Spectrum Supply and Demand Prediction Models

Charles H. Jones, PhD
C. H. Jones Consulting, LLC
Eugene, OR, 97405
chjonesconsulting@gmail.com

Michael K. Painter, P.E.
Knowledge Based Systems, Inc.
College Station, TX 77840-2335
mpainter@kbsi.com

ABSTRACT

There is a general belief that there is not enough spectrum available to meet T&E needs. How do we know this is true? The very few studies that have analyzed this have done so with limited data and limited modeling.

Spectrum is a natural resource. An analogy to gold mining can be useful. A certain amount of gold exists in the ground, but it takes equipment to extract it. It is only the extracted quantity that is available as supply. Transmitters and receivers are the mining equipment that extract spectrum.

Demand is different from requirements. A quagmire of debate surrounds requirements. Whereas, what testers want is their choice. There is evidence that not all demand is input into spectrum scheduling systems due to a combined perception by some testers of low priority and a lack of spectrum. Thus, use and request data do not even capture demand.

This paper provides models and techniques that can aid analyses trying to predict the gap between spectrum supply and demand.

INTRODUCTION

The decision process for determining how to invest in technology to meet the telemetry spectrum needs for Test & Evaluation (T&E) can be enhanced through a systematic analysis of spectrum supply and demand. (Cost is also a factor but is not addressed in this paper.) This paper overviews theoretical models for analyzing the interplay between these factors and investments and events that affect spectrum. The foundational approach is based on spectrum being a natural resource. As with gold mining, there is a certain amount of the resource available, but it takes mining equipment to provide a useful supply.

Telemetry equipment, such as transmitters and receivers, are the mining equipment for spectrum.

The fundamental question addressed is:

> Does existing telemetry equipment provide enough supply to meet user demand?

If not, two more questions arise:

> How will investments into telemetry technologies affect supply and demand?
> What impact does a lack of spectrum have?

The models presented are strongly influenced by two MITRE reports: *The Economic Importance of Adequate Aeronautical Telemetry Spectrum* [1] and *The Growth of Data Rates for Aeronautical Telemetering and the Implications for the Radio Spectrum* [2]. These reports provide a "model-of-models" approach that were used to analyze potential scenarios to support efforts to obtain additional spectrum for T&E during the World Radio Conference in 2007 (WRC 07). The models overviewed here are a considerable expansion on the MITRE models.

The MITRE reports provide a mechanism to answer the basic question: How do you report impact of technology investment? The mechanism starts by constructing a baseline supply and demand of current operations. It then develops impacts from different technology investment scenarios or other events that impact spectrum availability. Analysis of before and after differences aids investment decision making. Of particular note is that keeping track of supply and demand allows for a gap analysis. An approach taking by MITRE, and continued here, is to use the size of the gap to trigger inclusion of impact factors in the final analysis.

A significant difference between the MITRE reports and the models here is that MITRE considered supply in terms of Megahertz (MHz). The models here use MHz Hours (MH) as the baseline supply. Analyzing MHz limits the results to a maximum simultaneous spectrum demand. Using MH allows for a more granular analysis that incorporates the ability to meet demand through scheduling in time.

SPECTRUM GAP MATRIX

The ultimate objective of supply and demand analysis is to determine the spectrum gap between the two – both now and in the future. To do this, the first step is to determine a baseline prediction for both supply and demand without consideration of future investments in spectrum technology or other events that would affect spectrum. But both supply and demand will be affected by future activities so the second step is to adjust the baselines based on that affect. Table 1 illustrates the table that would capture this analysis. Knowing both the baseline and predicted gaps aids in determining if an investment produces a significant reduction in the gap.

Table 1 Spectrum Gap Matrix

Year	Baseline Supply	Baseline Demand	Adjusted Supply	Adjusted Demand	Baseline Spectrum Gap	Adjusted Spectrum Gap
1						
2						
…						
N						

SUPPLY MODEL

Transmitters and receivers are the mining tools to be supply spectrum. This is different from the amount of spectrum potentially available. A simple example is if there is only one receiver that can receive a single 20 MHz signal, then the supply is 20 MHz regardless of how many MHz are in the band. Extending this concept to MH, supply is also dependent on infrastructure availability over time. Within the T&E application, it is usually necessary to have test and support personnel as well as other non-spectrum resources involved. A simple example of this affecting supply is that control rooms are not normally manned 24/7.

Generally, tests are implemented within formally defined test areas such as R2508 or one of its subdivisions at Edwards AFB. (Although there are times when tests cross test areas boundaries.) Spectrum supply for a given test area is dependent on the receivers available to that test area. Supply is also dependent on available transmitters but, generally, transmitter capability for exceeds receiver capability. The bandwidth of a given band, such S or C band is an upper limit for spectrum supply.

Another limitation on supply for a test area is due to operational interference (OI) as defined in IRIG 106 [3]. If there is potential for a transmitter to interfere with a receiver other the ones it is transmitting to during a test, that transmitter causes OI and that receiver cannot be used (for that frequency) even if it is in a different test area. That is, OI reduces supply. IRIG 106 also introduces the concept of Areas of Mutual Use (AMU). An AMU is the set of test areas that have the potential for mutual OI. Thus, when calculating spectrum supply it is necessary to calculate a maximum loading for the entire AMU based on OI rather than simply summing the supply available in every test area.

The point here is that test areas do not necessarily have the geographic separation needed for each test area to use the same frequency simultaneously. That is, just because two test areas are being used for tests, it does not mean the spectrum supply doubles.

Keep in mind that supply is in MH, not MHz, so it is necessary to consider time domain factors as well in calculating supply. For example, different test areas may have different levels of personnel support available or some test areas might not be considered safe to fly in at night. It is important to capture these aspects of supply because of investments that might be made to alter these factors. For example, adding testing at night or on weekends, or moving a test to another area, are sometimes viable options – but at a cost.

An algorithm for calculating the maximum spectrum loading of an AMU for a single band has been developed but will not be presented here. But given that algorithm, we can calculate overall supply using the following model. Specifically, the total spectrum supply is the sum of all maximum loadings for every AMU over all bands.

Let

$S(y)$ = the baseline spectrum Supply (MH) for year y.
$S^{AMU}(y, b, m)$ = the spectrum supply (MH) in year y in band b in AMU_m. This includes limitations due to OI.
$b(y, m)$ = the number of bands in AMU_m in year y.
$u(y, m)$ = the number of AMUs in year y.

Then

$$S(y) = \sum_{m=1}^{u(y,m)} \sum_{b=1}^{b(y,m)} S^{AMU}(y, b, m).$$

In application, there are, of course, many subtleties and variations that might have to be considered. Those would need to be considered by an analyst for specific cases.

DEMAND MODEL

Fundamentally, spectrum demand is the sum of the demand from all programs – both known and unknown. (The model is a "demand" model vs. a "requirements" model. We let the users determine what is required.) However, there is also spectrum overhead. Every data transfer protocol requires bits that are used to implement the protocol that are not data used by programs. Examples include sync words, packet headers, and word buffer bits. There is also spectrum overhead from non-spectrum logistics. Preparing everything needed to perform a test is complex and doesn't always happen on schedule. Spectrum has to be available from the time it is scheduled whether everything else is or not. This can lead to periods when there is no transmission even though the spectrum is unusable by anyone else. Table 2 shows the structure of a demand aggregation matrix.

Table 2 Example Spectrum Demand Aggregation Matrix

Program\Year	1	2	...	Total
Program 1			...	
Program 2			...	
...			...	
Program m			...	

Unknown Programs			…	
Spectrum Overhead				
Total – *D(y)*			…	

This leads to a basic mathematical model.

Let

$D(y)$ = the total baseline spectrum demand (MH) for year y (or other time unit.)
$D_P(y)$ = the spectrum demand for Program P for year y.
$D_U(y)$ = the spectrum demand for Unknown future programs for year y.
$D_O(y)$ = the spectrum demand for spectrum Overhead for year y.

Then

$$D(y) = D_O(y) + D_U(y) + \sum_{P=1}^{m} D_P(y).$$

Determining program demand can be done in several ways. The first is simply to have each program fill in entries in the matrix. A more granular, and potentially more automated approach, would be to state demand in terms of operational pace. That is, identify how many of what types of tests will be conducted over a given time period. Another approach is to use analytic regression analysis on historical data. Some caution has to be used with analytic methods. For example, projecting long term demand based on the developmental test phase is probably not appropriate since it tends to use an order of magnitude more spectrum than during operational phases of a system.

Determining unknown programs is difficult. One approach was presented in the MITRE reports. Specifically, the method of Future and On Going (FOG) and Major User Programs (MUP). FOG might be considered the "noise floor" of spectrum demand with MUPs representing a strong "signal" on top. MITRE used this model for MHz. The method can be used for MH. (Using this method, MITRE was able to argue that the T&E community was reaching the point where a single vehicle would require more MHz than was available prior to WRC 07 when we acquired access to C band. A pretty good argument for requesting more spectrum.)

FOG = (mean number of users) * (estimated median user bandwidth demand)

The use of median user bandwidth for FOG is to offset MUPs which would skew the mean since MUPs are few and tend to use an order of magnitude more than the average user. Developing a growth curve for FOG reduces the need to try to predict unknown future programs. MITRE calculated a doubling of FOG demand of about 13 years. MITRE also estimated that a new MUP starts about every four years with a doubling of spectrum demand from the previous MUP.

TECHNOLOGY ADOPTION METHOD

Once baselines for spectrum supply and demand are established, the next step is to adjust the baselines based on implementation of new technologies or other events. This adoption method can be applied to anything that affects spectrum. That is, upgrading existing equipment or software, buying new equipment, developing new scheduling methods, or actual loss of available MHz. It can also be applied to costs associated with technology adoption.

The first part of the approach is to establish an adoption rate. This might be a percentage per year, adoption in a single year, or some variable adoption rate. The second part is to determine, as best as possible, how the technology affects supply and demand.

The main technology adoption over the last couple of decades has been new modulation techniques such as SOQPSK. This has reduced spectrum demand because it increases bits/sec. It takes less spectrum to transmit the data – which is the basis for the demand. The growth in complexity of systems is the main driver of an increase in spectrum demand, but there are other things that can increase demand. Examples of changing supply include loss or gain of bands or adding a new ground receiver.

The impact of a technology might translate into a simple percentage change in supply or demand or it might be more complicated. Implementing more than one technology at a time may complicate determining this affect if the effects are not independent.

Once the adoption rate and the impact to supply and demand has been determined, it is possible to provide adjustments to the baselines over time.

It is possible that a new technology can impact both supply and demand. Network telemetry is an example of this. PCM is very efficient in that it has small bit overhead. (Well below 5%.) Ethernet is an extreme example of overhead. Because of its contention-based protocol, 60% throughput used to be considered great. So, networks increase demand. But the ability to do dynamic format changes can increase supply. Traditionally, PCM has been used with a static format where the same data is transmitted through the entire test. Network protocols can allow pumping up the data flow during critical test events while reducing the data flow to safety of flight parameters between test points. By enabling other users to transmit during these low transmission periods, supply is increased.

Changes to supply and demand is technology specific and must be analyzed carefully.

IMPACTS FROM A SPECTRUM GAP

Even with technology investments, it is possible that there will be (and is) a spectrum gap. The impact of this is not easily determined. The base assumption is that a lack of spectrum leads to less or longer testing. This most likely leads to system shortcomings not being identified or delays in fielding systems. This can affect the warfighter in their ability to execute a mission and possibly lead to loss of life.

Spectrum supply and demand models take the first step to this analysis by identifying what the gap is. MITRE used a "trigger" technique to estimate some of the functional impacts. That is, given different size gaps, different estimates of cost impacts, delays, accidents, and loss of life are triggered in the analysis.

SUMMARY

Models for spectrum supply and demand have been developed. (Associated cost models are in work.) The objective of these models is to aid in determining the effect and value of investing in spectrum technologies and to asses the impact of spectrum related events. Because of the wide variety of potential solutions to supply spectrum, it is necessary to include many factors that might not normally be considered part of spectrum. Once the size of a spectrum gap is identified, an analysis of impacts to the warfighter can be attempted and decisions regarding investments can be aided.

REFERENCES

[1] *The Economic Importance of Adequate Aeronautical Telemetry Spectrum*, Darrell E. Ernst, Carolyn A. Kahn, David L. Portigal, MITRE Technical Report, MTR 060202, Feb 2007.

[2] *The Growth of Data Rates for Aeronautical Telemetering and the Implications for the Radio Spectrum*, Darrell E. Ernst, Yan-Shek Hoh, David L. Portigal, MITRE Technical Report, MTR 04W0000032, May 2004.

[3] *Telemetry Standards, IRIG STANDARD 106*, Secretariat, Range Commanders Council, White Sands Missile Range, Mew Mexico.

Acknowledgment of Support: This project is funded by the Test Resource Management Center (TRMC) Test and Evaluation/Science & Technology (T&E/S&T) Program through the U.S. Army Program Executive Office for Simulation, Training, and Instrumentation (PEO STRI) under Contract No. W900KK-16-C-0018. The Executing Agent and Program Manager work out of the AFTC.