QUANTIFICATION OF SPECTRUM USE: SPECTRUM MANAGEMENT TOOLS FOR THE TWENTY-FIRST CENTURY

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ABSTRACT

As the use of the radio frequency spectrum increases, automated tools are increasingly necessary for spectrum management. This paper presents two types of spectrum use quantification tools, one for individual systems and one for the aggregate of systems in a frequency band and a geographic region. Potential applications of these tools in the areas of system planning, spectrum planning and spectrum efficiency are described.

INTRODUCTION

As the twenty-first century approaches, the size and complexity of the electromagnetic environment continues to increase. Technological advances have opened new opportunities in telecommunications. The market for mobile telecommunication services, including mobile radio and cellular telephone, is growing rapidly.

Expanding telecommunications activity puts increasing demands on the finite radio frequency spectrum. Since frequency separation must be maintained between proximate systems to avoid interference, assigning frequencies to new systems becomes more difficult. Eventually, frequencies may not be available for new systems in congested bands.

The availability of spectrum to meet future needs depends on effectiveness in various facets of frequency management. First, frequency managers must consider both interference and spectrum efficiency in assigning frequencies to new systems. Second, the use of frequency bands must be carefully planned to ensure sufficient available spectrum to support future systems. Finally, measures must be developed to improve the spectrum efficiency of systems, encouraging the replacement of systems that use excess spectrum resources with spectrum efficient ones.

As effective spectrum management becomes more crucial, well-designed automated tools are necessary to support these activities. In particular, spectrum use quantification tools give the spectrum manager much useful, and hitherto unavailable, information about the effects of individual systems or groups of systems on the electromagnetic environment. This information allows spectrum managers to exploit the power of computers to more effectively manage the radio frequency spectrum.

CONCEPTS AND TERMINOLOGY

Spectrum Resources

A telecommunications system "uses" spectrum by making it unavailable to another system. Another system operating nearby on the same frequency may experience interference from and/or cause interference to the first system.

Over a large area, many telecommunications systems can share the same frequency without interference. While the term "spectrum use" implies only the use of the radio frequency spectrum, numerous factors, including physical separation, directional antenna gain, antenna polarization, modulation, and time must be considered in addition to frequency to determine whether interference will occur. These factors are called "spectrum resources" because they are the available means of providing communications for multiple users. The spectrum resources most commonly considered in spectrum use and spectrum efficiency studies are frequency, geometric space, and time.

When the operation of a new telecommunications system would result in interference, either to the new system or to an existing system, that combination of resources (its frequency, location, mainbeam azimuth, etc.) is unavailable to the new system. Spectrum resources are "used" by a telecommunications system when they are made unavailable to other systems. While the use of spectrum resources is most commonly attributed to transmitters, receivers also use spectrum resources, since nearby spectrum resources would be unavailable to a new transmitter.

Quantification of spectrum use is accomplished using a multi-dimensional "spectrum resource space". The dimensions of the spectrum resource space for a particular type of system are those parameters most pertinent to interference analyses for that type of system. For example, antenna mainbeam azimuth and polarization would be pertinent dimensions for a typical fixed service system while time would not. The reverse would be true for a mobile service system.

Three additional points should be made about spectrum resource spaces. First, the number of spatial dimensions can vary for different types of systems: an airborne system might have three while a terrestrial system would have two and a geostationary satellite would have one (the geostationary arc). Second, while the dimensions are usually continuous, they are occasionally discrete, as with frequency in a band with discrete channels. Third, if the total number of dimensions of the spectrum resource space is
manageable (three or fewer), the space can be represented graphically.

Spectrum Use Criteria

As mentioned above, spectrum use is based on the potential for interference between telecommunication systems. One possible criterion for spectrum use is a power or susceptibility threshold. For a transmitter, a combination of resources (e.g. a frequency at a location) is used if the emissions at that frequency and location from the transmitter exceed a certain threshold level. For a receiver, the combination of resources is used if the receiver susceptibility, referenced to that combination, exceeds the threshold level.

Another method for determining spectrum use employs a "reference system", a hypothetical transmitter-receiver pair. A transmitter uses a certain combination of spectrum resources if these resources would be unavailable to the reference receiver. Likewise, a receiver uses a combination of resources if it makes that combination unavailable to the reference transmitter.

TOOLS FOR QUANTIFYING SPECTRUM USE

The concepts described above can be used with technical data and automated models to quantify spectrum use. Two cases are considered here: the spectrum resources used by an individual system and those used by the aggregate of systems in a given environment.

Spectrum Use of a System

For an individual system, spectrum use is quantified by integrating the resources used over the spectrum resource space. This procedure produces a quantity with the dimensions of the resource space.

Figure 1 shows a surface enclosing spectrum resources used by a fixed service transmitter in a three-dimensional spectrum resource space. Two of the dimensions are spatial, while the height is frequency. Using cylindrical coordinates, r is the distance from the transmitter and θ is the bearing relative to the antenna mainbeam. The z axis is the frequency separation between the transmitter and the reference receiver.

Figure 1. Surface Enclosing Space and Frequency Resources Used by a Fixed Service Transmitter.
The diagram is simplified in that it uses an envelope antenna pattern and does not include effects such as intermodulation and harmonics. A similar volume below the r-f plane is also used by the transmitter, but is not shown in this figure.

Aggregate Spectrum Use

The use of spectrum resources by a group of systems is quantified by defining a subspace of the spectrum resource space (e.g. a range of frequencies within a specified geographic region) and determining the union of the spectrum resources used by all the systems in the group. This total is then divided by the total size of the subspace, yielding a fraction or percentage of the subspace. If this fraction is determined relative to a reference system, it also represents the probability of interference, assuming uniform distribution of all reference system parameters.

The National Telecommunications and Information Administration (NTIA), which is responsible for spectrum management for the agencies of the U.S. Federal Government, has been developing a quantification model known as the Spectrum Use Measure (SUM). The program is designed for mapping spectrum use of systems having a spectrum resource space with two spatial dimensions, latitude and longitude. By quantifying spectrum use at a point, SUM can show graphically the variations of spectrum use over a region.

Quantifying spectrum use at a point eliminates the spatial dimensions from the spectrum resource subspace. The spectrum use factor (SUF) at a point is the spectrum resources used divided by the total size of the subspace. Averaging the SUF values over a region yields a single value of spectrum use for the region that includes the spatial dimensions of the subspace. In the SUM model, this quantity is called the spectrum use index (SUI).

Figure 2 is an example of a SUF map for a military mobile service band. The map, prepared using the SUM model, shows the heaviest use of the frequency band (90% or more of the spectrum resources used) around Washington DC, San Francisco, and other areas with major military installations. The spectrum use index for this example is 0.3030.

If the only pertinent non-spatial dimension is frequency (as in the example in Figure 1), it is sometimes useful to express aggregate spectrum use as the total spectrum resources used in the subspace. The SUM model also calculates this quantity at a point, calling it the spectrum use bandwidth (SUB) since it has only a frequency dimension. Over the entire subspace, the spatial dimensions are added, yielding units such as MHz-km².

Figure 2. Map of Spectrum Use Factor (SUF) Values for a Mobile Service Frequency Band.
APPLICATIONS OF QUANTIFICATION TOOLS

Quantification techniques for individual systems and for an aggregate of systems have applications in at least three areas of spectrum management: planning for specific new systems, planning for future use of spectrum resources, and improving spectrum efficiency. While most of the applications described here pertain to the U.S. Federal Government frequency management activities of NTIA, most other spectrum management organizations have comparable activities for which these techniques could be useful.

System Planning

System Development. Before U.S. Government agencies introduce certain new telecommunications systems, NTIA must certify that the required spectrum is available. Certification of spectrum support for a system involves NTIA review of the system at several stages in its evolution. The purpose of these system reviews is to assist the responsible agency in ensuring that the system will neither cause interference to nor receive interference from other authorized users when placed in its intended environment.

During the early stages of the system development (before the locations of transmitters and receivers have been decided), the SUM technique can be used to assess the compatibility of the proposed system with the existing environment. Using as a reference system the system under development, maps of SUF values portray the difficulty of implementing the proposed system. Areas where implementation would be troublesome can easily be identified. If more than one frequency band is being considered, the SUM analysis of each band identifies the most desirable band from a compatibility standpoint.

If more than one type of system is being considered for an application, the most spectrum efficient design can be determined by quantifying the spectrum resources used by each of the candidate systems. In this sense, the most spectrum efficient system is the one using the least spectrum resources while meeting the requirements for system performance.

Frequency Assignment. To obtain the actual authorization to use a frequency for a telecommunications system, a U.S. Government agency makes the necessary technical studies, selects potential frequencies, coordinates with other agencies involved, and prepares and files an application with NTIA. Authorization is granted to an agency in the form of a frequency assignment. If several frequencies are being considered in the selection process, they can be evaluated using the SUM technique based on the extent of their use by existing systems. In this application, the SUM model is applied to the specific frequencies rather than to the entire frequency band.

NTIA frequency assignment guidelines for U.S. Government telecommunications systems state that each new assignment "should be made in such a way that the increase in the total spectrum space committed is as small as possible." The SUM technique can be used to compare the frequencies based on this criterion. For each candidate frequency, the proposed system is added to a database of the existing systems and the increase in the spectrum use index is calculated.

Spectrum Planning

Frequency Band Assessments. NTIA manages a program to assess spectrum use and to identify potential spectrum sharing problems within specific frequency bands allocated to the Federal Government. Studies completed under this program, known as spectrum resource assessments, are used in the development of spectrum policy, as background material for system reviews, and for planning by the various Federal agencies.

Maps and indices generated using the SUM technique add a new dimension to spectrum resource assessments. In addition to evaluating spectrum use of the frequency band, SUM is valuable for comparing spectrum use in similarly allocated frequency bands.

Changes in spectrum use can be illustrated and quantified using SUM maps and indices based on current and previous versions of a data base. Figure 3 is a SUF map for the same frequency band as Figure 2, but with a 10% increase in the number of frequency assignments. The effects of this increase can be seen in eastern Washington state, central Missouri, and upstate New York. In this simulation, the spectrum use index has increased from 0.3030 to 0.3157, or about 4%.

Forecasting. NTIA is responsible for developing, in cooperation with the Federal Communications Commission, a comprehensive long-range plan for improved management of all electromagnetic spectrum resources. Variations in the spectrum use index over time can be used with numerical forecasting techniques to predict long-range growth in the use of frequency bands.

Spectrum Efficiency

A primary goal of spectrum management is to maximize the spectrum efficiency of the telecommunications environment. As with spectrum use, spectrum efficiency applies both to individual systems and to groups of systems. The spectrum efficiency of an individual telecommunications system is inversely proportional to the spectrum resources it uses. Increasing spectrum efficiency involves decreasing the spectrum resources used, if possible, while still meeting the requirements for the system. Aggregate spectrum efficiency is determined by the apportionment of spectrum resources to telecommunications systems. Spectrum efficiency is increased by decreasing aggregate spectrum use while maintaining the compatible operation of the individual systems.

As spectrum management has historically been the responsibility of regulatory organizations, regulatory standards for transmitters and receivers have been used to promote spectrum efficiency of individual telecommunications systems. Aggregate spectrum efficiency has been maintained by using the system planning and spectrum planning techniques described above, among others. Much recent discussion, both in the U.S. and abroad, has focused on economic incentives for spectrum efficiency, including the use of market-based alternatives for spectrum apportionment.

Spectrum Standards. NTIA defines a radio frequency spectrum standard as a principle, rule, or criterion that bounds the spectrum-related parameters and characteristics of a radio station or system for the purpose of managing the radio frequency spectrum. NTIA develops spectrum standards for U.S. Government telecommunications systems. Since spectrum standards limit the spectrum resources used by a system, they promote spectrum efficiency.

Proposed spectrum standards can be evaluated using the SUM technique. A copy of the frequency assignment data base is modified so that all systems meet the proposed standard. Comparison of SUM maps and indices for the original and modified data bases shows the effects of implementation of the spectrum standard, in terms of any reduction in spectrum use.

Figure 4 is a SUF map similar to that in Figure 3, except that bandwidth standards have been tightened, allowing channel width to be reduced from 25 kHz to 12.5 kHz. The result is a predictable, but nonetheless dramatic reduction in spectrum use. The spectrum use index is decreased by 50% to 0.1579.

In some cases, particular spectrum standards established by NTIA apply only to areas of the United States where heavy use of a frequency band makes them necessary. SUM maps can also be used to identify areas of the country where particular spectrum standards should be implemented.
Economic Incentives. Current procedures for authorizing the use of frequencies give the user no economic incentive for conserving spectrum resources. On the contrary, a substantial cost is generally associated with replacing outdated and inefficient equipment, which may be wholly satisfactory to the user. This disincentive would be reduced or removed if the user were required by the government to pay a fee based on the use of spectrum resources. If the fee were sufficiently high, the savings realized by using a more spectrum efficient system would exceed the cost of replacing the outdated equipment.

Since the fee per unit of spectrum resources used would almost certainly vary geographically, SUM maps could be used to set the rate based on the level of spectrum use in an area. The technique described above for quantifying the spectrum resources used by a system could be used to determine the actual fee for a specific system.

Market-based Spectrum Apportionment. The use of auctions for apportioning spectrum resources would arguably allow the market to set a fair price for their use. Under such a system, the high bidder, either a user or a "spectrum broker", would be responsible for spectrum management of the resources he controls and would have an economic incentive to use them efficiently. The government would be responsible for parceling and auctioning the spectrum resources, setting standards for levels of interference between parcels, and protecting the rights of the users and brokers. The quantitative techniques described herein would be useful for whomever supplies spectrum management services to the spectrum brokers.

Model Development

NTIA began developing SUM in fiscal year (FY) 1988. The initial model determined spectrum use of fixed service and mobile service systems relative to a fixed service reference system. In FY 1989, the model was expanded to include spectrum use relative to a land mobile service reference system. The current (FY 1990) effort is focusing on fixed radar reference systems.

Over the next several years, NTIA plans to expand the SUM model to handle as many of the radiocommunication services as prove feasible. While many of the remaining services have similarities with those already analyzed, others will require significant changes to the model. For example, the spatial dimensions of the spectrum resources used by space systems will be very different from those for terrestrial systems.

Validation

NTIA also plans a limited validation of the SUM model using data collected by the NTIA Radio Spectrum Measurement System (RSMS). Using the RSMS receiver and a directional antenna as the reference system, received power levels will be measured over azimuth and frequency in a fixed service band. Spectrum use values measured in the field will be compared with

Figure 3. Revised SUF Map Showing the Effects of a 10% Increase in the Number of Assignments.
Applications

Thus far, the SUM technique has been applied to NTIA's system review and spectrum resource assessment activities. NTIA has recently undertaken a comprehensive review of U.S. spectrum policy, the results of which may affect NTIA's eventual use of quantification techniques. The topics addressed in the study include revenue enhancement, spectrum auctions, spectrum standards, and forecasting.

The study is also addressing the feasibility and desirability of NTIA and the Federal Communications Commission (FCC) developing a joint data base of government and nongovernment frequency use. If such a data base were available, SUM analysis could produce maps showing a more complete picture of spectrum use in the United States.

Use of these quantification techniques is not limited to individual administrations. If a suitable automated data base were available, these methods could have applications in bilateral coordination between administrations and in international spectrum management.

CONCLUSIONS

Spectrum use quantification tools have extensive applications in several areas of spectrum management. They provide a powerful new tool for effectively apportioning frequencies for new telecommunications systems and planning the exploitation of spectrum resources. Moreover, they provide new opportunities for using valuable spectrum resources more efficiently.

With the rapid expansion of demand for telecommunications in the coming decades, the electromagnetic spectrum will be increasingly taxed. Its management will grow increasingly complex. Using the power of modern data processing systems, spectrum use quantification techniques will play a vital role in meeting the spectrum management needs of the twenty-first century.

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