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May 28, 2019

Ms. Marlene S. Dortch
Secretary
Federal Communications Commission
445 12th Street S.W.
Room 2-B450
Washington, DC 20554

**Re: Ex Parte Submission**
**WT Docket No. 19-140**

Dear Ms. Dortch:

On May 16 the Commission released a draft of the Notice of Proposed Rulemaking in the above-referenced proceeding. At paragraph 42, a statement is made to the effect that, "The Aerospace and Flight Test Radio Coordinating Council, Inc. ("AFTRCC") claims that there is increased spectrum demand for flight testing due to the increased use of digital video to obtain important flight test data and to loss of other spectrum for flight test systems." The draft then cites to comments filed by AFTRCC.

To be clear, it was the United States, not AFTRCC, which ultimately determined that the aeronautical mobile telemetry ("AMT") community faced a serious spectrum shortfall. More specifically, the United States demonstrated a shortfall of no less than 650 MHz in an official United States Government contribution to the International Telecommunications Union, Radiocommunication Sector. A copy of this submission is attached.

In light of these circumstances, it is requested that paragraph 42 be revised to add after the first sentence, "In fact, the United States determined that flight testing will require an additional 650 MHz of spectrum by the year 2024 (ITU-R Doc. 8B/143-E, March 31, 2005, page 5)."

A copy of this ex parte submission is being filed in the docket.

Any questions regarding this filing may be directed to the undersigned.

Respectfully submitted,

William K. Keane
*Counsel for AFTRCC*

Attachment

INTERNATIONAL TELECOMMUNICATION UNION

**RADIOCOMMUNICATION STUDY GROUPS**

**Document 8B/143-E**
**31 March 2005**
**English only**

Received: 29 March 2005

**United States of America**

# SPECTRUM REQUIREMENT FOR AERONAUTICAL MOBILE TELEMETRY

## Agenda item 1.5 (WRC-07)

This paper sets forth the spectrum requirement for aeronautical mobile telemetry ("AMT") in the context of WRC-07 Agenda item 1.5. It provides an introduction to the issue, an overview of the methodology used to predict future needs, and an explanation of the calculations upon which the estimates are based.

## I. Introduction

Telemetry spectrum is an enabler for aerospace development. Aeronautical telemetry transmits real-time data from the test vehicle, enabling pilots and ground-based engineers to conduct safe, effective, and efficient missions.

Over the last 30 years, measurements collected during flight-testing have been steadily increasing. While there are a number of contributing factors, one of the most significant is the increasing complexity of aircraft under test. When coupled with ongoing advances in aerodynamics, fuels, and other technologies, it creates ever more challenging test environments. Those environments require greater amounts of measurement data in order to determine if the system can perform as intended.

In addition, more and more systems on-board an aircraft must share data. Each system need not acquire 'airspeed' in order to perform its mission: 'Airspeed' is acquired once and passed to the various systems that need it. With today's large aircraft, moving volumes of data can require anywhere from a single avionics bus to a hundred. Each of these busses needs to be monitored and verified to ensure that the data is flowing where and when it should.

As digital video cameras become increasingly practical for flight test use, they represent yet another data source. For example, when trying to show pilot workload during flight, cameras can show flight test engineers on the ground what the pilot sees, and how he or she is reacting to the various gauges, warning lights, and other stressful situations.

Another area of measurement growth is passenger electronics. These devices include everything from Air-Phones to personal audio and video devices. Some carriers are actively marketing Direct Broadcast Satellite television for each passenger, as well as Internet and e-mail connectivity while airborne. From a flight safety standpoint, testing these systems is important to ensure they do not interfere with the avionics.

Finally, modern aircraft are increasingly designed to operate closer to the point of maximum efficiency, a point which is also closer to the edge of instability. For example, winglets and non-circular engine nacelles are more efficient, but much more precision is required to ensure that the design is correct; use of layered composites in wings greatly increases the number of parameters that must be tested; and certification of wide-body, twin-engine passenger aircraft for extended range, single-engine operation on overwater routes requires an even higher level of test rigor and fidelity. Airline passengers take these and other advances for granted. But absent much more extensive flight-testing, such advances could compromise flight safety.

In the 1950s, flight-testing of a typical new commercial airliner could be completed with a few hundred measurements. Forty years later, flight-testing of one new commercial aircraft generated approximately 100,000 measurements. Not only was the sheer number of measurements vastly increased, but also they were taken with much greater frequency and precision.

Given the increase in measurements, data rates have also increased. In general, the amount of instantaneous data collected today requires a much higher data rate than in years past. Sophisticated electronics likewise require more precision and resolution than in previous years. Sensors today convert their analog inputs into digital outputs using 12, 16 and sometimes 32 bits per sample; 20 years ago, 8 or 10 bits per sample was common. With more capable computers processing the data, the requirements for the accuracy of timing resolution have also increased. Where once 10 milliseconds was the norm, most systems today require 1 microsecond. This represents a change of four orders of magnitude. Aeronautical engineers are considering the need to improve time accuracy to the 1-nanosecond level. Certification of next generation commercial aircraft will require data rates in the 100 to 200 Mbps range.

As the number of measurement points and accuracies have increased over the years, the flight-test community has been increasingly constrained by the lack of sufficient AMT spectrum. The amount of data that can be telemetered for real-time monitoring now represents a steadily decreasing percentage of the total measurements needed for the test. This entails significantly greater risk to pilots and ground personnel. It also extends the length of each flight test program, increasing the cost of aircraft certification, slowing time to market, and increasing the cost of aircraft.

## II. Spectrum Requirement

### A The Current Shortfall

Flight test centers are typically required to support simultaneous flight test projects from different organizations (civil, space-related, and national security). Flight test projects may experience costly delays due to many competing projects vying for the same scarce spectrum in the same area.

Depending upon the Administration, major flight tests centers or "ranges", particularly those located in the same geographic areas may coordinate their operations not only at the local level, but also via a range deconfliction (or coordination) system. This system is used to schedule

spectrum usage between and among participating flight test centers so as to ensure harmonious spectrum usage.

Data collected from one coordination system for a typical week shows that the amount of spectrum actually used is more than that allocated for flight test telemetry. For example, 15,050 MHz-hours are allocated by one Administration for testing manned and unmanned aerial vehicles (seven days per week x 10 hours per day (most tests must be conducted in daylight hours for safety reasons) x 215 MHz allocated). At the same time, a total of 19,809 MHz-hours were actually used in this area by the ranges, each of which must coordinate with the others, or more than the amount theoretically available. This phenomenon is the result of coordinated, geographic reuse. Unfortunately, geographic reuse is becoming less of an option as vehicles fly higher and faster.

Moreover, program managers have access to the coordination system. Interviews with program managers reveal that they frequently do not even attempt to schedule a mission when they observe that the spectrum resource is not available. In other words, demand exceeds supply -- the data from the coordination system does not accurately reflect the total desired, i.e. optimal, usage of the spectrum resource.

Finally, test flights are not infrequently delayed or cancelled. This can happen due to an inability to get on the local schedule, or an inability to get on the inter-range schedule, or the fact that a program may be bumped from the schedule even after it has a time-spectrum slot. Analysis of the coordination system data and interviews with knowledgeable range personnel shows that that this occurs one-third of the time, and that lack of spectrum is a factor in roughly half of these cases. The bottom line is that between 15 and 20 percent of all test flights are currently delayed/cancelled due to spectrum shortage. In other words, the growth in data rates, the usage data, and the scheduling data demonstrate that there is a significant shortfall in telemetry spectrum.

## B The Cost of Delays

The lack of sufficient spectrum, however, tells only part of the story. The fact is that the spectrum shortfall has major consequences for aircraft development and the travelling public.

Significant resources are devoted to flight-testing, including support equipment, personnel, and range costs. Furthermore, a one-day delay in testing may cause a delay of several additional days due to unavailability of all of the required resources and assets (e.g., chase aircraft, equipment calibration, range availability and, most notably, spectrum), which must be re-scheduled.

Thus, test delays entail significant financial penalties. While the cost varies from program to program, the cost for a major program can easily exceed $1 million per hour. The testing budget for the X-43, for example, was $250 million for only three flights. While costs for flight-testing a new corporate jet are only a small fraction of that, time is money and delays can represent a material adverse event in certifying the craft's airworthiness and delivering it to the customer. Delays due to insufficient telemetry spectrum also impact global competitiveness. As deliveries are delayed and test costs rise, sales may be lost. Indirect costs such as these are even more problematic.

Finally, insufficient telemetry spectrum impacts test quality. Some systems cannot be tested in their full deployment mode due to lack of spectrum. This effect may be more difficult to quantify, but is no less real. Put another way, if more spectrum were available now, aircraft

manufacturers could profitably use that spectrum to improve the quality of testing and to develop their products more efficiently.

## C Prediction Methodology

The need for additional flight test spectrum has been studied by several Administrations. One Administration has suggested that as much as 1 GHz might be required to satisfy future needs. Another Administration has determined that 650 MHz is the appropriate total. While each Administration should be free to determine what amount of additional spectrum, if any, to specify within its own territory for AMT purposes, the following material sets forth the basis for the 650 MHz estimate.

### 1 Overview

Beginning in 1997, the aerospace research and flight test communities (referred to hereafter as the "flight test community") within one Administration conducted a series of studies relating to AMT spectrum availability and trends. The first was a survey of AMT spectrum usage at 22 test centers. The survey found that, in general, there was a steady growth in the megahertz-hours per week of spectrum usage.

A subsequent study in 2003 expanded the earlier results with more test center data, and then validated the data. A statistical analysis was then performed on the resulting 30 years of historical data. Regression analyses revealed that data rates had increased exponentially with a doubling about every four years. The confidence level for this result was 98%, an unusually high value. Further investigation into the cause of the near-deterministic relationship between time and data rate concluded that the increase was tied to vehicles that depended on advanced technology microelectronics.

(The microelectronics industry has doubled the component density of integrated circuit chips approximately every 18 months. This phenomenon, referred to as "Moore's Law", is responsible for the advances in electronic technologies that underpin almost all technological advances, including those responsible for high performance aerial vehicles such as commercial airliners, the Space Shuttle, and other aircraft. The consistent increase in telemetry data rates represents Moore's Law in action.)

This study further determined that, even if the most advanced, spectrally-efficient modulation techniques available were used for telemetering, by the year 2017 a single aerial vehicle would not have sufficient spectrum to send its data, even assuming all other users in the area ceased operation. The study also showed that, given current trends no less than 650 MHz would be required for a single test vehicle by the year 2024.

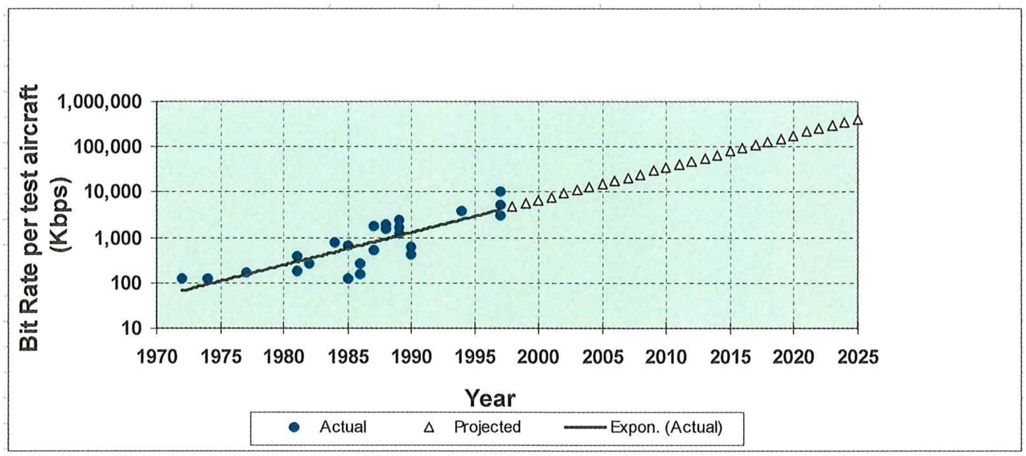


FIGURE 1

**Projected growth of data rates**

Additional studies were then conducted to explore means of mitigating the growth in spectrum requirements. These studies considered several factors:

– Historical and current levels of telemetry usage at commercial and government test ranges;

– The existing shortfall in AMT spectrum allocations relative to current demand;

– The expected decrease in geographic reuse of AMT spectrum, due to higher altitudes and longer flight paths of future aircraft, in spectrum-congested areas where multiple users must share spectrum resources;

– The relationship among the growth in the number of onboard measurements, new technology introduction rates, and telemetry throughput; and

– Recent advances in telemetry modulation and potential networking techniques.

The above factors were combined with standard communications parameters. Estimates for the parameters were derived from the studies described above, and from standard communications engineering practices. The approach used was to compute the traffic estimate and then compute the spectrum estimate using the traffic estimate as an input. Since certain of the values chosen for the parameters were based on statistical analyses and/or engineering best judgment, the estimates are subject to a certain degree of uncertainty.

The methodology underlying the calculations of requirements are standard queuing analysis techniques. Queuing analyses are standard in the telephony industry, circuit switched systems, where they were codified many years ago by the Danish mathematician, Agner Krarup Erlang (1878 – 1929) into a methodology for determining the number of serving channels required to support an expected busy hour load of call attempts while providing a specified blocking percentage, i.e., call attempts which the system could not serve. The proposed Telemetry Network System (TmNS) is more similar to the Internet than to a telephony system in that it is based on a packet switched architecture. The traffic models for circuit switched and packet switched systems are radically dissimilar. However, queuing analyses are also used to engineer packet switched systems. A simplified queuing analysis based on average traffic parameters has been used to analyze requirements for the TmNS. This analysis is the appropriate analog to the use of an Erlang methodology in telephony. Because of the differences in the traffic models for the two types of systems, the telephony type of analysis that has been codified into Erlang Tables for simplified estimation of required resources is almost never applied for packet switched systems.

The spectrum requirement was estimated by adding the requirements associated with routine operations to the requirements associated with newer programs. In each case the method entailed multiplication of current demand (current capacity plus current shortfall) by the data rate growth curve. An assumed deployment rate for spectrum-mitigation technologies was then factored into the equation using a deployment rate consistent with industry norms.

The study and the associated sensitivity analysis produced the following prediction of spectrum requirements: test ranges in one Administration will require an additional 650 MHz.

These values were obtained from the equation set using nominal or "average" values for the various equation parameters. Accordingly, the numbers are not rounded off above the fractional megahertz level.

It must be stressed that work is on-going within various Administrations looking to implement advanced modulation and networking techniques as a means of mitigating the spectrum demand. The calculations set forth below *assume* that such measures prove practical. If they do not, the estimates set forth here would prove to be well short of the need.

## 2 Calculation

The total amount of AMT spectrum required for future tests was estimated in four steps:

1. Estimate the amount of spectrum needed to support routine operations, referred to as "future on-going workload." This value is denoted by $\Phi$ in the following equations.
2. Estimate the data traffic for each component of the system. This value is denoted by $C_{ij}$.
3. Estimate the spectrum bandwidth required for each component. This value is denoted by $\Sigma_{ij}$.
4. Aggregate the bandwidth estimates to obtain the total amount of spectrum that will be required. This value is denoted by $\Sigma_{TOTAL}$.

(a) Routine Operations Calculation

$$\Phi = 215(1+D)(1+L)G \qquad (1)$$

Where $\Phi$ = Amount of spectrum bandwidth needed for routine operations, in MHz

215 = Amount of spectrum currently available for AMT, in MHz

D = Current unmet demand for spectrum ("current shortfall")

L = Loss of ability to reuse channels in a given geographic region

$\mathcal{G}$ = Growth factor as defined below

$$\mathcal{G} = \prod_{i=1}^{5} \left( (1 + g_i)^{y^i} \right) \tag{1.1}$$

$g_1 = 0.0667 \quad y_1 = 3$
$g_2 = 0.0500 \quad y_2 = 3$
$g_3 = 0.0333 \quad y_3 = 4$
$g_4 = 0.0025 \quad y_4 = 4$
$g_5 = 0.0012 \quad y_5 = 6$

(b) Newer Programs Calculation

$$C_{ij} = N_{TAi} N_{cij} R_{ij} I_{ij} (1 + \Omega_{ij} + \varepsilon_{ij}) (1/U_{ij}) \tag{2}$$

$$C_{i4} = 0.1\ C_{i2}$$

Where $C_{ij}$ = Capacity in megabits per second (Mbps) for the ij component of the system

i= 1⇒aircraft, 2⇒susbsystem A, 3⇒susbsystem B

j= 1⇒safety link, 2⇒network downlink data TM, 3⇒network downlink video TM, 4⇒ uplink

$N_{TAi}$= Number of test articles

$N_{cij}$=Number of channels

$R_{ij}$= Information rate generated by test article

$I_{ij}$= Information percent transmitted

$\Omega_{ij}$= Overhead

$\varepsilon_{ij}$= Error correction

$U_{ij}$= Usage

(c) Spectrum Calculation

$$\Sigma_{ij} = (C_{ij} / M_{ij}) (1 + T_{ij}) (1 + G_{ij} + P_{ij}) \tag{3}$$

Where $\Sigma_{ij}$= Total spectrum in megahertz (MHz) for the ij component of the system

i= 1⇒aircraft, 2⇒subsystem A, 3⇒subsystem B (vehicle types)

j= 1⇒safety link, 2⇒network downlink data, 3⇒network downlink video, 4⇒ uplink (channel types)

$M_{ij}$ = Modem efficiency in bits per Hertz (bps/Hz)

$T_{ij}$ = Time guard

$G_{ij}$= Frequency guard in percentage of bandwidth

$P_{ij}$= Packing inefficiency in percent of bandwidth

The total amount of spectrum that will be needed is derived by summing the twelve spectrum estimates. The additional spectrum required is obtained by subtracting the current spectrum allocation (215 MHz) from the total.

$$\text{Total spectrum required} = \Sigma_{TOTAL} = \sum_{ij} \Sigma_{ij}$$

$$\text{Additional spectrum} = \Sigma_{TOTAL} - 215 = 621 \text{ MHz}$$

However, the sensitivity analysis set forth – in Section 3 shows that the appropriate spectrum requirement should be 650 MHz[1]

The following table defines the principle parameters used in the equations. The "Values" column contains shows the values of the parameters used. Beginning with the "ij" variables, the "Value" column shows three value sets for each variable; one for each of the three system vehicle types. Each value set contains three values, one for each of the three system channel types as defined above, but excluding the uplink channel (defined as a percentage of the network downlink channel).

[1] The 650 MHz is comprised of spectrum required for safety-related and time-critical information (legacy telemetry), networked downlink telemetry, video downlinks, and uplink traffic. However, with respect to the bands identified in Doc. USWP8B05-11 (Rev3), the additional spectrum will be used exclusively for non-safety related, downlink telemetry only, e.g. networked telemetry, video links, etc.

TABLE 1

**Parameters for Equations 1, 1.1, 2 and 3**

| Term | Description | Values | Units |
|---|---|---|---|
| $\Phi$ | Total amount of spectrum bandwidth needed for routine operations | Computed | MHz |
| $D$ | Current unmet demand for spectrum ("current shortfall")(total unmet demand obtained from historical data of 34% x 50% factor due to shortfall due to unavailable AMT spectrum) | 0.17 | %/100 |
| $L$ | Loss of ability to reuse channels in a given geographic region. Current reuse is approx.32%. Predicted to decrease by 25%. 0.32 x 0.25=0.08 loss | 0.08 | %/100 |
| $\mathcal{G}$ | Growth factor. Derived by applying an estimate of how fast spectrum efficient technology will be deployed to the exponential data rate growth | See Eq. 1.1 | none |
| $C_{ij}$ | Capacity in megabits per second (Mbps) | Computed | Mbps |
| $N_{TAi}$ | Number of test articles | (4, 4, 8) | None |
| $N_{cij}$ | Number of channels | (1, 1, 1)<br>(1, 1, 1)<br>(1, 0, 0) | None |
| $R_{ij}$ | Information rate generated by test article | (2, 120, 2)<br>(1.5, 40, 1.5)<br>(1, 0, 0) | Mbps |
| $I_{ij}$ | Information percent transmitted from test article (ratio of information telemetered to information rate collected on the test article) | (1, 0.25, 1)<br>(1, 0.2, 1)<br>(1, 0, 0) | %/100 |
| $\Omega_{ij}$ | Network overhead (protocol and message headers) | (0, 0.1, 0)<br>(0, 0.1, 0)<br>(0, 0.1, 0) | %/100 |
| $\varepsilon_{ij}$ | Error correction expressed as a percentage of traffic | (0, 0.1, 0)<br>(0, 0.1, 0)<br>(0, 0.1, 0) | %/100 |
| $U_{ij}$ | Usage: Proportion of time channel is used to transmit data (on-demand traffic is statistically bursty and may not fill the available channel capacity completely.) | (1, 0.8, 1)<br>(1, 0.8, 1)<br>(1, 0.8, 1) | %/100 |
| $\Sigma_{ij}$ | Total spectrum in megahertz for each system component | Computed | MHz |
| $M_{ij}$ | Modem efficiency | (0.5, 1, 1)<br>(0.5, 1, 1)<br>(0.5, 1, 1) | bps/Hz |
| $T_{ij}$ | Time guard (proposed Time Division Multiple Access, TDMA, architecture requires time between adjacent slots to allow for system-wide time reference inaccuracies, e.g., propagation time differences.) | (0, 0.1, 0)<br>(0, 0.1, 0)<br>(0, 0.1, 0) | %/100 |
| $G_{ij}$ | Frequency guard band expressed as a percentage of occupied ("Expanded") spectrum | (0, 0.1, 0.1)<br>(0, 0.1, 0.1)<br>(0, 0.1, 0.1) | %/100 |
| $P_{ij}$ | Packing inefficiency: the amount of spectrum that, although unused, cannot be used because it is not large enough to be occupied by a telemetry channel. | (0.1, 0.1, 0.1)<br>(0.1, 0.1, 0.1)<br>(0.1, 0.1, 0.1) | %/100 |

## 3 Sensitivity Analysis

An analysis was then conducted to determine the sensitivity of the estimates to changes in the values of key parameters. This was done by selecting one parameter at a time and changing the value above and below the nominal value by an appropriate amount. The equations were reset to the baseline values after each variation and the succeeding parameter varied. The sensitivity analysis showed that the spectrum requirement ranged from a low of 523 MHz to a high of 884 MHz. Since the median was higher than the mean, the amount of additional spectrum required to support AMT operations within the territory of one Administration was determined to be approximately 650 MHz.

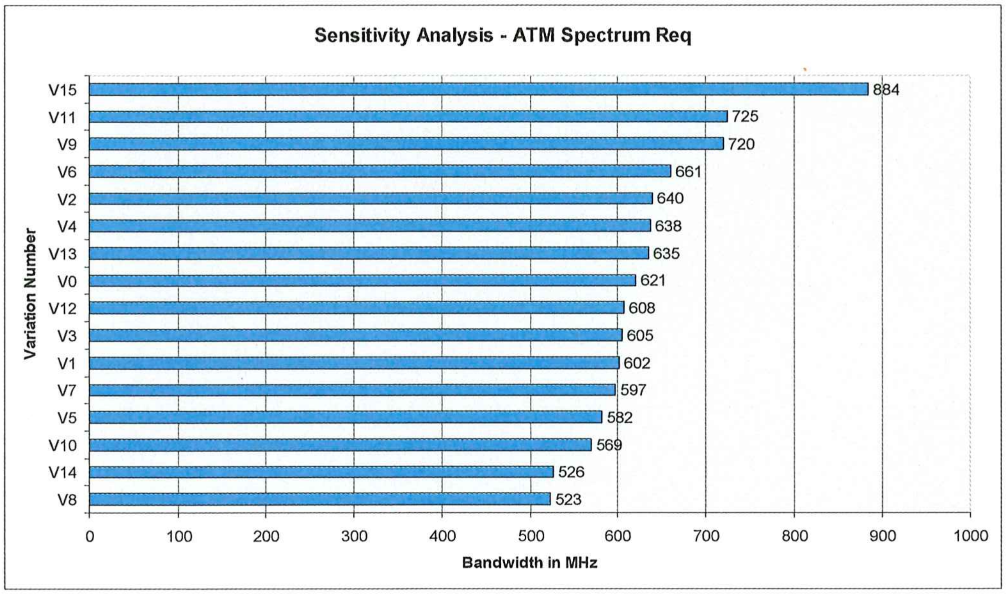


FIGURE 2

**Results of sensitivity analysis**

Figure 2 shows the results of varying each of the parameters by the amounts shown in Table 3.

To interpret the data:

1. Observe the "Variation Number" on the left side of the chart and then look for that number in the "Chart Label" column of Table 3.
2. If the variation number is the first value, the value used for this variation is in the column labelled "Low Value ". If the variation number is the second entry, look in the column labelled "High Value". The baseline values used in the Sarnoff report can be found in Table 1. The baseline parameter result (621 MHz) is labelled "V0" is Figure 2. Note that there are three variations for the modem efficiency parameter "$M_{ij}$". These are variations 7, 8 and 9 (V7, V8, V9). Refer to the "Description Column" for an explanation.
3. The amount of additional required spectrum predicted by each variation is shown in the column immediately to the right of parameter value. These are the columns labelled "$\Sigma_s$ Low" and "$\Sigma_s$ High".

Example: The largest value on the chart is 884 MHz for "V15" (variation #15). Referring to Table 3, the parameter value is "dbl", and the parameter that was varied was "$\mathcal{G}$" (growth factor). Hence, by doubling the technology growth parameter from that used in the baseline calculations, the amount of extra spectrum that would be required is estimated to be 884 MHz. Table 3 shows the parameters that were varied and by how much. Only the parameters from Table 1 that were varied are shown in this table. Only parameters that were judged to be subject to significant variation in range of values were varied. The column labelled "Chart Labels" refers to the labels shown on the chart in Figure 2. An asterisk (*) in the value columns refers to explanatory notes in the "Description" column.

TABLE 3

**Summary of parameter variations**

| **Term** | **Chart Labels** | **Low Value** | $\Sigma_S$ **Low** | **High Value** | $\Sigma_S$ **High** | **Description** |
|---|---|---|---|---|---|---|
| $D$ | V1, V2 | 0.12 | 602 | 0.22 | 640 | Current unmet demand for spectrum ("current shortfall") Total unmet demand obtained from historical data of 34% x 50% factor due to shortfall due to unavailable AMT spectrum |
| $L$ | V3, V4 | 0.04 | 605 | 0.12 | 638 | Loss of ability to reuse channels in a given geographic region. Current reuse is approx. 32%. Predicted to decrease by 25%. 0.32 x 0.25=0.08 loss |
| $\mathcal{G}$ | V14, V15 | half | 526 | dbl | 884 | Growth factor for routine operations. The growth curve used in the baseline was varied by first assuming the technology deployment rate was half that used for the baseline and then doubling the rate. The results at first appear counter-intuitive but in fact are representative of what actually occurs in practice – new technology creates demand. However, the new technology would also be available to the vehicles involved in complex tests using the predicated network technology, thereby offsetting growth in spectrum needed for routine operations. This coupling between routine and complex tests is not reflected in the equations. |
| $R_{ij}$ | V5, V6 | -10%* | 582 | +10%* | 661 | Information rate generated by test articles. * All data rates were decreased and increased by 10% of the values shown in Table 1. |

| Term | Chart Labels | Low Value | $\Sigma_S$ Low | High Value | $\Sigma_S$ High | Description |
|---|---|---|---|---|---|---|
| $I_{ij}$ | V10, V11 | 0.2* | 569 | 0.35* | 725 | Information percent transmitted from test article (ratio of information telemetered to information rate collected on the test article). * The percentage used in the baseline (see Table 1) varies depending on the system component category and the channel type. For these two variations only the aircraft network component values were varied since they are the major elements. Each aircraft value (i=1, j=2) was decreased by 5% for the "low" variation and increased by 10% for the "high" variation. |
| $\varepsilon_{ij}$ | V12, V13 | 0.05 | 608 | 0.15 | 635 | Error correction expressed as a percentage of traffic. The baseline value was varied by 5% wherever it appeared (j=2). |
| $M_{ij}$ | V7, V8 | 1.0* | 597 | 1.25* | 523 | Modem efficiency. * In the baseline calculation the modem efficiency was either 0.5 or 1.0, depending on the channel type (see Table 1). For this analysis, all the values were set to 1.0 for variation #7, based on the premise that all the radios used for the safety channel could eventually use the more efficient modems in development. Variation #8 sets all values to 1.25, forecasting the gain that may be achieved if the current research into more efficient modems is successful. A third variation, V9, was performed using a value of 0.75. This estimate reflects an engineering estimate of an average value of modem efficiency in the event that current developments fail to achieve the objectives set for them. This is a pessimistic estimate. The amount of additional spectrum estimated by this variation is 720 MHz |