs for each of the strategies and configurations, and for each level of trajectory deviations and delays of aeronautical mobile users. The values that appear in the pareto front are highlighted.

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