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A Comparative Study of the USA and EU Allocation Tables Using a Knowledge Graph Model

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Abstract

This paper presents the development of a knowledge graph-based tool that enables a comparative analysis of the radio frequency spectrum allocation tables of the United States and European countries, highlighting key differences and similarities in the management of radio frequency spectrum. Spectrum is a finite and valuable resource, critical for ensuring seamless communication and supporting technological innovation. Efficient management and periodic reorganization of spectrum are essential to accommodate the increasing demand from emerging technologies requiring large bandwidths.

The study leverages knowledge graphs to integrate diverse data sources, facilitating a unified view of spectrum allocation and utilization. By employing this approach, we provide insights into the structural differences, potential bandwidth, and common radio services between the US and the EU. Knowledge graphs offer significant advantages in this context, including the ability to seamlessly integrate and organize complex datasets from various sources, providing a structured and interconnected format. This approach enhances data accessibility and enables advanced analytics, supporting comprehensive and detailed analysis of spectrum management practices. The system developed in this study provides a robust tool for decision-makers to analyse different scenarios and their impacts on spectrum allocation and usage.

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1 Introduction

This thesis presents the creation of a knowledge graph-based tool that allows for a comparison of the radio frequency spectrum allocation tables between the US and European nations. It shows significant distinctions and parallels in the management of radio frequency spectrum. Spectrum is a "conceptual tool used to organize and map the physical phenomena of electromagnetic waves" according to the National Telecommunications and Information Administration [1]. The entire range of electromagnetic frequencies is included in the spectrum. A fraction of these frequencies is set aside for industry and service-related communications [2].

Efficient radio frequency spectrum management is essential for smooth communication and technological progress in a world where connections are growing. Spectrum management determine the types of services and technologies that are allowed to operate within a country, as well as the technical specifications and radiocommunication service allocations [3]. It must lessen interference and guarantee that radio spectrum is utilized as efficiently as feasible for the benefit of the broader public. A continuous radio frequency transmission is necessary for some services, such as life-saving ones like fire, rescue, law enforcement, and emergency medical services, even when little radio signal interference may not appear significant.

Because of new technologies, more applications are able to use a greater range of frequency bands, which suggests that there is a growing need for access to many spectrum segments. The radio spectrum is a limited resource that is rapidly running out, according to the US Department of Transportation [4]. The government is considering repurposing a number of radio frequencies in response to the need for commercial spectrum to support broadband wireless communications.

The spectrum is a sovereign resource, which means that the government or other national regulatory body of each country controls, manages, and grants the required permits for its use. In the United States, the Federal Communications Commission (FCC) controls the emission of non-federal, commercial radio signals, directing what can and cannot be broadcast. The National Telecommunications and Information Administration (NTIA) oversees the Federal government's use of spectrum. The national administrations of European countries, on the other hand, are in charge of managing the radio spectrum. Spectrum regulation is a collaborative effort among various commissioners and committees within the European Conference of Postal and Telecommunications Administrations (CEPT) at the European level. The Electronic Communications Committee (ECC), the European Commission (EC), and the European Telecommunications Standards Institute (ETSI) are these organizations.

The goal of this project is to analyze and understand the allocation and utilization of the radio frequency spectrum in the United States, with the joint work later extending to European countries. This thesis is a component of a larger, more intricate investigation that my EMSE colleague Carlos Yuste and I conducted together. It is a component of a study we did at the Illinois Institute of Technology for our master's in computer science under Associate Professor Cynthia Hood. The analysis presented here is a collaborative effort, particularly focusing on the comparative assessment of the US and EU frequency allocation tables. I first discuss the US frequency allocation table analysis procedure, and then we jointly compare the US and EU frequency allocation tables.

The main goal is to learn more about US spectrum management procedures by dissecting the allocation structure and behavior. I have integrated qualitative and quantitative information about spectrum measurements in order to achieve that. My goal in conducting this research is to make it easier for various stakeholders to obtain a high-level grasp of these measures without necessitating extensive knowledge of spectrum management.

At the moment, there isn't a single website platform that compiles this data from different nations into one easily accessible location. Rather, we find ourselves in a disjointed environment where data is dispersed across various sources, each subject to a convoluted legal structure. Using a graph model, we suggest connecting and unifying quantitative and qualitative data. The goal of this strategy is to provide stakeholders with an integrated view of the data so they can evaluate and comprehend the measurements' applicability more rapidly. In doing so, we want to offer insightful information about the spectrum allocation tables and management procedures in the US and EU, which will ultimately help with better informed spectrum management decision-making.

Due to their ability to integrate many data sources, knowledge graphs have been chosen as our unified system for studying and comparing spectrum frequency allocation tables from various nations and areas [5]. By arranging material into a structured and connected style, knowledge graphs promote understanding and explainability. We can simply add new frequency allocation tables at any time thanks to their scalability and extensibility.

In this thesis, a prototype spectrum knowledge graph with details on the US spectrum frequency allocation table and a comparison of the US and EU frequency allocation tables are described. Section 2 evaluates pertinent prior work, while Section 3 describes the complete prototype development process, from data search to model creation. The analysis of the data is presented in Section 4, and the conclusions drawn from the study are covered in Section 5. Section 6 concludes by outlining the findings and the goals for further research.

2 Related Work

2.1 Background

The importance of spectrum measurements in understanding and managing the radio frequency spectrum is well-documented. Spectrum measurements provide critical data necessary for analyzing current usage, identifying opportunities for spectrum sharing, and informing policy decisions. However, the complexity of spectrum data, which includes spatiotemporal datasets and contextual information, presents significant challenges. Hood et al. [6] discusses how these measurements are crucial for both policy and real-time spectrum management perspectives. They emphasize the need for comprehensive measurement campaigns and the integration of contextual information to fully understand spectrum usage.

Knowledge graphs have emerged as a powerful tool for organizing and analyzing complex datasets. Hood et al. presents a knowledge graph approach to spectrum explainability, which unifies relevant contextual information with spectrum measurement summaries. This prototype, implemented on the Neo4j graph data platform, integrates over four years of multiband measurement data with additional contextual information such as spectrum allocation, licensing, usage conventions, and events.

The paper by Das et al. [7] explores an advanced system architecture designed to support decision-making processes related to spectrum management. This architecture integrates measurement systems, data storage, and processing units to collect, analyze, and interpret spectrum data efficiently. By consolidating these components, the system facilitates the processing of complex spectrum measurements and makes the data readily available for decision-making

2.2 Knowledge Graphs

IBM describes knowledge graphs as a representation of a network of entities that illustrates the relationship between them [8]. Google made this term popular with the announcement of its knowledge graph in 2012 [9].

A Knowledge Graph is centered around a knowledge model that consists of interconnected descriptions of concepts, entities, relationships, and events. By incorporating semantic metadata and linking data, knowledge graphs contextualize information, enabling seamless integration, unified analytics, and data sharing across various sources and domains. This framework enhances understanding and facilitates advanced data-driven applications and insights.

The data structure integrates different characteristics from data management operations. They operate like databases by allowing structured queries for exploring data. They also function as graphs, enabling analysis where relationships between entities are pivotal. Additionally, they resemble knowledge bases due to their formal semantics, which aid in interpreting data and deriving new insights or facts through inference processes. This synthesis of capabilities supports sophisticated data exploration, integration, and semantic understanding across complex datasets.

3 Approach

Our method's objective is to extract, prepare, and arrange data on spectrum frequency allocation in order to build an extensive knowledge graph and database. This section describes our technique in three key sections: the architecture and structure of our knowledge graph and database; the methodologies and tools utilized for data extraction; and the data sources we have employed, which are credible sources from official governmental entities.

3.1 Institutions

3.1.1 NTIA

Within the US Department of Commerce, the National Telecommunications and Information Administration (NTIA) is an agency tasked with providing the President with advice on matters pertaining to information and communications policy. It is essential to controlling federal spectrum use, encouraging the growth of broadband, and maintaining US competitiveness in the international telecom industry. The NTIA is also in charge of several programs that improve communications for public safety and increase digital inclusion and literacy. The NTIA works closely with the Federal Communications Commission (FCC) to coordinate spectrum use between federal and non-federal users [10].

In terms of spectrum management, the NTIA guarantees the effective use of spectrum and the essential spectrum access for federal agencies to fulfill their tasks. To foster innovation and economic expansion, the NTIA also seeks to locate and reuse spectrum for commercial use. This entails holding spectrum auctions, establishing guidelines to stop interference, and promoting global collaboration on spectrum management.

Key responsibilities and activities are as follows [11]:

- The NTIA investigates the best ways to use spectrum and creates regulations to support it. This includes long-term planning to find options for spectrum sharing and to fulfill future needs for spectrum.
- The NTIA assigns frequency bands to federal agencies based on their operational requirements.
- The NTIA works with the FCC to ensure that federal and non-federal spectrum use is coordinated and that there is minimal interference between users. This is done in spectrum auctions and joint policy development.
- The NTIA represents US interests in international spectrum management forums, such as the International Telecommunication Union (ITU) **¡Error! No se encuentra el origen de la referencia.**. This ensures that US spectrum policies are aligned with global standards and that the U.S. can influence international spectrum allocation decisions.
- The NTIA provides technical expertise and support to federal agencies in the use of spectrum. This includes conducting interference analysis, developing spectrum sharing frameworks, and testing new technologies.

Figure 1 shows the US Frequency Allocation chart in 2016:

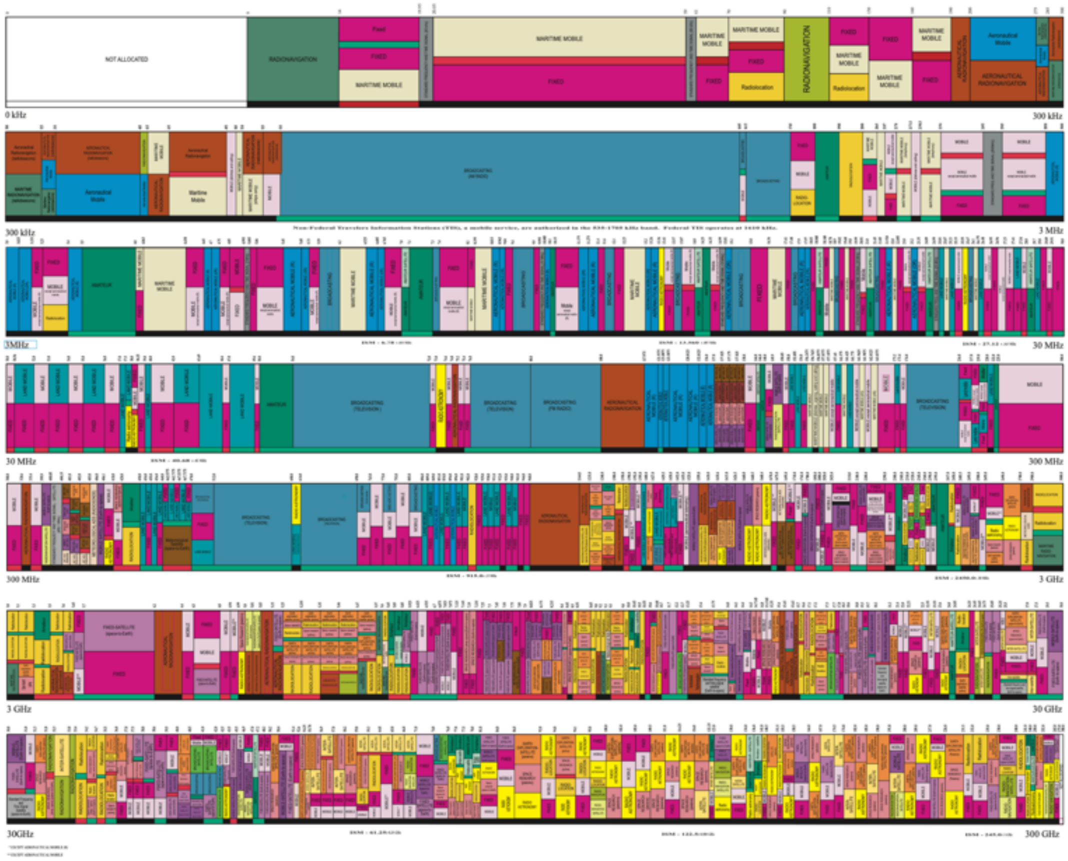


Figure 1. US Frequency Allocation chart [12].

3.2 Methodology

The Agile technique was used in the completion of the thesis. The development process of this methodology is progressive and iterative, with requirements changing as the project demands them to do so.

Agile organizes work into short intervals called sprints, which are usually two to three weeks long. For this project, the sprints were two weeks long, during which time various functions were produced. In addition to this, requirements analysis, high-level design creation, platform development, and testing were all carried out. Documentation was also prepared. The following Gantt chart shows the project timeline from January to July.

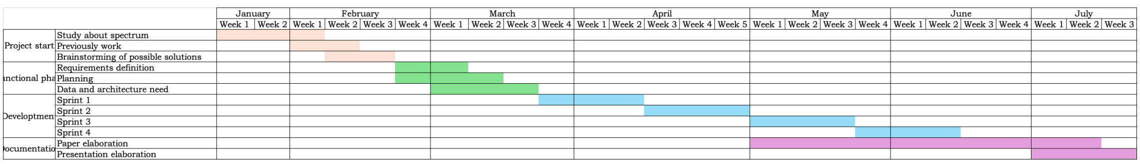


Figure 2. Gantt chart of the project.

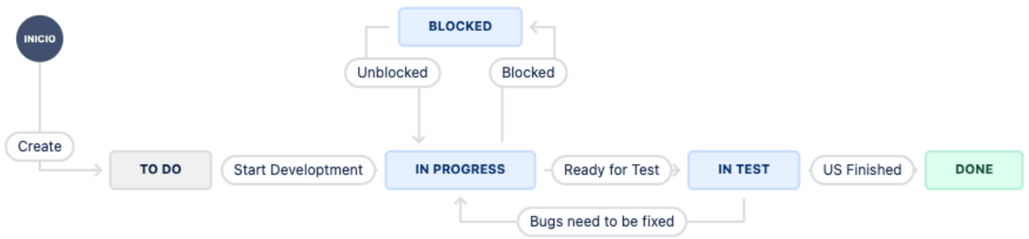
Jira Software has been the platform used to carry out this planning. It's an internet application that facilitates managing project tasks and keeping track of potential problems.

3.2.1 Jira

Planning for the project has been done within this application. User stories that have specific functionalities have been used to structure the organization.

Depending on its complexity, each user story is divided into one or more jobs. These assignments must give a thorough explanation of what has to be done. There might be subtasks or subsidiary tasks for some tasks. These subtasks are functions that are nested inside the main task, therefore developing the corresponding subtask is necessary to finish the main job.

Every task goes through several states of transition. Most states are sequential, as the flow diagram below illustrates, and going back to a prior state is not possible. The following states are included in this list: "To Do" denotes the status of an unfinished task. "In Progress" denotes the point at which the task starts to take shape. The job enters the "Blocked" state if a problem occurs during development that stops further work at that time. It is advised to write a comment explaining the transition if a task gets blocked. "In Test" indicates that testing is currently underway for the capability. Lastly, "Done" denotes the user story's final completion.



All of these activities were put to the backlog, and each sprint's tasks were assigned a priority based on the expected backlog. The total quantity of work that has to be done for the project is represented by the backlog. A job scheduled for a particular sprint might not get finished and will need to be carried over to the following one. In these situations, a note should be included outlining the reason the assignment was not completed on time as well as what still has to be done to finish it.

3.3 Requirements

This section outlines the key requirements for the system, categorized into business, user, and functional requirements. These requirements define the system's capabilities in facilitating spectrum frequency analysis, enabling data comparison between US and EU, and supporting the creation of knowledge graphs for informed decision-making. Additionally, the system will provide functionalities for users to query, save, and manage data efficiently, as well as generate customizable reports in multiple formats.

3.3.1 Business requirements

- BR1: The system shall allow telecommunication specialists to perform analysis in spectrum frequency allocation.
- BR2: The system shall allow telecommunication specialists to compare spectrum frequency allocation tables from US and EU.
- BR3: The system shall leverage knowledge graphs to integrate diverse spectrum allocation data sources from US and EU into a unified format.
- BR4: The system shall enable decision-makers to evaluate different spectrum management strategies and their impacts.

3.3.2 User requirements

- UR1: The system shall allow users to create, download and export (in csv and JSON) customize reports.
- UR2: The system shall allow users to query all information from interconnected datasets from various sources.
- UR3: The system shall allow users to save predefined queries.
- UR4: The system shall allow users to construct knowledge graphs from interconnected datasets from various sources.
- UR5: The system shall allow users to save predefined knowledge graphs.
- UR6: The system shall allow users to search and filter spectrum allocation data by frequency band, country, radio service, station class, or application.

3.3.3 Functional requirements

- FR1: The system shall be able to import and integrate spectrum allocation data from diverse sources, including the US and EU spectrum tables.
- FR2: The system must create and manage a knowledge graph that links spectrum allocation data across different countries and services.
- FR3: The system shall enable users to search and filter spectrum allocation data by frequency band, country, or service type.

3.4 User Stories

In this section, we outline the comprehensive user stories that are necessary to complete the project's needs. To help guarantee that the project satisfies expectations and goals, user stories offer a clear description of the features from the viewpoint of the end user. By developing these user stories, we hope to guide the development process and ensure that it is in accordance with user needs throughout the whole project lifecycle.

3.4.1 US1 – Download US

Download US spectrum allocation table xml from the official source NTIA and perform reverse engineer to transform the data into a csv file.

3.4.2 US3 – Preprocessing US allocations table

Preprocess the US allocation table to have the following attributes:

- Frequency Band
- Start Frequency in Hz
- Stop Frequency in Hz
- Radio Service
- Primary/Secondary
- Station Class Code
- Station Type
- Station Type 1
- Station Type 2

3.4.3 US4 – Preprocessing US radio service description table

Preprocess the US radio service description table:

- Radio Service
- Description

3.4.4 US5 – Preprocessing US station class

Preprocess the US station class description table:

- Station Class Code

- Description

3.4.5 US7 – Design and create the knowledge graph model in the platform Neo4j

Build the model to construct knowledge graphs.

These are the table attributes that constitute the nodes of the model for US.

- Frequency Band.
- Radio Service.
- Station Class Code.
- Station Type.

These are the table attributes that constitute the nodes of the model for EU.

- Frequency Band.
- Radio Service.
- Country.

Regarding the US relationships, the frequency band is linked to the radio service, which is linked to the station type, which is linked to the station class code. The radio services and frequency bands shared by US and EU models connect them.

3.4.6 US8 – Design queries in the platform Neo4j

Create and implement the queries that will be most helpful to the decision-makers.

4 Implementation

The technique and tools used for system development are described in this section. It offers information on the instruments utilized, how to download and prepare the data, how to construct the knowledge network, and which particular queries were used for the analysis.

4.1 Tools and Technologies

4.1.1 XML

The raw data, containing the information from the US frequency allocation table, was primarily stored in an XML file.

4.1.2 CSV

The final datasets, after downloading and preprocessing the data for US frequency allocation tables, were stored as csv files.

4.1.3 Python

Python was selected as the programming language for the entire data preprocessing process. For the US frequency allocation table, the only libraries used to reverse engineer the data from XML to CSV were csv and xml.etree.ElementTreeNeo4j.

4.1.4 Neo4j

Neo4j is a native graph database that facilitated the development of our system with its intuitive user interface. By connecting to Neo4j and creating an instance in their cloud, we were able to design our model from scratch. The process involved signing up into the Neo4j website, accessing the Cloud Console, and creating a new instance by choosing a region, and configuring security settings.

Neo4j's flexible schema allowed us to add new data and modify the model, properties, and relationships without the need to rebuild the database. After deciding on our model and importing all the data, we used Cypher, Neo4j's powerful query language, to retrieve any information from the graph database. The user interface displayed graphs and tables with detailed information, such as node names, properties, and relationships.

Additionally, Neo4j enabled us to take various measurements and perform analyses by adding conditions and rules to the data or limiting the information displayed. The ability to extend a node to explore more details or find the shortest path between two nodes to uncover relationships further enhanced our analysis capabilities. By incorporating semantic metadata and linking data, knowledge graphs provide context for each data point, enhancing the understanding of relationships and dependencies.

One of Neo4j's standout features is its ability to store query results for in-depth analysis or comparison with other results. This functionality was instrumental in helping us draw meaningful conclusions from our data analysis, such as identifying common radio services across regions or comparing bandwidth allocations.

4.2 Development

4.2.1 Data Download and Preprocessing

This section details the complete process of downloading and preprocessing the data from the sources described in Section 3.1.

The authoritative source for the US allocations is the NTIA Redbook [13] which is not publicly available in a machine-consumable form. Whereas previous work

[6] manually transcribed the allocations, we recently learned that there is a publicly available XML version of the allocation table dating from October 2020 as part of the Equipment Location – Certification Information Database (EL-CID) [14].

A major part of this project involved transforming the XML data into CSV files suitable for analysis. In this case, we chose to use a knowledge graph database to store the data and a knowledge graph model to establish relationships between the different tables. To achieve this, we have developed a python program that creates the data frames to construct the CSV file we have used for our analysis. As the final step, we merged all csv files in order to have one single table that contains all the information.

The XML contains three main elements: “Allocation Frequency”, “Radio Services”, and “Station Class Codes”. Due to its specific structure, we decided to split the file *export.xml* into three separate files, each corresponding to a different element.

To prepare the data for analysis in CSV format, we created a project in Visual Studio Code with three directories. Each directory contains specific programs designed to reverse engineer the XML data and convert it into a structured table.

The first file contained the “Allocation Frequency” element, which encompasses all frequency bands present in the table, assigning a unique index to each band. These bands represent the range of radio frequencies utilized for signal transmission, identified by their lower and upper limits [15]. The first table we created lists all distinct frequency allocation bands.

The “Radio Services” element lists all the radio services appearing in the table along with the frequency band index they belong to. The radio service specifies the type of service assigned to each frequency band, such as broadcasting, mobile communication, satellite communication, and navigation. It also includes a detailed description of each radio service [16].

Finally, the element “Station Class Codes” contains each Station Class Code, the frequency band index it appears in, and its description. These codes categorize different types of stations within each radio service. The type and purpose of the transmitter are described by the Station Class Code, which can aid in explaining the radio system. The search results will list a lot of frequencies more than once, with distinct Station Class Codes for each frequency.

After extracting the three main elements, we merged the data joining the tables by similar attributes. The first directory “Merged_Allocation_RadioService” merged every radioService with each corresponding allocation frequency band.

The second merging directory “Merged_RadioService_StationClass” associate radio services with their respecting station classes. From the second element, "Radio Services," we extracted the station class codes associated with each radio service, as well as the different station types where the radio service is transmitted and received. For example, if the station type is "Airborne," this indicates that the stations are located on airborne platforms. Each radio service is associated with two station types for a specific station class code. Additionally, there can be multiple combinations of the same station class with different station types for the same radio service.

The following figure shows the directory folder with all the python programs we have used to extract and clean the dataset from the XML. The code is available in the following repository: *https://gitlab.com/martacorrochano/spectrum.*

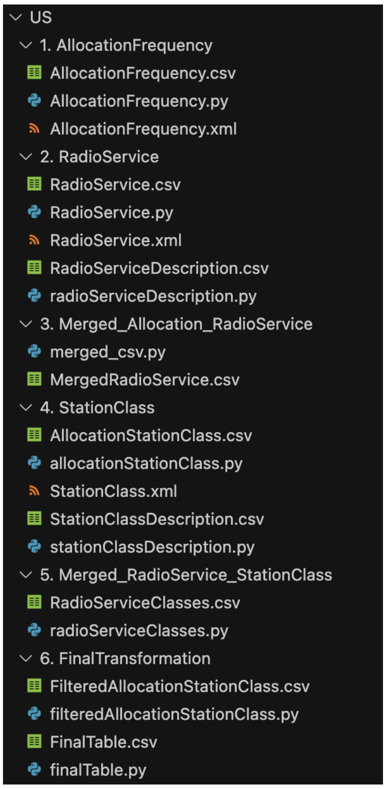


Figure 3. Project directory in Visual Studio Code.

Figure 3 shows the structure of the table resulting after downloading, preprocessing and cleaning the dataset. The table is structured in a way that each row represents a unique record. The column "FrequencyBand" indicates the range of frequencies covered, which in this table the entire range goes from 0 to 300 GHz expressed in Hz. The following two columns show the starting frequency and stopping frequency in Hertz for each band. The column "RadioService" identifies the type of the radio service, while the column "PrimarySecondary" specifies whether the radio service is primary or secondary in that frequency band. The column "StationClassCode" includes a code for the class of the station. Last three columns describe the station types. The table has a total of 59671 rows.

USATableFinal

FrequencyBand	startFrequencyHz	stopFrequencyHz	RadioService	PrimarySecondary	StationClassCode	StationType	StationType1	StationType2
9000-14000	9000	14000	Radiodetermination	Primary	AMA	Secondary Radar-Land_Radar-Air	Secondary Radar-Land	Radar-Air
9000-14000	9000	14000	Radiodetermination	Primary	AMA	Radar-Air_Secondary Radar-Land	Radar-Air	Secondary Radar-Land
9000-14000	9000	14000	Radiodetermination	Primary	AMA	Radar-Land_Secondary Radar-Land	Radar-Land	Secondary Radar-Land

Figure 4. Some rows of US Final Table csv file.

Additionally, we built two more CSV files. One containing a detailed description of each radio service and another one with the descriptions of each station class.

4.2.2 Knowledge Graph Database

To store our data, we decided to use a knowledge graph database. The following image represents a framework for transforming raw data into wisdom, following a multi-layered process: Data Acquisition, Information Extraction, Knowledge Computing, and Knowledge Reasoning, ultimately supporting decision-making and dynamic analysis. In our case the data acquisition layer consists of uploading the csv files to our database through Neo4j Aura's intuitive front end. Later, we decided our data model we will show later. The second and third layer was all done by the software. Finally, the top layer uses advanced analysis to derive actionable insights and visualization, which provides "wisdom" to support high-level decision-making. In our case we have used cypher language to write queries that help us analyzing the data and its intrinsic relationships.

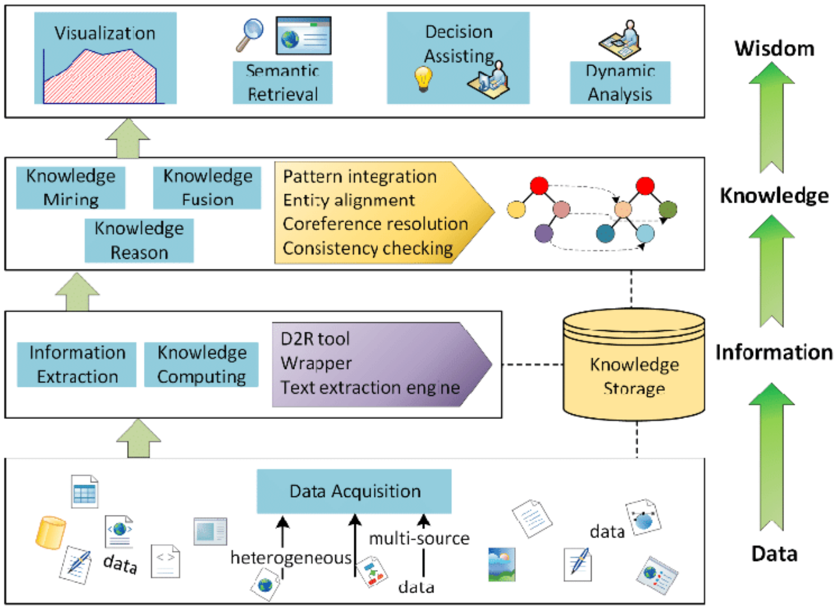


Figure 5. Knowledge Graph Diagram.

Neo4j Aura, as a managed cloud service, makes it easier to deploy, manage, and scale a knowledge graph database without handling infrastructure. This allows the project to focus on integrating data, extracting knowledge, and applying insights efficiently, making it well-suited for projects that need real-time insights or advanced analysis across complex, interconnected data.

4.2.3 Knowledge Graph Model

Ones we had built the database, we constructed the knowledge graph based it on a model specifically designed to represent the structure of the US frequency allocation table, which was later linked to the EU model for comparative analysis. This structured framework, developed in Neo4j, ensures consistency and coherence in how the frequency data is represented and how relationships between different spectrum management entities are maintained. Additionally, the model facilitates the integration of various resources by extracting data from multiple sources, allowing for a comprehensive and unified analysis.

The developed model is shown in Figure 6.

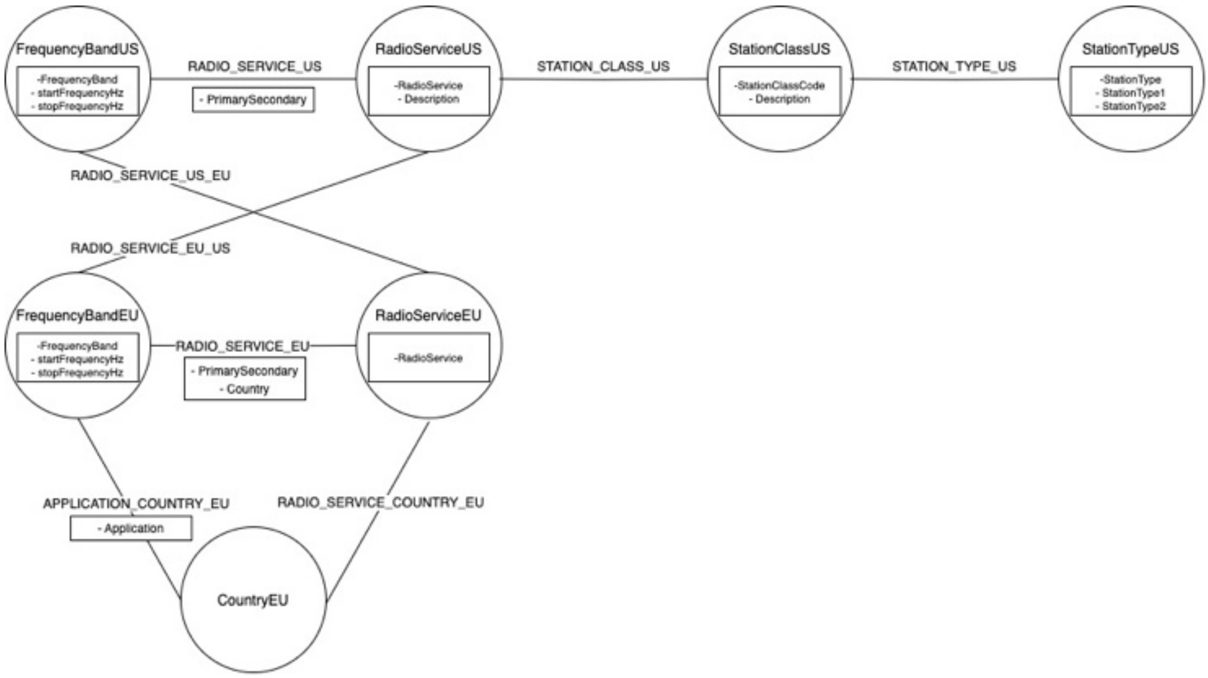


Figure 6. Model in Neo4j.

<u>Nodes</u>

We have a total of 7 types of nodes in the model. Figures 6-13 show detailed descriptions of each type of node along with the parameters.

Node	**FrequencyBandUS**
Description	Represents all frequency bands that are allocated to radio services in the US spectrum.
Parameters	- FrequencyBand: Interval indicating the range of the frequency, with the start and end separated by a hyphen. Unit: Hz - startFrequencyHz: indicates where band starts. - stopFrequencyHz: indicates where band ends.

Figure 7. Table of node Frequency Band for US.

Node	**RadioServiceUS**
Description	Represents all radio services that US spectrum has.
Parameters	- RadioService: is the name of the radio service. - Description: describes more detailed information of the radio service.

Figure 8. Table of node Radio Service for US.

Node	**StationClassUS**
Description	Represents station classes that a radio service has in US spectrum.
Parameters	- StationClassCode: represents the code (3 or 4 digits/letters) of the station class. - Description: describes detailed information of the station class.

Figure 9. Table of node Station Class for US.

Node	StationTypeUS
Description	Represents station type that a station class has in US spectrum.
Parameters	- StationType: represents both station types separated by a "-". - StationType1: is the first station type. - StationType2: is the second station type.

Figure 10. Table of node Station Type for US.

Node	FrequencyBandEU
Description	Represents all frequency bands that EU spectrum has including all the countries that belong to ECO.
Parameters	- FrequencyBand: Interval indicating the range of the frequency, with the start and end separated by a hyphen. Unit: Hz - startFrequencyHz: indicates where band starts. - stopFrequencyHz: indicates where band ends.

Figure 11. Table of node Frequency Band for EU.

Node	RadioServiceEU
Description	Represents all radio services that US spectrum has.
Parameters	- RadioService: is the name of the radio service.

Figure 12. Table of node Radio Service for EU.

Node	Country EU
Description	Represents one country from ECO.
Parameters	- N/A

Figure 13. Table of node Country for EU.

Relations

The model has a total of 8 types of relationships. A description of each type along with associated parameters is shown in figures 14-21.

Relationship	RADIO_SERVICE_US
Description	Represents the relationship between the frequency band and which radio service/s are inside that frequency band in US.
Parameters	- Primary/Secondary: represents if that radio service is primary or secondary

Figure 14. Table of relationship Frequency Band - Radio Service for US.

Relationship	STATION_CLASS_US
Description	Represents the relationship between the radio service and in which station class that radio service is.
Parameters	- N/A

Figure 15. Table of relationship Radio Service - Station Class for US.

Relationship	STATION_TYPE_US

Description	Represents the relationship between the station class and which types has that station class. It is possible for the same radio service with the same station class to have different station types.
Parameters	- N/A

Figure 16. Table of relationship Station Class - Station Type for US.

Relationship	**RADIO_SERVICE_US_EU**
Description	Represents the relationship between the frequency bands from the US and which radio services from Europe belong to those frequency bands.
Parameters	- N/A

Figure 17. Table of relationship Frequency Band US - Radio Service EU.

Relationship	**RADIO_SERVICE_EU_US**
Description	Represents the relationship between the frequency bands from the EU and which radio services from US belong to those frequency bands.
Parameters	- N/A

Figure 18. Table of relationship Frequency Band EU - Radio Service US.

Relationship	**RADIO_SERVICE_EU**
Description	Represents the relationship between the frequency band and which radio service/s are inside that frequency band.
Parameters	- Primary/Secondary: represents if that radio service is primary or secondary. - Country: represents the country in which the radio service is with a specific frequency band.

Figure 19. Table of relationship Frequency Band - Radio Service for EU.

Relationship	**APPLICATION_COUNTRY_EU**
Description	Represents the relationship between the frequency band and the country that uses it.
Parameters	- Application: what the radio service is used for.

Figure 20. Table of relationship Frequency Band - Country for EU.

Relationship	**RADIO_SERVICE_COUNTRY_EU**
Description	Represents the relationship between the country and the radio services that are in that country.
Parameters	- N/A

Figure 21. Table of relationship Country - Radio Service for EU.

4.2.4 Cypher Workbench Architecture

The following image shows the architecture and workflow of Neo4j cloud-based interface for managing databases, specifically with a focus on using model development, query building, and debugging. Neo4j queries are composed in the Cypher query language.

Neo4j Aura has a primary front end where users interact with the system. It allows them to build, collaborate, and share their data models and queries without needing to manage the database infrastructure. Then its data modeling tool allows users to create, import, or export data models, which define the structure of the knowledge graph, including nodes, relationships, and properties.

The Cypher component in the diagram serves as the core of the data operations, interacting with data models to define and manipulate the knowledge graph. While the Visual Cypher is a tool for building Cypher queries visually, making it easier for users who may not be familiar with Cypher syntax to create queries by using a graphical interface. Visual Cypher helps users explore the graph and structure queries intuitively.

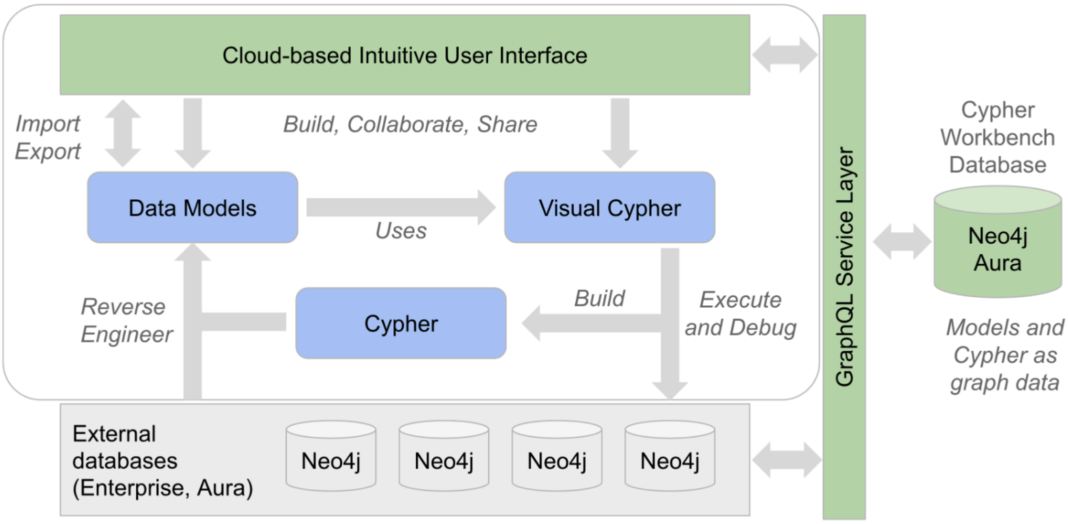


Figure 22. Cypher Workbench Architecture.

4.2.5 Queries

This section presents the results of a subset of queries we have created using Neo4j Aura Visual Cypher to showcase its functionality and efficiency.

1. Most used radio service in US:

```
MATCH (:FrequencyBandUS)-[r:RADIO_SERVICE_US]->(rsUS:RadioServiceUS) WITH rsUS,
COUNT(r) AS Count
ORDER BY Count DESC LIMIT 1
MATCH (fbUS:FrequencyBandUS)-[rs:RADIO_SERVICE_US]->(rsUS)
RETURN rsUS, fbUS, rs
```

This query first finds the most used radio service in the US (based on how many frequency bands are associated with each radio service), and then it retrieves all the frequency bands and the relationships between them and that radio service.

2. Frequency bands by radio service in US:

```
MATCH (fbUS:FrequencyBandUS)-[r:RADIO_SERVICE_US ]-
>(rsUS:RadioServiceUS{RadioServiceUS: $RS})
RETURN fbUS, r, rsUS
```

In this query, the parameter $RS represents the desired radio service for which we want to identify the frequency bands present in the US spectrum. We have also executed the same query for EU.

3. Common radio services between EU and US:

```
MATCH (:FrequencyBandEU)-[r:RADIO_SERVICE_EU_US]->(rs:RadioServiceUS) WITH rs, COUNT(r) AS Count
ORDER BY Count DESC WITH rs
RETURN rs.RadioService
```

This query returns the radio services that are shared by the US and the EU, taking into account all of the EU's allocation tables and only including those that show up in both regions' allocation tables. We have also calculated the most common used radio service in US and EU by:

```
MATCH (:FrequencyBandEU)-[r:RADIO_SERVICE_EU_US]->(rs:RadioServiceUS) WITH rs, COUNT(r) AS Count
ORDER BY Count DESC LIMIT 1
WITH rs
RETURN rs
```

Finally, we have also run a query that returns the radio services in the EU that are not in the US and vice versa by:

```
MATCH (:FrequencyBandEU)-[:RADIO_SERVICE_EU]->(rsEU:RadioServiceEU)
WHERE NOT EXISTS {
  MATCH (:FrequencyBandUS)-[r:RADIO_SERVICE_US]->(rsUS:RadioServiceUS) WHERE
  rsUS.RadioService = rsEU.RadioService}
RETURN DISTINCT rsEU.RadioService AS DifferentRadioServices
```

4. Frequency band in US with more radio services:

```
MATCH (fbUS:FrequencyBandUS)-[r:RADIO_SERVICE_US]->(:RadioServiceUS)
WITH fbUS, COUNT(r) AS Count
ORDER BY Count DESC LIMIT 1
MATCH(fbUS)-[rs:RADIO_SERVICE_US]->(rsUS:RadioServiceUS )
RETURN fbUS, rsUS, rs
```

This query returns the frequency band with more radio services in US, as well as the radio services and their relationships. We have also executed this query filtering by a specific frequency band.

5. Radio services with a specific station class in US:

```
MATCH(rsUS:RadioServiceUS)-[r:STATION_CLASS_US]-
>(scUS:StationClassUS{StationClassCode: $SC}) RETURN rsUS, scUS, r
```

This query returns all the radio services that are linked to a specific radio service. In this query, the parameter $SC represents the desired Station class for which we want to identify the radio services present in US spectrum.While the following query shows the 10 most used Station class in US.

```
MATCH (:RadioServiceUS)-[r:STATION_CLASS_US]->(scUS:StationClassUS)
```

```
WITH scUS, COUNT(r) AS Count
ORDER BY Count DESC LIMIT 10
MATCH (rsUS:RadioServiceUS)-[sc:STATION_CLASS_US]->(scUS)
RETURN rsUS, scUS, sc
```

4.2.6 Analysis

Several tables and graphs were shown as a result of these queries. For the graphs that are shown, Neo4j allows the node count to grow by choosing a relationship. This feature gave us access to all the details about the nodes and their relationships, including definitions and characteristics, and it also let us see which nodes were connected to one another.

These are some of the preliminary graphs and tables we displayed by executing the queries explained in the previous section.

1) The following graph shows the result of Query 1. The graph shows the most used radio service in the US according to the number of frequency bands is linked to. The radio service is "Maritime Mobile" and it is linked to 381 frequency bands.

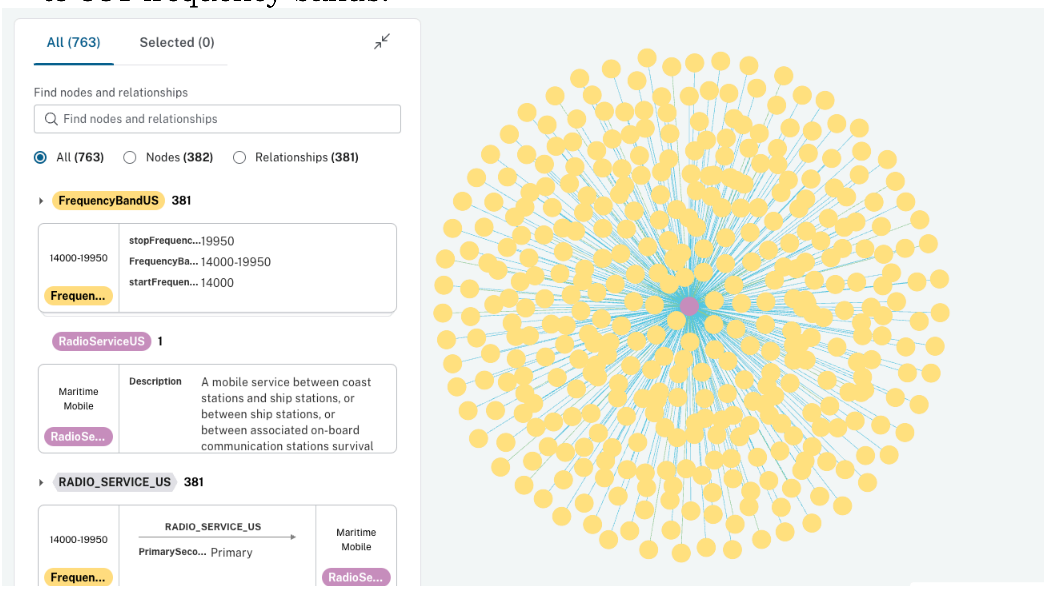


Figure 23. Most Used Radio Service in US.

The following table shows the results of a query using the US allocation table that displays the four radio services in the US with the most bandwidth. This query was calculated by adding the total bandwidth of a radio service.

country	RadioService	Bandwidth_Hz
US	Space Research (passive)	244,522,900,000
US	Earth Exploration-Satellite (passive)	228,705,000,000
US	Space Tracking	168,860,736,500
US	Land Mobile	146,467,778,500

Figure 24. Table with biggest bandwidth for US.

2) The following graph shows the result of Query 2. The graph displays all the frequency bands for a given radio service. In this example, the radio service shown is 'Space Research (passive).' The relationships marked in blue indicate that the radio service is primary in those frequency bands, while those in green indicate it is secondary.

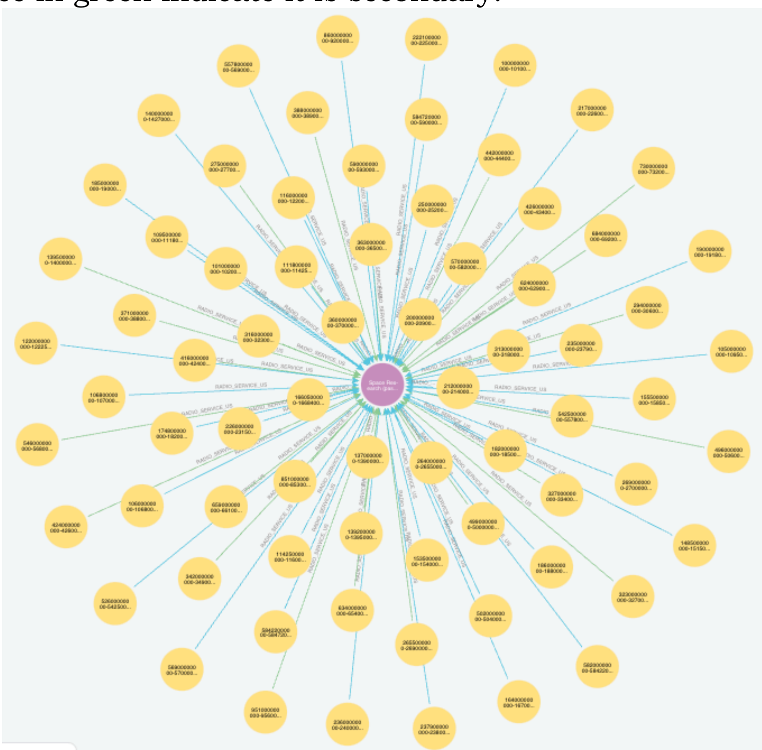


Figure 25. Frequency Bands for Space Research (passive) radio service in US.

3) The following table shows the results of Query 3. There are the radio services that are common to both the EU and the US.

RadioService
Aeronautical Mobile
Aeronautical Mobile (OR)
Aeronautical Mobile (R)
Aeronautical Mobile-Satellite
Aeronautical Radionavigation
Aeronautical Radionavigation-Satellite
Amateur
Broadcasting
Broadcasting-Satellite
Earth Exploration-Satellite
Earth Exploration-Satellite (active)
Earth Exploration-Satellite (passive)
Fixed
Fixed-Satellite
Inter-Satellite
Land Mobile

Figure 26. Table of common radio services between US and EU.

This table can be viewed as a disconnected graph:

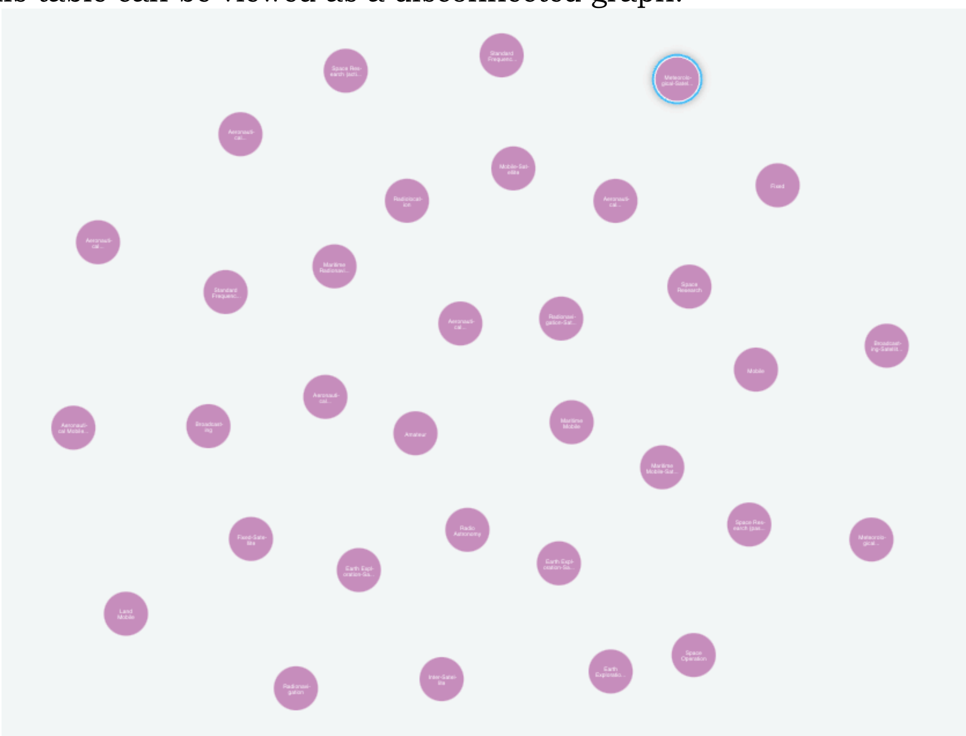


Figure 27. Disconnected graph of common radio services between US and EU.

Neo4j enables us to expand each node by picking it and deciding on the type of relationship we want to observe. For instance, we can observe that there are three relationships connected to the node "Radionavigation-Satellite" when we pick it. Radio service nodes are connected to frequency band nodes by the relationships 'RADIO_SERVICE_US' and 'RADIO_SERVICE_EU_US'. The first one is linked to every frequency band where it appears in the allocation tables of the EU member states, whereas the second one is linked to every frequency band where it appears in the US. We may also see the nodes with station class codes that are connected to this radio service.

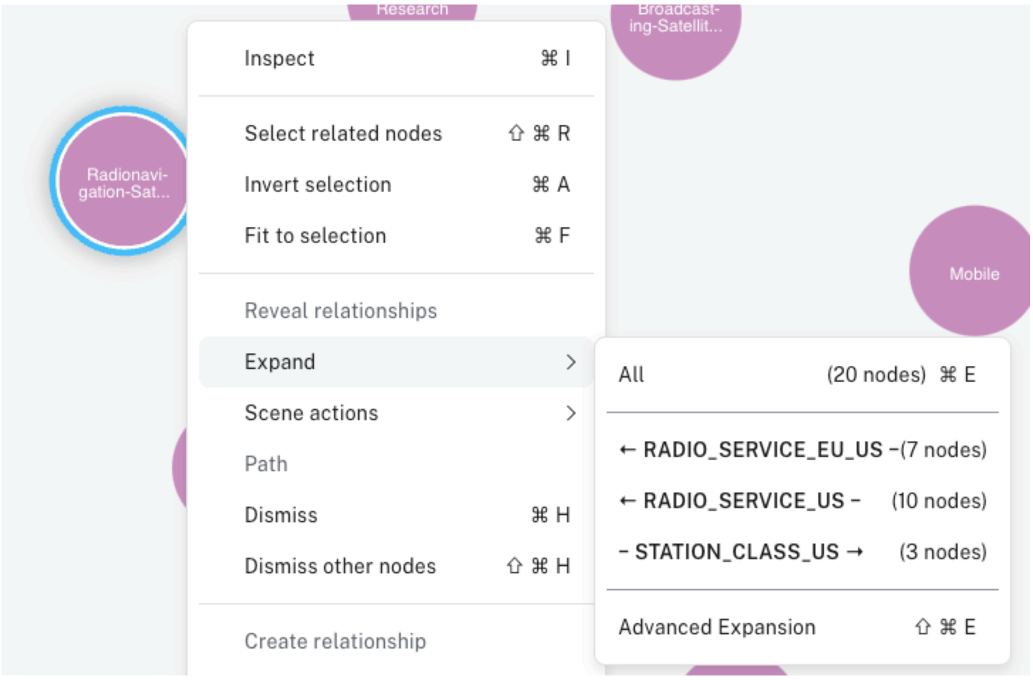


Figure 28. Expansion of Radionavigation-Satellite service options.

The following graph displays the frequency bands of EU countries in red and the frequency bands of US in yellow, for the radio service “Radionavigation-Satellite” given as an example.

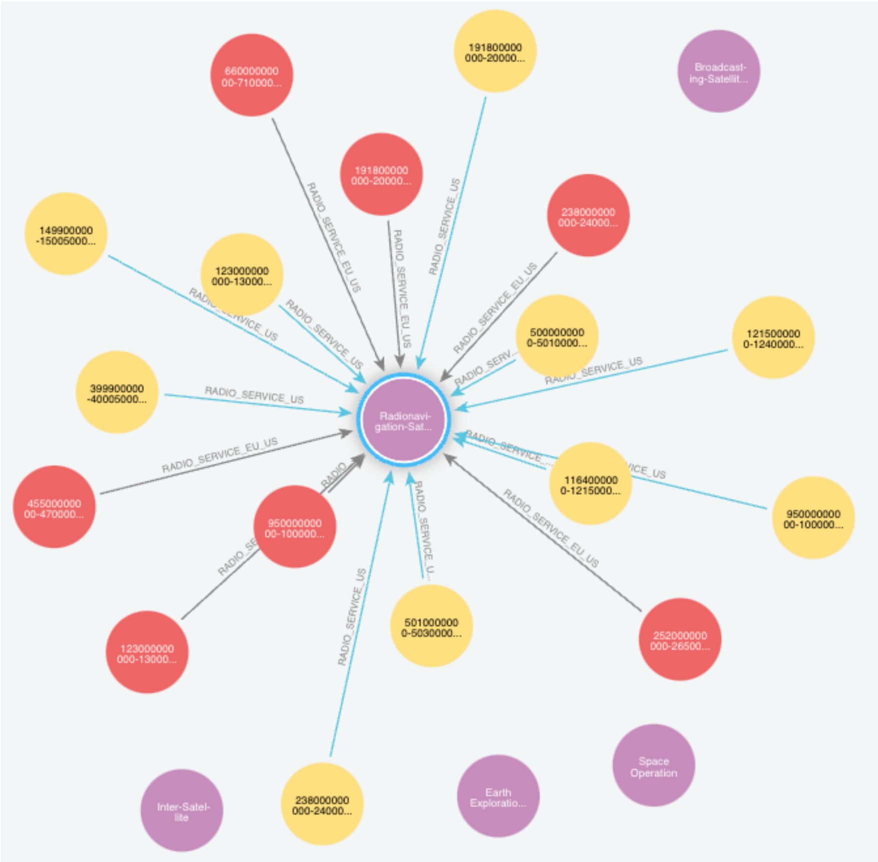


Figure 29. Frequency Bands from EU and US of Radionavigation-Satellite radio service expanded.

The following graph shows the most common used radio service in both the US and EU according to the number of frequency bands it is linked to. In the example we can see that this is "Fixed".

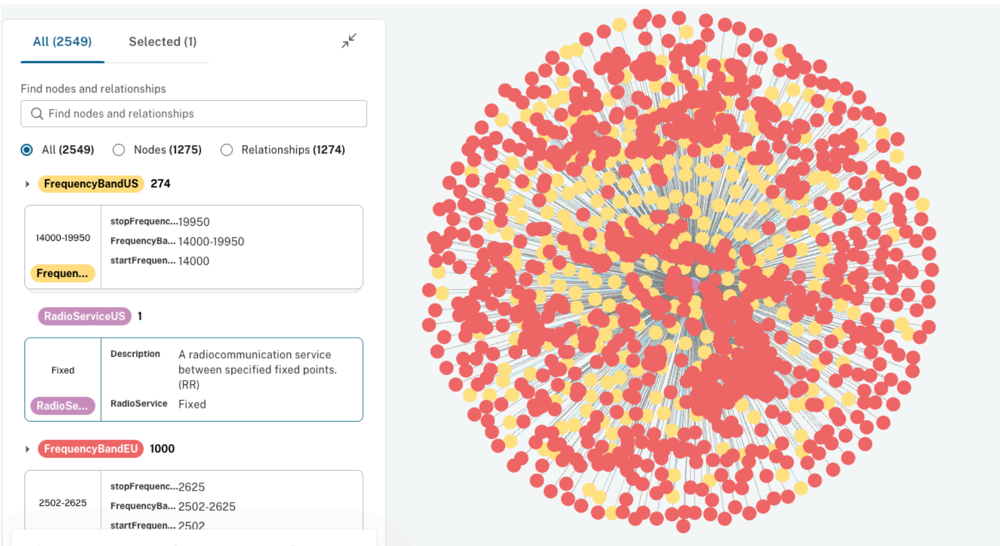


Figure 30. Most common used Radio Service in US and EU.

4) The following graph shows the result of Query 4. The image shows the frequency band with more radio services (16 in total) from US. It is possible to configure this query for the EU, too.

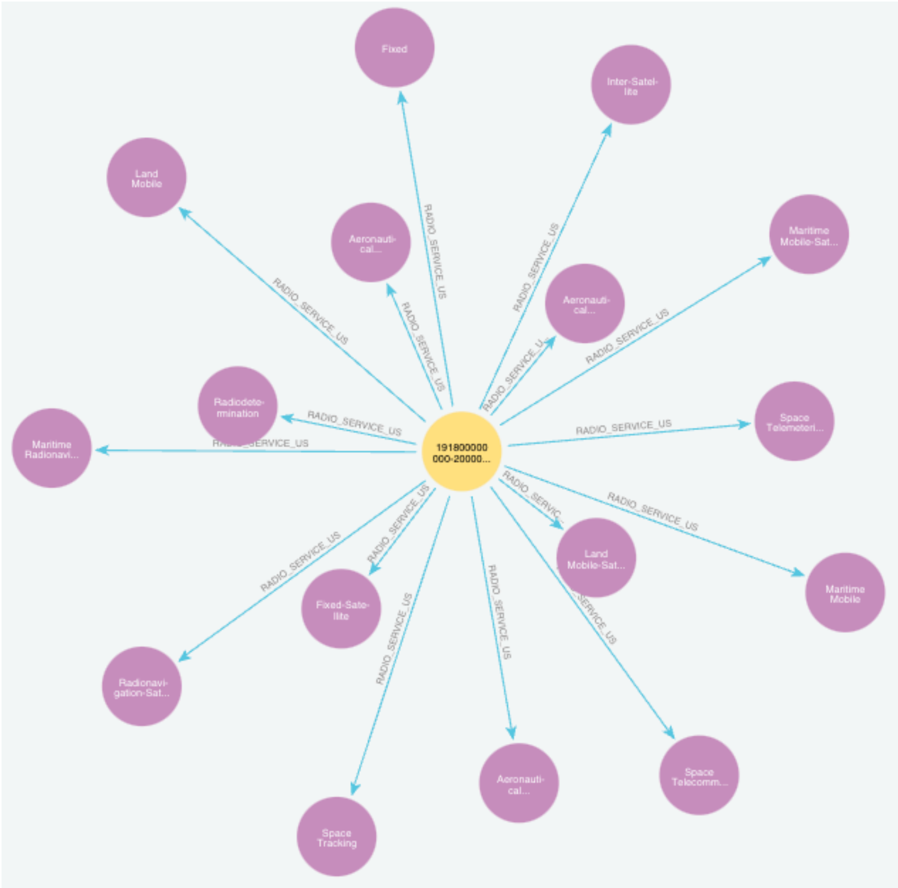


Figure 31. Graph of frequency band with more radio services.

In Neo4j, the bottom left corner also contains a legend where all nodes and relationships are displayed along with their respective attributes and properties.

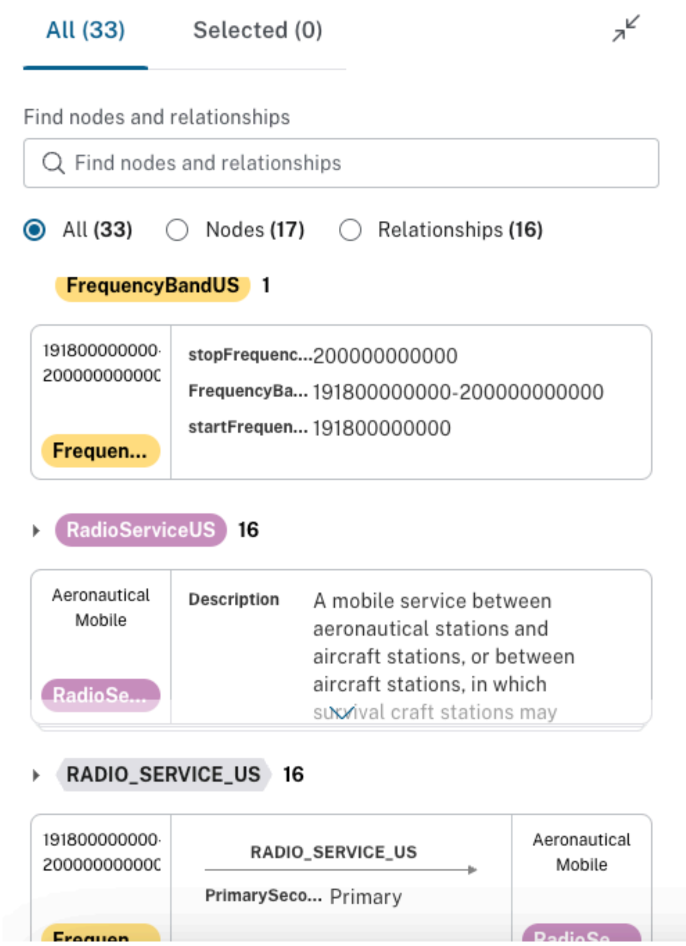


Figure 32. Neo4j legend browser of previous graph.

5) The following graph shows the result of executing Query 5. The image displays the radio service(s) that have a specific station class code given as a parameter. In this case, it is displayed for "Land Earth Station," which has the acronym VA.

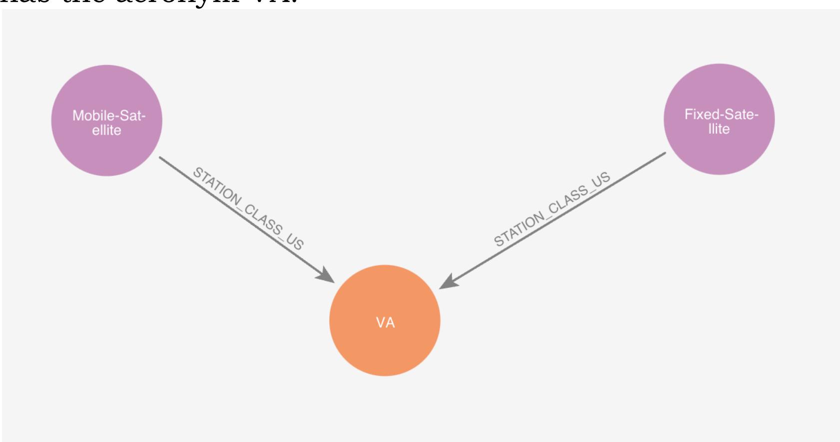


Figure 33. Graph with radio services with specific station class for US.

In this case, it is possible to expand the station class code node with the relationship “STATION_TYPE_US”, in order to know the station types that are used for that radio service with that station class code.

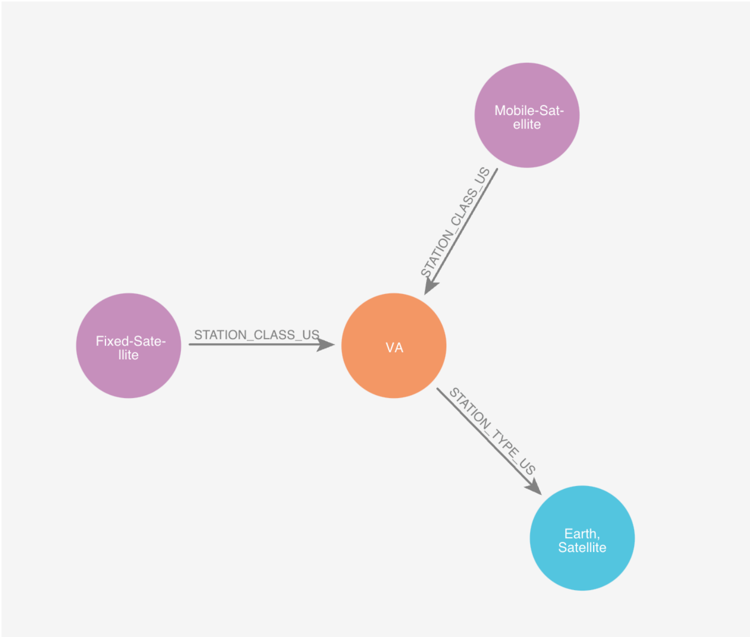


Figure 34. Graph with Station Type expanded of the previous graph.

This radio service (VA) can also be viewed with the frequency bands where it appears as shown in figure 32.

Figure 35. Frequency bands of one of the radio services with a specific station class.

The following graph shows the 10 most used station classes in the US and the radio services to which they are connected to.

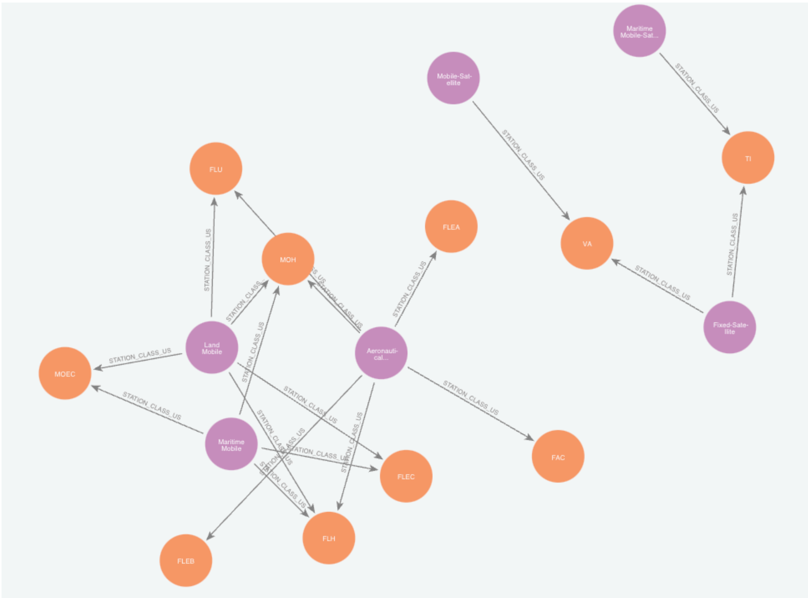


Figure 36. 10 most used radio services in the US.

5 Results

With a focus on three main metrics, we were able to obtain numerous important conclusions from our investigation. The identification of shared and distinct radio services between the US and EU, the structural distinctions between the US and EU frequency allocation tables, and the potential bandwidths for radio services are the three main metrics. We provide an in-depth knowledge of spectrum management techniques in the US and the EU by covering these aspects. This method can be applied to future spectrum management that is more coordinated and efficient, in addition to providing clarity about spectrum usage today.

We can see notable distinctions between the US and EU frequency allocation tables thanks to the knowledge graph. According to this thesis, the US table, which is overseen by the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA), emphasizes coordination between federal and non-federal uses to ensure that the spectrum is effectively used by the public and private sectors. The table also tends to focus on a wide range of services. The dynamic frequency allocation made possible by this dual management system supports a wide range of services, such as emergency, commercial, and military communications.

Regarding bandwidth utilization, the knowledge graph provides a clear view of how different radio services are allocated bandwidth in each region. In the US, significant bandwidth is allocated to services like space research and exploration, reflecting the country's investment in these areas. For example, the "Space Research (passive)" service has a substantial allocation, underscoring the importance of satellite and space-related communications. The US largest allocation is for "Space Research (passive)," with 244,522,900,000 Hz (approximately 244.5 GHz).

In general, the knowledge graph system illustrates the strategic and structural distinctions in spectrum management between the US and the EU, offering insights into the radio frequency allocation and prioritization practices of each region.

There are several radio services that are shared by the US and the EU, indicating some level of global cooperation and standardization. Among these radio programs are:

- Aeronautical Mobile-Satellite: Long-distance communications between aircraft and ground stations as well as among aircraft, particularly in isolated places and over oceans, are its main applications.
- Aeronautical Radionavigation: This service offers navigation signals to aid in the positional and safe navigation of aircraft.
- Earth Exploration-Satellite (active and passive): Its uses include scientific research, mapping, meteorology, and environmental monitoring. While passive sensors measure the natural radiation that the Earth emits, active sensors emit signals and measure the reflectio.
- Radionavigation-Satellite: This service provides satellite navigation signals, essential for global navigation, such as Global Positioning System (GPS).
- Radiolocation: Used to radar for military and civilian applications, air traffic control, and surveillance and detection systems.

Our study not only provides the data, but it also makes decision-making easier. To improve spectrum management tactics, decision-makers might examine various scenarios and their effects on spectrum consumption and distribution. Although spectrum is a finite resource, reorganization evaluation can make use of this instrument. With the emergence of new technologies that demand high bandwidths, this tool makes it possible to restructure the spectrum by identifying overlaps and unused bands.

Finally, I would like to mention that during the course of this research project, a scientific paper was written and published in collaboration with Professor Cynthia Hood from the Illinois Institute of Technology. The paper is titled *A Comparative Study of the USA and EU Allocation Tables Using a Knowledge Graph Model* and was authored by Marta Corrochano, Carlos Yuste and Cynthia Hood [17].

I would also like to highlight that the tool we used to store and manage our database, Neo4j, no longer allows us to access the instance we had created in the cloud. As a result, to recreate the knowledge graph, we would need to create a new instance in the tool, insert the data, rebuild the model, and rerun the queries.

6 Conclusions and Future Work

This study describes the development of a knowledge graph-based tool that enables a comparative analysis of the frequency spectrum allocation tables between the United States and the European Union, highlighting key differences and similarities in spectrum management practices. By leveraging a knowledge graph system, we were able to integrate diverse data sources and provide a unified view of spectrum allocation and utilization. This approach facilitated a deeper understanding of the structural differences, bandwidth utilization, and common radio services between the two regions.

Our analysis revealed significant structural differences between the US and EU frequency allocation tables. The US table, managed by the National Telecommunications and Information Administration (NTIA) and the Federal Communications Commission (FCC), focuses on a broad range of services and emphasizes coordination between federal and non-federal uses. In contrast, the EU's allocation, coordinated by the European Communications Office (ECO) under CEPT, involves detailed cooperation among numerous countries, emphasizing harmonization across member states.

Building on the insights gained from this study, future work will focus on several key areas to further enhance spectrum management practices:

- Incorporate additional data sources, including real-time spectrum measurements and usage patterns, to provide a more comprehensive and dynamic view of spectrum allocation and utilization.
- Develop more sophisticated queries in order to improve and broaden the analysis.
- Enhance coordination with international regulatory bodies such as the ITU to ensure that spectrum management practices are aligned with global standards and to facilitate cross-border spectrum sharing and collaboration.

By addressing these areas, we aim to continue advancing the field of spectrum management, leveraging the power of knowledge graphs to support more informed decision-making and foster innovation in wireless communications.

7 Bibliografía

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Appendix

The following pages present a paper titled *A Comparative Study of the USA and EU Allocation Tables Using a Knowledge Graph Model* written by Professor Hood, from Illinois Institute of Technology, Carlos Yuste, my EMSE colleague and myself.

Marta Corrochano Garrido (A20553760) | Carlos Yuste Señorans (A20553699)

A Comparative Study of the USA and EU Allocation Tables Using a Knowledge Graph Model

Corrochano. Marta (*mcorrochanogarrido@hawk.iit.edu)*, Yuste. Carlos (*cyustesenornas@hawk.iit.edu)*, and Hood. Cynthia (*hood@iit.edu)*

Abstract—**This paper presents the development of a knowledge graph-based tool that enables a comparative analysis of the radio frequency spectrum allocation tables of the United States and European countries, highlighting key differences and similarities in the management of radio frequency spectrum. Spectrum is a finite and valuable resource, critical for ensuring seamless communication and supporting technological innovation. Efficient management and periodic reorganization of spectrum are essential to accommodate the increasing demand from emerging technologies requiring large bandwidths.**

The study leverages knowledge graphs to integrate diverse data sources, facilitating a unified view of spectrum allocation and utilization. By employing this approach, we provide insights into the structural differences, potential bandwidth, and common radio services between the US and the EU. Knowledge graphs offer significant advantages in this context, including the ability to seamlessly integrate and organize complex datasets from various sources, providing a structured and interconnected format. This approach enhances data accessibility and enables advanced analytics, supporting comprehensive and detailed analysis of spectrum management practices. The system developed in this study provides a robust tool for decision-makers to analyze different scenarios and their impacts on spectrum allocation and usage.

I. INTRODUCTION

THIS paper presents the development of a knowledge graph-based tool that enables a comparative analysis of the radio frequency spectrum allocation tables between the United States and European countries, highlighting key differences and similarities in the management of radio frequency spectrum. The National Telecommunications and Information Administration defines spectrum as "conceptual tool used to organize and map the physical phenomena of electromagnetic waves" [1]. The spectrum encompasses the full range of electromagnetic frequencies. A portion of these frequencies is allocated for communications across various services and industries [2].

In an increasingly interconnected word, the efficient management of the radio frequency spectrum is vital for seamless communication and technological innovation. Spectrum management establishes the technical requirements, the allocations of radiocommunication services, and the kinds of services and technology that are permitted to function within a nation [3]. It must reduce interference and make sure radio spectrum is used as effectively as possible for the general public's advantage. While minimal radio signal interference may not seem important, an uninterrupted radio frequency transmission is essential to some services such as live-saving services including fire, rescue, law enforcement and emergency medical services.

Thanks to new technologies, more applications can utilize a wider range of frequency bands which implies that the demand for access to numerous spectrum segments is increasing. The US Department of Transportation affirms that the radio spectrum is a finite resource that is running out quickly [4]. Repurposing of several radio frequencies is being considered by the government due to the demand for commercial spectrum to facilitate broadband wireless communications.

The spectrum is a sovereign asset, meaning that each country's government or designated national regulatory authority oversees its use, managing it and issuing the necessary licenses. In the US, The National Telecommunications and Information Administration (NTIA) manages the Federal government's use of spectrum, while the Federal Communications Commission (FCC) regulates the emission of non-Federal, private radio signals, dictating what is allowed and what it not. On the other hand, in Europe the radio spectrum at the national level in managed by National Administrations. At the European level, different commissions and committees belonging to the European Conference of Postal and Telecommunications Administrations (CEPT) cooperate on the regulation of spectrum. These are European Commission (EC), European telecommunications Standards Institute (ETSI) and the Electronic Communications Committee (ECC).

The purpose of this project is to analyze and understand the allocation and utilization of the radio frequency spectrum across the US and EU countries. By analyzing the structure of spectrum allocation and the behavior of countries in each region, we aim to gain insights into their spectrum management practices. To do that we need to combine quantitative data regarding spectrum measurements with qualitative data. With this analysis we aim to enable a high-level understanding of these measurements to be more easily accessed by a range of stakeholders without necessitating a deep expertise of spectrum management.

Currently, there is no single web platform that consolidates this data from various countries into one accessible source. Instead, we encounter a fragmented landscape where information is scattered across different sources, each governed by its own complex regulatory framework. We propose to unify and connect quantitative and qualitative information using a graph model. This approach aims to give stakeholders an integrated view of the data, helping them to quickly assess and understand the relevance of the measurements. By doing so, we hope to provide valuable insights into the spectrum allocation tables and management practices in the US and EU, ultimately contributing to more informed decision-making in the realm of spectrum management.

We have selected knowledge graphs as our unified system for analyzing and comparing spectrum frequency allocation tables from different countries and regions because they enable the integration of diverse data sources [5]. Knowledge graphs facilitate learning and explainability by organizing data into a structured and interconnected format. They are also scalable and extensible, allowing us to easily add more frequency allocation tables at any time.

The paper describes a prototype spectrum knowledge graph that includes information about spectrum frequency allocation tables from different countries and organizations including US, European Union and the International Telecommunication Union (ITU) from the United Nations. Section 2 reviews relevant previous work, while section 3 details the entire process of developing the prototype, from the data search to the model design. Section 4 presents the analysis conducted on the data, and section 5 discusses the results derived from the analysis. Finally, section 6 describes the conclusion, and the future work purposed.

II. Related work

A. *Background*

The importance of spectrum measurements in understanding and managing the radio frequency spectrum is well-documented. Spectrum measurements provide critical data necessary for analyzing current usage, identifying opportunities for spectrum sharing, and informing policy decisions. However, the complexity of spectrum data, which includes spatiotemporal datasets and contextual information, presents significant challenges. Hood et al. [6] discusses how these measurements are crucial for both policy and real-time spectrum management perspectives. They emphasize the need for comprehensive measurement campaigns and the integration of contextual information to fully understand spectrum usage.

Knowledge graphs have emerged as a powerful tool for organizing and analyzing complex datasets. Hood et al. presents a knowledge graph approach to spectrum explainability, which unifies relevant contextual information with spectrum measurement summaries. This prototype, implemented on the Neo4j graph data platform, integrates over four years of multiband measurement data with additional contextual information such as spectrum allocation, licensing, usage conventions, and events.

The paper by Das et al. [7] explores an advanced system architecture designed to support decision-making processes related to spectrum management. This architecture integrates measurement systems, data storage, and processing units to collect, analyze, and interpret spectrum data efficiently. By consolidating these components, the system facilitates the processing of complex spectrum measurements and makes the data readily available for decision-making.

B. *Knowledge Graphs*

IBM describes knowledge graphs as a representation of a network of entities that illustrates the relationship between them [8]. Google made this term popular with the announcement of its knowledge graph in 2012 [9].

A Knowledge Graph is centered around a knowledge model that consists of interconnected descriptions of concepts, entities, relationships, and events. By incorporating semantic metadata and linking data, knowledge graphs contextualize information, enabling seamless integration, unified analytics, and data sharing across various sources and domains. This framework enhances understanding and facilitates advanced data-driven applications and insights.

The data structure integrates different characteristics from data management operations. They operate like databases by allowing structured queries for exploring data. They also function as graphs, enabling analysis where relationships between entities are pivotal. Additionally, they resemble knowledge bases due to their formal semantics, which aid in interpreting data and deriving new insights or facts through inference processes. This synthesis of capabilities supports sophisticated data exploration, integration, and semantic understanding across complex datasets.

III. approach

The goal of our approach is to extract, preprocess and organize spectrum frequency allocation data to create a comprehensive knowledge graph and database. This section outlines our methodology, divided into three main parts: the data sources we have used, which are authoritative sources from official governmental institutions, the methods and tools used for data extraction and the design and structure of our knowledge graph and database.

A. *Institutions*

NTIA

Within the US Department of Commerce, the National Telecommunications and Information Administration (NTIA) is an agency tasked with providing the President with advice on matters pertaining to information and communications policy. It is essential to controlling federal spectrum use, encouraging the growth of broadband, and maintaining US competitiveness in the international telecom industry. The NTIA is also in charge of several programs that improve communications for public safety and increase digital inclusion and literacy. The NTIA works closely with the Federal Communications Commission (FCC) to coordinate spectrum use between federal and non-federal users [10].

In terms of spectrum management, the NTIA guarantees the effective use of spectrum and the essential spectrum access for federal agencies to fulfill their tasks. To foster innovation and economic expansion, the NTIA also seeks to locate and reuse spectrum for commercial use. This entails holding spectrum auctions, establishing guidelines to stop interference, and promoting global collaboration on spectrum management.

Key responsibilities and activities are as follows [11]:

- The NTIA investigates the best ways to use spectrum and creates regulations to support it. This includes long-term planning to find options for spectrum sharing and to fulfill future needs for spectrum.

- The NTIA assigns frequency bands to federal agencies based on their operational requirements.
- The NTIA works with the FCC to ensure that federal and non-federal spectrum use is coordinated and that there is minimal interference between users. This is done in spectrum auctions and joint policy development.
- The NTIA represents US interests in international spectrum management forums, such as the International Telecommunication Union (ITU) ITU (Global). This ensures that US spectrum policies are aligned with global standards and that the U.S. can influence international spectrum allocation decisions.
- The NTIA provides technical expertise and support to federal agencies in the use of spectrum. This includes conducting interference analysis, developing spectrum sharing frameworks, and testing new technologies.

Figure 1 shows the US Frequency Allocation chart in 2016:

Figure 1. US Frequency Allocation chart [12].

ECO (EU)

The European Communications Office (ECO) is the permanent office of the European Conference of Postal and Telecommunications Administrations (CEPT). CEPT is formed by 46 countries of Europe (to see all countries you can click here [13]). ECO provides administrative and technical support to CEPT, helping to coordinate telecommunications and postal policies across Europe with a focus on spectrum management and regulatory harmonization. ECO plays a crucial role in spectrum management, ensuring the efficient and coordinated use of radio frequency spectrum across Europe. It also assists in aligning telecommunications regulations among member countries to promote consistent policies and standards. ECO is also represented in international telecommunications forums and participates actively in ITU (Global). CEPT works in close collaboration with the ITU to ensure that European spectrum management practices align with global standards.

ECO maintains a close relationship with the European Commission, working together to develop policies and regulations that align with the broader goals of the European Union (EU). This include providing input on legislative proposals and regulatory frameworks, particularly those related to spectrum management and telecommunications [14]. Figure 2 illustrates the European regulatory environment.

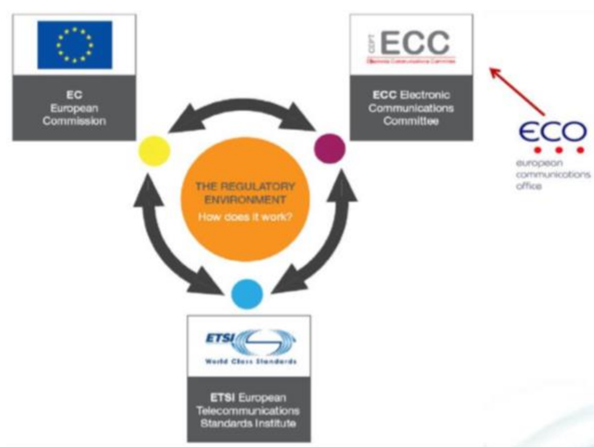


Figure 2. European regulatory environment for radio equipment and spectrum [14].

Figure 3 shows a part of the European Common Allocation (ECA) Table, as the ECA has a frequency range from 8.3 kHz to 3000 GHz.

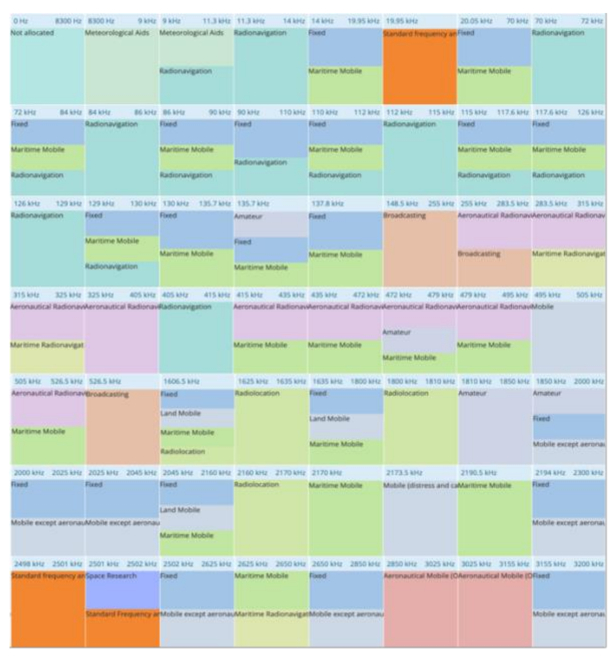


Figure 3. ECA Frequency Allocation chart [15].

ITU (Global)

The ITU (International Telecommunication Union) [16] is a specialized agency of the United Nations responsible for issues related to information and communication technologies. 193 countries belong to this organization, including the US, the ECA countries and other very important countries such as Canada, China, Japan, Australia, Brazil and South Africa (to see all countries you can click here [17]).

ITU has 5 areas of action:

- Standardization (ITU-T) responsible for developing technical standards that ensure global interoperability and efficiency of telecommunications networks and services.
- Radiocommunications (ITU-R): ITU-R manages the use of the radio spectrum and satellite orbits worldwide to avoid interference between different radio services. It also facilitates common radio services between different regions such as USA and ECO (EU).
- Development (ITU-D): ITU-D works to improve telecommunication infrastructures in developing countries, promoting digital inclusion and facilitating access to ICTs.
- Events and Conferences: ITU organizes various international conferences and events.
- Technical Assistance: ITU provides technical assistance and support to member countries in implementing telecommunication technologies and formulating national policies.

B. Data

Download and preprocessing US allocations

The authoritative source for the US allocations is the NTIA Redbook [18] which is not publicly available in a machine-consumable form. Whereas previous work [6] manually transcribed the allocations, we recently learned that there is a publicly available XML version of the allocation table dating from October 2020 as part of the Equipment Location – Certification Information Database (EL-CID) [19].

The XML contains three main elements: "Allocation Frequency", "Radio Services", and "Station Class Codes". The "Allocation Frequency" element encompasses all frequency bands present in the table, assigning a unique index to each band. These bands represent the range of radio frequencies utilized for signal transmission, identified by their lower and upper limits [20].

The "Radio Services" element lists all the radio services appearing in the table along with the frequency band index they belong to. The radio service specifies the type of service assigned to each frequency band, such as broadcasting, mobile communication, satellite communication, and navigation. It also includes a detailed description of each radio service [21].

Finally, the element "Station Class Codes" contains each Station Class Code, the frequency band index it appears in, and its description. These codes categorize different types of stations within each radio service. The type and purpose of the transmitter are described by the Station Class Code, which can aid in explaining the radio system. The search results will list a lot of frequencies more than once, with distinct Station Class Codes for each frequency.

From the second element, "Radio Services," we can also extract the station class codes associated with each radio service, as well as the different station types where the radio service is transmitted and received. For example, if the station type is "Airborne," this indicates that the stations are located on airborne platforms. Each radio service is associated with two station types for a specific station class code. Additionally, there can be multiple combinations of the same station class with different station types for the same radio service.

After reviewing the XML, we used reverse engineering to extract the relevant information and transform it into different desirable CSV files. To achieve this, we have developed a python program that creates the data frames to construct the CSV file we have used for our analysis. As the final step, we merged all csv files in order to have one single table that contains all the information.

Figure 4 shows the structure of the table resulting after downloading, preprocessing and cleaning the dataset. The table is structured in a way that each row represents a unique record. The column "FrequencyBand" indicates the range of frequencies covered, which in this table the entire range goes from 0 to 300 GHz expressed in Hz. The following two columns show the starting frequency and stopping frequency in Hertz for each band. The column "RadioService" identifies the type of the radio service, while the column "PrimarySecondary" specifies whether the radio service is primary or secondary in that frequency band. The column "StationClassCode" includes a code for the class of the station. Last three columns describe the station types. The table has a total of 59671 rows.

USATableFinal

FrequencyBand	startFrequencyHz	stopFrequencyHz	RadioService	PrimarySecondary	StationClassCode	StationType	StationType1	StationType2
9000-14000	9000	14000	Radiodetermination	Primary	AMA	Secondary Radar-Land_Radar-Air	Secondary Radar-Land	Radar-Air
9000-14000	9000	14000	Radiodetermination	Primary	AMA	Radar-Air_Secondary Radar-Land	Radar-Air	Secondary Radar-Land
9000-14000	9000	14000	Radiodetermination	Primary	AMA	Radar-Land_Secondary Radar-Land	Radar-Land	Secondary Radar-Land

Figure 4. Some rows of US Final Table csv file

Additionally, we built two more CSV files. One containing a detailed description of each radio service and another one with the descriptions of each station class

Download and preprocessing EU

To download EU spectrum data, we extracted it from the ECO official source. The data on the website is divided into two tables. Additionally, since ECO provides data from the ITU, we decided to include it in our dataset [22].

In the first table, the elements related to radio services are listed. The attributes that we needed to extract are frequency band, the radio services and if the service is primary or secondary. This data has been extracted with an API request filling all the necessary headers and parameters. We have developed a list of countries to make an API request for each country to gather the information of all countries belonging to ECO including the data related to ITU. The response of the request is an html script [23].

In the second table, the elements related to applications are listed. The attributes that we needed to extract are frequency band and the application. This data has been extracted also with an API request filling all the necessary headers and parameters. The response of the request is an html script, too [24].

After saving the response from the request, we extracted the relevant elements for our dataset. We performed data preprocessing to ensure that the final EU table adhered to the same format as the US table, facilitating a more accurate comparison. In both datasets, we standardized the frequency bands to have all data in the same units (Hz).

The first dataset contains "FrequencyBand", "startFrequencyHz", "stopFrequencyHz", "Country", "RadioService" and "PrimarySecondary". The second dataset contains also "FrequecnyBand", "startFrequencyHz", "stopFrequencyHz", "Country" and "Application". Both datasets have been stored in CSV files.

Once we had two separate files, we merged them under the condition that they had to have the same frequency band and belong to the same country and radio service. Figure 5 shows a portion of the final dataset which has 7 and columns and 25628 rows.

EuropeFinalTable

FrequencyBand	startFrequencyHz	stopFrequencyHz	Country	RadioService	PrimarySecondary	Application
8300-9000	8300	9000	ECA	Meteorological Aids	Primary	Lightning detection systems
9000-11300	9000	11300	ECA	Meteorological Aids	Primary	Inductive applications, Active medical implants, Lightning detection systems
9000-11300	9000	11300	ECA	Radionavigation	Primary	Inductive applications, Active medical implants, Lightning detection systems
11300-14000	11300	14000	ECA	Radionavigation	Primary	Active medical implants, Inductive applications
14000-19950	14000	19950	ECA	Fixed	Primary	Maritime military systems, Active medical implants, Inductive applications, Land military systems
14000-19950	14000	19950	ECA	Maritime Mobile	Primary	Maritime military systems, Active medical implants, Inductive applications, Land military systems
19950-20050	19950	20050	ECA	Standard frequency and time signal	Primary	Active medical implants, Inductive applications

Figure 5. Some rows of EU Final Table csv file

C. Model

To construct a knowledge graph, we need to base it on a model. This is essential because the model provides a structured framework that ensures consistency and coherence in how data is represented and how relationships within the graph are maintained. Additionally, it facilitates the integration of various resources by extracting data from different files.

The developed model is shown in Figure 6.

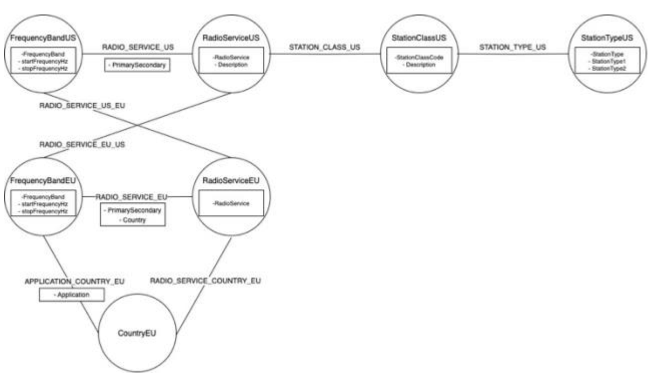


Figure 6. Model in Neo4j.

Nodes

We have a total of 7 types of nodes in the model. Figures 6-13 show detailed descriptions of each type of node along with the parameters.

Node	FrequencyBandUS
Description	Represents all frequency bands that are allocated to radio services in the US spectrum.
Parameters	- FrequencyBand: Interval indicating the range of the frequency, with the start and end separated by a hyphen. Unit: Hz - startFrequencyHz: indicates where band starts. - stopFrequencyHz: indicates where band ends.

Figure 7. Table of node Frequency Band for US.

Node	RadioServiceUS
Description	Represents all radio services that US spectrum has.
Parameters	- RadioService: is the name of the radio service. - Description: describes more detailed information of the radio service.

Figure 8. Table of node Radio Service for US.

Node	StationClassUS
Description	Represents station classes that a radio service has in US spectrum.
Parameters	- StationClassCode: represents the code (3 or 4 digits/letters) of the station class. - Description: describes detailed information of the station class.

Figure 9. Table of node Station Class for US.

Node	StationTypeUS
Description	Represents station type that a station class has in US spectrum.
Parameters	- StationType: represents both station types separated by a "-". - StationType1: is the first station type. - StationType2: is the second station type.

Figure 10. Table of node Station Type for US.

Node	FrequencyBandEU
Description	Represents all frequency bands that EU spectrum has including all the countries that belong to ECO.
Parameters	- FrequencyBand: Interval indicating the range of the frequency, with the start and end separated by a hyphen. Unit: Hz - startFrequencyHz: indicates where band starts. - stopFrequencyHz: indicates where band ends.

Figure 11. Table of node Frequency Band for EU.

Node	RadioServiceEU
Description	Represents all radio services that US spectrum has.
Parameters	- RadioService: is the name of the radio service.

Figure 12. Table of node Radio Service for EU.

Node	Country EU
Description	Represents one country from ECO.
Parameters	- N/A

Figure 13. Table of node Country for EU.

Relations

The model has a total of 8 types of relationships. A description of each type along with associated parameters is shown in figures 14-21.

Relationship	RADIO_SERVICE_US
Description	Represents the relationship between the frequency band and which radio service/s are inside that frequency band in US.
Parameters	- Primary/Secondary: represents if that radio service is primary or secondary

Figure 14. Table of relationship Frequency Band - Radio Service for US.

Relationship	STATION_CLASS_US
Description	Represents the relationship between the radio service and in which station class that radio service is.
Parameters	- N/A

Figure 15. Table of relationship Radio Service - Station Class for US.

Relationship	STATION_TYPE_US
Description	Represents the relationship between the station class and which types has that station class. It is possible for the same radio service with the same station class to have different station types.
Parameters	- N/A

Figure 16. Table of relationship Station Class - Station Type for US.

Relationship	RADIO_SERVICE_US_EU
Description	Represents the relationship between the frequency bands from the US and which radio services from Europe belong to those frequency bands.
Parameters	- N/A

Figure 17. Table of relationship Frequency Band US - Radio Service EU.

Relationship	RADIO_SERVICE_EU_US
Description	Represents the relationship between the frequency bands from the EU and which radio services from US belong to those frequency bands.
Parameters	- N/A

Figure 18. Table of relationship Frequency Band EU - Radio Service US.

Relationship	RADIO_SERVICE_EU
Description	Represents the relationship between the frequency band and which radio service/s are inside that frequency band.
Parameters	- Primary/Secondary: represents if that radio service is primary or secondary. - Country: represents the country in which the radio service is with a specific frequency band.

Figure 19. Table of relationship Frequency Band - Radio Service for EU.

Relationship	APPLICATION_COUNTRY_EU
Description	Represents the relationship between the frequency band and the country that uses it.
Parameters	- Application: what the radio service is used for.

Figure 20. Table of relationship Frequency Band - Country for EU.

Relationship	RADIO_SERVICE_COUNTRY_EU
Description	Represents the relationship between the country and the radio services that are in that country.
Parameters	- N/A

Figure 21. Table of relationship Country - Radio Service for EU.

IV. Implementation

A. Neo4j

Neo4j is a native graph database that facilitated the development of our system with its intuitive user interface. By connecting to Neo4j and creating an instance in their cloud, we were able to design our model from scratch. The process involved signing up into the Neo4j website, accessing the Cloud Console, and creating a new instance by choosing a region, and configuring security settings.

Neo4j's flexible schema allowed us to add new data and modify the model, properties, and relationships without the need to rebuild the database. After deciding on our model and importing all the data, we used Cypher, Neo4j's powerful query language, to retrieve any information from the graph database. The user interface displayed graphs and tables with detailed information, such as node names, properties, and relationships.

Additionally, Neo4j enabled us to take various measurements and perform analyses by adding conditions and rules to the data or limiting the information displayed. The ability to extend a node to explore more details or find the shortest path between two nodes to uncover relationships further enhanced our analysis capabilities. By incorporating semantic metadata and linking data, knowledge graphs provide context for each data point, enhancing the understanding of relationships and dependencies.

One of Neo4j's standout features is its ability to store query results for in-depth analysis or comparison with other results. This functionality was instrumental in helping us draw meaningful conclusions from our data analysis, such as identifying common radio services across regions or comparing bandwidth allocations.

B. Queries

We present the results of a subset of queries on the Neo4j to showcase its functionality and efficiency. Neo4j queries are composed in the Cypher query language.

1. Radio service’s bandwidths per country:

```
MATCH (fbEU:FrequencyBandEU)-
[r:RADIO_SERVICE_EU] >(rsEU:RadioServiceEU)
WHERE r.Country <> 'Azerbaijan' AND r.Country
<> 'Monaco' AND r.Country <> 'San Marino' AND
```

```
r.Country <> 'Ukraine' AND r.Country <>
'Vatican'
WITH rsEU, r.Country AS country,
fbEU.startFrequencyHz AS start,
fbEU.stopFrequencyHz AS stop
WITH rsEU, country, stop - start AS
difference
WITH country, rsEU, collect(difference) AS
differences
RETURN country, rsEU.RadioService AS
Radioservice, reduce(total = 0, diff IN
differences | total + diff) AS bandwidth
ORDER BY Radioservice, bandwidth DESC
```

This query returns a table with the radio services and their bandwidths in each country. We executed two different queries, one for the countries in EU and one for US. We have also executed a query that allows us filtering by a radio service that returns the countries in which the radio service is used and its bandwidth. We have excluded some countries from the query as there is not any information about radio services operating in those areas. These countries are Azerbaijan, Monaco, San Marino, Ukraine and Vatican.

2. Frequency bands by radio service in US:

```
MATCH (fbUS:FrequencyBandUS)-
[r:RADIO_SERVICE_US ]-
>(rsUS:RadioServiceUS{RadioServiceUS: $RS})
RETURN fbUS, r, rsUS
```

In this query, the parameter `$RS` represents the desired radio service for which we want to identify the frequency bands present in the US spectrum. We have also executed the same query for EU.

3. Common radio services between EU and US:

```
MATCH (:FrequencyBandEU)-
[r:RADIO_SERVICE_EU_US]->(rs:RadioServiceUS)
WITH rs, COUNT(r) AS Count
ORDER BY Count DESC WITH rs
RETURN rs.RadioService
```

This query returns the radio services that are common to both the EU and the US. It includes only those radio services that appear in the allocation tables of both regions. It considers all the allocation tables of EU.
We have also executed a query that returns the radio services in EU that are not in US and vice versa by:

```
MATCH (:FrequencyBandEU)-[:RADIO_SERVICE_EU]-
>(rsEU:RadioServiceEU)
WHERE NOT EXISTS {
  MATCH (:FrequencyBandUS)-
  [r:RADIO_SERVICE_US]->(rsUS:RadioServiceUS)
  WHERE rsUS.RadioService =
  rsEU.RadioService}
RETURN DISTINCT rsEU.RadioService AS
DifferentRadioServices
```

4. Frequency band in US with more radio services:

```
MATCH (fbUS:FrequencyBandUS)-
[r:RADIO_SERVICE_US]->(:RadioServiceUS)
WITH fbUS, COUNT(r) AS Count
ORDER BY Count DESC LIMIT 1
MATCH(fbUS)-[rs:RADIO_SERVICE_US]-
>(rsUS:RadioServiceUS )
RETURN fbUS, rsUS, rs
```

This query returns the frequency band with more radio services in US, as well as the radio services and their relationships. We executed the same query for EU. We have also executed this query filtering by a specific frequency band.

5. Radio services with station class in US:

```
MATCH (rsUS:RadioServiceUS)-
[r:STATION_CLASS_US]-
>(scUS:StationClassUS{StationClassCode: $SC})
RETURN rsUS, scUS, r
```

In this query, the parameter `$SC` represents the desired Station class for which we want to identify the radio services present in US spectrum.

C. Analysis

As a result of these queries, different graphs and tables were displayed. These figures allowed us to conduct an in-depth analysis of the results. In the case of the displayed graphs, Neo4j enables the expansion of nodes by selecting a relationship. This feature allowed us to see which nodes were connected to each other and provided all the information about the nodes and relationships, such as definitions and properties.

These are some of the preliminary graphs and tables we displayed by executing the queries explained in the previous section.

1) The following table shows a sample of the results of Query 1. This example displays 10 different radio services used in some EU countries and ECA allocation tables. It is sorted by the sum of the bandwidth of all the frequency bands in which the radio service appears.

country	Radioservice	bandwidth_Hz
United Kingdom	Amateur	300,23,566,957,100
Germany	Amateur	2,725,190,150,000
ECA	Radio Astronomy	143,976,950,000
Türkiye	Amateur	128,592,745,000
United Kingdom	Fixed	128,007,552,300
ECA	Mobile	110,241,165,000
Denmark	Earth Exploration-Satellite (active)	91,000,000,000
ECA	Space Research (passive)	86,119,900,000
United Kingdom	Earth Exploration-Satellite (passive)	73,512,000,000
Türkiye	Earth Exploration-Satellite	58,575,000,000

Figure 22. Table with biggest bandwidth for EU.

The following table shows the results of the same query using the US allocation table. The example displays the four radio services in the US with the most bandwidth.

country	RadioService	Bandwidth_Hz
US	Space Research (passive)	244,522,900,000
US	Earth Exploration-Satellite (passive)	228,705,000,000
US	Space Tracking	168,860,736,500
US	Land Mobile	146,467,778,500

Figure 23. Table with biggest bandwidth for US.

The following table shows the results of the same query using EU countries allocation table filtering the radio service shorted by bandwidth. The example displays 7 different countries in which the radio service “Aeronautical Mobile” appears and their bandwidth.

country	Radioservice	Bandwidth_Hz
Switzerland	Aeronautical Mobile	2,000,100,000
Spain	Aeronautical Mobile	1,500,000,000
Czech Republic	Aeronautical Mobile	240,800,000
France	Aeronautical Mobile	240,000,000
Slovenia	Aeronautical Mobile	200,000,000
Ireland	Aeronautical Mobile	177,351,000
Slovakia	Aeronautical Mobile	153,100,000

Figure 24. Table with biggest bandwidth filtered by a radio service for EU.

2) The following graph shows the result of Query 2. The graph displays all the frequency bands for a given radio service. In this example, the radio service shown is 'Space Research (passive).' The relationships marked in blue indicate that the radio service is primary in those frequency bands, while those in green indicate it is secondary.

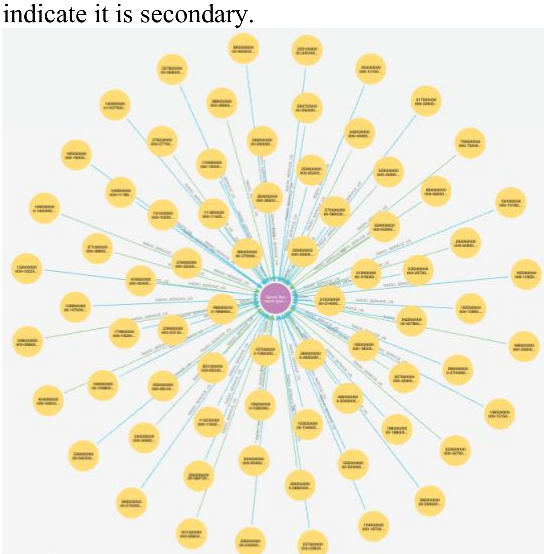


Figure 25. Frequency Bands for Space Research (passive) radio service in US.

3) The following table shows the results of Query 3. There are the radio services that are common to both the EU and the US.

RadioService
Aeronautical Mobile
Aeronautical Mobile (OR)
Aeronautical Mobile (R)
Aeronautical Mobile-Satellite
Aeronautical Radionavigation
Aeronautical Radionavigation-Satellite
Amateur
Broadcasting
Broadcasting-Satellite
Earth Exploration-Satellite
Earth Exploration-Satellite (active)
Earth Exploration-Satellite (passive)
Fixed
Fixed-Satellite
Inter-Satellite
Land Mobile

Figure 26. Table of common radio services between US and EU.

This table can be viewed as a disconnected graph:

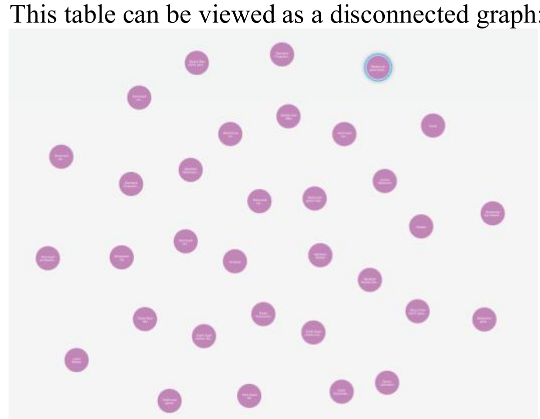


Figure 27. Disconnected graph of common radio services between US and EU.

Neo4j allows for the expansion of each node by selecting it and choosing the relationship we would like to see. For example, when we select the node 'Radionavigation-Satellite,' we can see that there are three relationships associated with this node. The relationships 'RADIO_SERVICE_EU_US' and 'RADIO_SERVICE_US' connect radio service nodes to frequency band nodes. The first one is connected to all the frequency bands in the EU countries' allocation tables where it appears, while the second one is connected to all the frequency bands in the US where it appears. Additionally, we can view the station class codes nodes to which this radio service is connected.

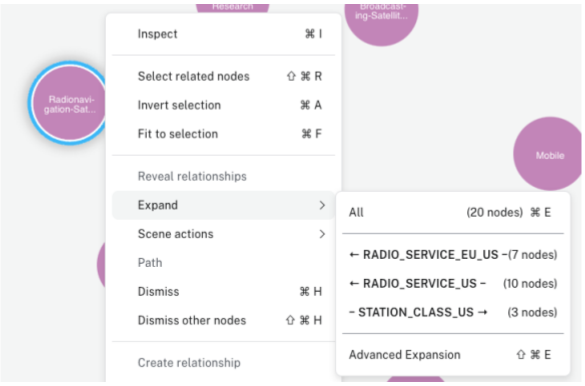


Figure 28. Expansion of Radionavigation-Satellite service options.

The following graph displays the frequency bands of EU countries in red and the frequency bands of US in yellow, for the radio service "Radionavigation-Satellite" given as an example.

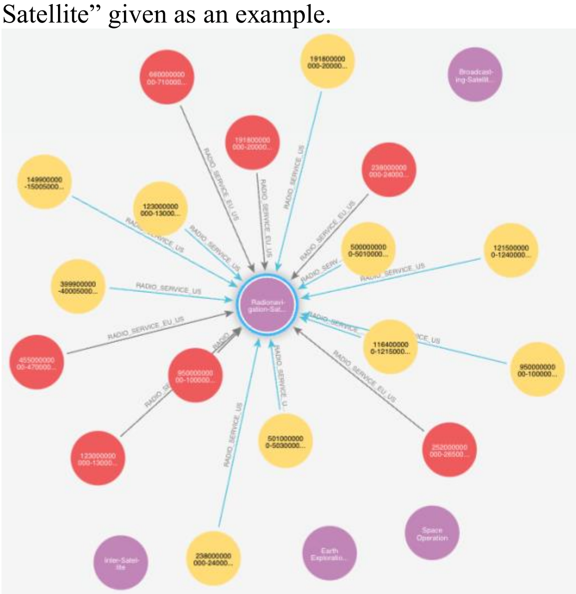


Figure 29. Frequency Bands from EU and US of Radionavigation-Satellite radio service expanded.

4) The following graph shows the result of Query 4. The image shows the frequency band with more radio services (16 in total) from US. It is possible to configure this query for the EU, too.

Figure 30. Graph of frequency band with more radio services.

In Neo4j, the bottom left corner also contains a legend where all nodes and relationships are displayed along with their respective attributes and properties.

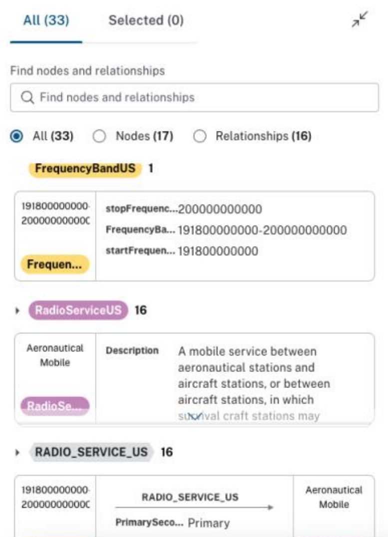


Figure 31. Neo4j legend browser of previous graph.

5) The following graph shows the result of executing Query 5. The image displays the radio service(s) that have a specific station class code given as a parameter. In this case, it is displayed for "Land Earth Station," which has the acronym VA.

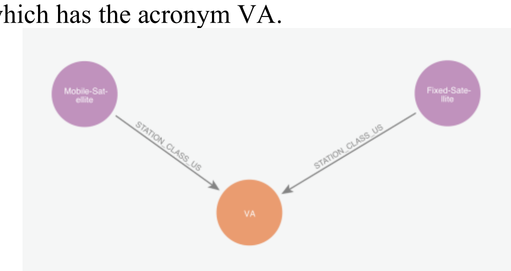


Figure 32. Graph with radio services with specific station class for US.

In this case, it is possible to expand the station class code node with the relationship "STATION_TYPE_US", in order to know the station types that are used for that radio service with that station class code.

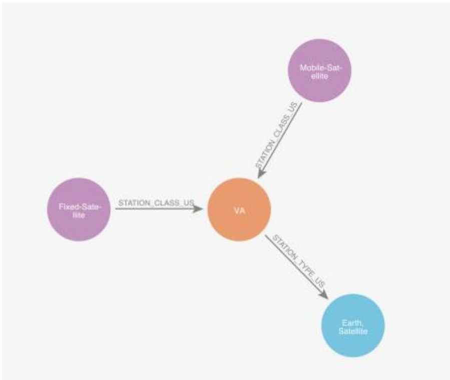


Figure 33. Graph with Station Type expanded of the previous graph.

This radio service (VA) can also be viewed with the frequency bands where it appears as shown in figure 32.

Figure 34. Frequency bands of one of the radio services with a specific station class.

V. Results

From our analysis, we derived several meaningful insights, focusing on three primary measures. The three key measures are the structural differences between US and EU frequency allocation tables, the radio services potential bandwidths, and the identification of common and unique radio services between both regions. By addressing these aspects, we provide a comprehensive understanding of spectrum management practices in the US and the EU. This approach not only clarifies the current state of spectrum usage but can also be used as a tool for more efficient and coordinated spectrum management in the future.

Our knowledge graph allows us to identify significant differences between the frequency allocation tables in the US and EU. We could see that the US table, managed by the National Telecommunications and Information Administration (NTIA) and the Federal Communications Commission (FCC), tends to focus on a broad range of services, emphasizing coordination between federal and non-federal uses, ensuring that both public and private sectors can utilize the spectrum effectively. This dual management system allows for a dynamic allocation of frequencies, accommodating a wide variety of services including military, emergency, and commercial communications. In contrast, the EU's allocation, coordinated by the European Communications Office (ECO) under CEPT, involves detailed cooperation among numerous countries, emphasizing harmonization across the member states.

Regarding bandwidth utilization, our knowledge graph provides a clear view of how different radio services are allocated bandwidth in each region. In the US, significant bandwidth is allocated to services like space research and exploration, reflecting the country's investment in these areas. For example, the "Space Research (passive)" service has a substantial allocation, underscoring the importance of satellite and space-related communications. The US largest allocation is for "Space Research (passive)," with 244,522,900,000 Hz (approximately 244.5 GHz).

In the EU, bandwidth allocation also reflects a diverse range of services but with a greater emphasis on harmonization and shared use among member states. Services such as "Amateur" radio in the UK demonstrate a high bandwidth allocation, with 30,023,566,957,100 Hz (approximately 30,024 GHz), indicating robust support for non-commercial and experimental uses. This approach ensures that a wide variety of services can coexist with minimal interference, supporting both commercial and non-commercial activities.

Overall, the knowledge graph system highlights the structural and strategic differences in spectrum management between the US and EU, providing insights into how each region prioritizes and allocates its radio frequencies.

Several radio services are common between the USA and the EU, reflecting a degree of international standardization and cooperation. Some of these radio services are:

- Aeronautical Mobile-Satellite: Its application consists of long-distance communications between aircraft and ground stations, and among aircraft, especially in remote areas and over oceans.
- Aeronautical Radionavigation: This service provides navigation signals to help aircraft determine their position and navigate safely.
- Earth Exploration-Satellite (active and passive): its applications are Environmental monitoring, mapping, meteorology, and scientific studies. Active sensors emit signals and measure the reflection, while passive sensors measure the natural radiation emitted by the Earth.
- Radionavigation-Satellite: This service provides satellite navigation signals, essential for global navigation, such as Global Positioning System (GPS).
- Radiolocation: Used to radar for military and civilian applications, air traffic control, and surveillance and detection systems.

In addition to the data provision, our analysis also facilitates decision-making. Decision-makers can analyze different scenarios and their impacts on spectrum allocation and usage, helping to optimize spectrum management strategies. Spectrum is a limited resource, and this tool can be used for reorganization evaluation. With the rise of emerging new technologies that require large bandwidths, this tool enables the identification of overlaps and underutilized bands to reorganize the spectrum.

VI. Conclusions and Future Work

This study describes the development of a knowledge graph-based tool that enables a comparative analysis of the frequency spectrum allocation tables between the United States and the European Union, highlighting key differences and similarities in spectrum management practices. By leveraging a knowledge graph system, we were able to integrate diverse data sources and provide a unified view of spectrum allocation and utilization. This approach facilitated a deeper understanding of the structural differences, bandwidth utilization, and common radio services between the two regions.

Our analysis revealed significant structural differences between the US and EU frequency allocation tables. The US table, managed by the National Telecommunications and Information Administration (NTIA) and the Federal Communications Commission (FCC), focuses on a broad range of services and emphasizes coordination between federal and non-federal uses. In contrast, the EU's allocation, coordinated by the European Communications Office (ECO) under CEPT, involves detailed cooperation among numerous countries, emphasizing harmonization across member states.

Regarding bandwidth utilization, the US allocates significant bandwidth to services like space research and exploration, reflecting its investment in these areas. The EU, on the other hand, demonstrates a high bandwidth allocation for services such as "Amateur" radio, indicating robust support for non-commercial and experimental uses. These findings highlight the different priorities and strategies employed by each region in managing their spectrum resources.

Building on the insights gained from this study, future work will focus on several key areas to further enhance spectrum management practices:

- Incorporate additional data sources, including real-time spectrum measurements and usage patterns, to provide a more comprehensive and dynamic view of spectrum allocation and utilization.
- Develop more sophisticated queries in order to improve and broaden the analysis.
- Enhance coordination with international regulatory bodies such as the ITU to ensure that spectrum management practices are aligned with global standards and to facilitate cross-border spectrum sharing and collaboration.

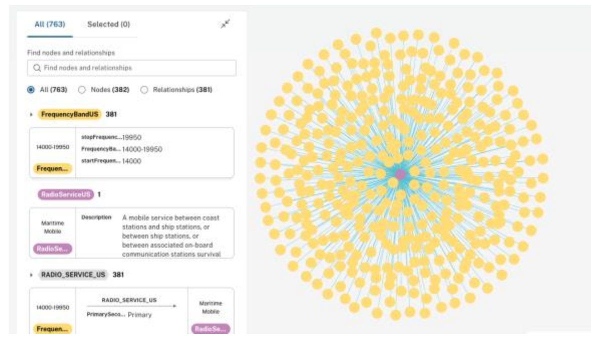
By addressing these areas, we aim to continue advancing the field of spectrum management, leveraging the power of knowledge graphs to support more informed decision-making and foster innovation in wireless communications.

Appendix

More queries and results:

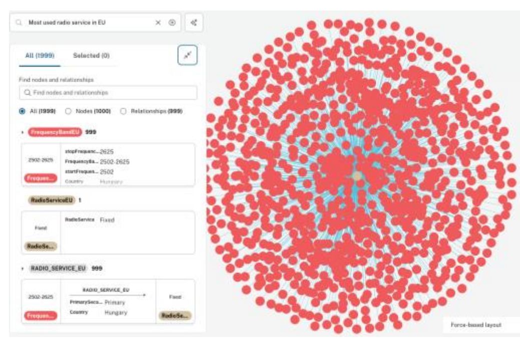
1. Most used radio service in US:

```
MATCH (:FrequencyBandUS)-
[r:RADIO_SERVICE_US]->(rsUS:RadioServiceUS)
WITH rsUS, COUNT(r) AS Count
ORDER BY Count DESC LIMIT 1
MATCH (fbUS:FrequencyBandUS)-
[rs:RADIO_SERVICE_US]->(rsUS)
RETURN rsUS, fbUS, rs
```



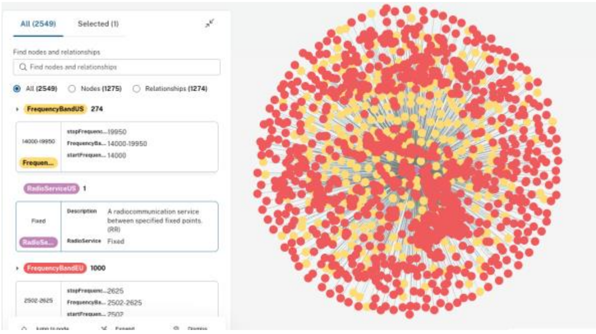
2. Most used radio service in EU:

```
MATCH (:FrequencyBandEU)-
[r:RADIO_SERVICE_EU]->(rsEU:RadioServiceEU)
WITH rsEU, COUNT(r) AS Count
ORDER BY Count DESC LIMIT 1
MATCH (fbEU:FrequencyBandEU)-
[rs:RADIO_SERVICE_EU]->(rsEU)
RETURN rsEU, fbEU, rs
```



3. Most common used radio service in US and EU:

```
MATCH (:FrequencyBandEU)-
[r:RADIO_SERVICE_EU_US]->(rs:RadioServiceUS)
WITH rs, COUNT(r) AS Count
ORDER BY Count DESC LIMIT 1
WITH rs
RETURN rs
```

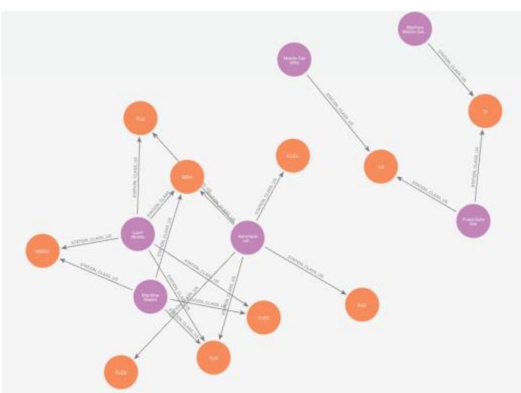


4. Frequency band in EU with more radio services:

```
MATCH (fbEU:FrequencyBandEU)-
[r:RADIO_SERVICE_EU]->(:RadioServiceEU)
WITH fbEU, COUNT(r) AS Count
ORDER BY Count DESC
LIMIT 1
MATCH(fbEU)-[rs:RADIO_SERVICE_EU]-
>(rsEU:RadioServiceEU )
RETURN fbEU, rsEU, rs
```

5. Most used Station class in US (Limit 10):

```
MATCH (:RadioServiceUS)-[r:STATION_CLASS_US]-
>(scUS:StationClassUS)
WITH scUS, COUNT(r) AS Count
ORDER BY Count DESC LIMIT 10
MATCH (rsUS:RadioServiceUS)-
[sc:STATION_CLASS_US]->(scUS)
RETURN rsUS, scUS, sc
```



6. Bandwith median per country in Europe:

```
MATCH (fbEU:FrequencyBandEU)-
[:APPLICATION_COUNTRY_EU]->(c:CountryEU)
WHERE c.Country <> 'Azerbaijan' AND c.Country
<> 'Monaco' AND c.Country <> 'San Marino' AND
c.Country <> 'Ukraine' AND c.Country <>
'Vatican'
WITH c.Country AS country,
fbEU.startFrequencyHz AS start,
fbEU.stopFrequencyHz AS stop
WITH country, stop - start AS difference
ORDER BY country, difference
WITH country, collect(difference) AS
differences
RETURN country,
       size(differences) AS
numFrequencyBands,

differences[toInteger(floor(size(differences)
/ 2))] AS median
ORDER BY median DESC
```

country	numFrequencyBands	median
Denmark	576	12,700,000
Georgia	500	12,700,000
Lithuania	592	12,500,000
Italy	592	12,300,000
Austria	647	10,000,000
Estonia	663	10,000,000
Hungary	673	10,000,000
Iceland	516	10,000,000

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