5. USE OF THE MAN-MADE NOISE ESTIMATES IN DETERMINING SYSTEM PERFORMANCE

The usefulness of the man-made radio noise predictions given here will be determined by the degree to which they are applicable to the solution of frequency management or system design problems. We now have a means of estimating the average power, the average envelope voltage, and the average log of the envelope voltage as a function of location, time, and frequency. The question of what can be done with these parameters to provide an estimate of the performance of a system that is going to operate in an environment described by the parameters must be considered.

The first determination that can be made is whether or not the system will be limited by this type of noise and, if so, for what percentage of time this is likely to be the case. There are several limitations that might prevent the system from operating satisfactorily. Let us first consider other types of noise external to the receiving system. At the lower frequencies, that is at HF and below, atmospheric radio noise often will be the limiting type of interference for a fairly large percentage of the time, especially in rural areas. A comparison of the predicted levels of atmospheric radio noise for a given location and for various times as given by CCIR (1964) with the expected man-made noise will determine the choice between these two types of external radio noise to use in the particular design calculations to be made. Since both types of noise have similar characteristics, i.e., impulsive noise spikes superimposed on a white Gaussian noise background, a comparison of the F_a values generally will provide sufficient information on the relative importance of the two. At the higher frequencies where distant sky-wave propagation will not be present, the atmospheric radio noise can almost always be neglected. Only the noise from local activity will interfere under these conditions. In some cases where high reliability circuits are being considered, it may be necessary to determine the effect of local thunderstorm activity. In general, local activity will have the effect of disrupting the system for several milliseconds anywhere from two to three times a minute to once every 5 min over a period from 15 min to about 2 hrs. In areas of high thunderstorm activity, this intermittent interference may occur as much as 0.5 percent to 1 percent of the year. Since such circuits generally are designed to operate satisfactorily with a time availability of 0.95 (CCIR, 1966), the effect of local thunderstorm activity usually can be neglected at these higher frequencies.

The second type of noise to consider is galactic radio noise. At some locations, this may be the controlling type of noise for a large percentage of the time at any frequency above 20 MHz, but usually the man-made radio noise will be higher than the galactic noise up to someplace between 100 to 300 MHz. The predicted curve of galactic radio noise received on a short vertical antenna is shown on figure 1 (from CCIR, 1964). While the variation of this type of noise will be only about $\pm$ 2 dB with location and time for this antenna (Crichlow et al., 1955), the level at the terminals of any narrow beam antenna can vary considerably, depending upon the part of the sky within the antenna beam. For an antenna pointing in a fixed direction relative to the earth, the variations of the galactic noise level, if this is the predominant noise, can be measured easily as various parts of the galaxy pass through the antenna beam. Once this pattern has been found for a one-year cycle, it generally will be repeated with only minor variations. The largest variation would be due to the sun passing through the antenna beam if a 0.5° (or less) beamwidth were used. If the galactic noise information is required prior to the installation of a highly directional antenna, the expected levels can be calculated using sky temperature charts and knowing the antenna characteristics. Galactic noise is Gaussian in character, and this must be considered when comparing it with man-made radio noise. That is, even though the F_a value for the man-made noise may be below the F_a value for the galactic noise, the impulsive nature of the man-made noise can result in noise pulses greatly exceeding the galactic noise level.

If an omnidirectional antenna is used or any type of directional antenna used in a position where the ground is in the antenna beam, thermal noise from the ground, being at reference temperature, must also be considered. However, the only time that this contribution is of any consequence is when the external noise from all other sources is equal to or less than an F_a value of 6 dB. This type noise is also Gaussian in character, and, therefore, the APD is Rayleigh.

Consideration must also be given to the noise factor of the receiving system including antenna circuit losses, transmission line losses, and the noise figure of the receiver, including any preamplifiers or lossy circuits. In general, the receiving system noise figure does not need to be much lower than the expected external noise. If it is much higher than the expected external noise, redesign or improvement in the system noise figure generally will allow improvement in the performance of the communications system. Other factors (signal fading characteristics, intermodulation products, overload characteristics, etc.) may be the limiting factor in the system. If this is the case, equipment or system redesign may decrease these problems.

If it has been established that man-made radio noise will be the limitation to the operation of the system under consideration, the system performance in the predicted environment must be determined. In order to make this determination, a knowledge of how the system will operate in various noise environments is necessary. The required signal-to-noise ratio (SNR) will be dependent on the character of the additive noise and the characteristics of the system under consideration. When the SNR required to give satisfactory service in the expected type of environment has been determined, the required signal power at the terminals of a lossless receiving antenna (assuming all circuits will affect the signal and noise in the same manner) can be found by

$$P_s = F_a + B + R - 204 \text{ dBW} ,$$

where P_s = the required signal power at the receiving antenna terminals and R = the signal-to-noise ratio, in dB, required for satisfactory service. The value of F_a used here can be the estimated value for some percentage of time based on the median predicted value for the location, the decile value given for that type of location, and an estimate of the expected diurnal variation. This will then provide an estimate of the percentage of time that the required signal-to-noise ratio (and satisfactory service) will be achieved. The difficult part, of course, is determining the required SNR. Some values of required SNR's for certain systems have been established by the International Radio Consultative Committee (CCIR), The Electronics Industries Association (EIA), the Federal Communications Commission (FCC), etc. These values often are given based on the assumption that the interfering noise is Gaussian. Impulsive noise will affect system performance quite differently, and this must be taken into account when using these SNR's. The dashed line on figure 33 is the envelope distribution for Gaussian noise with the same rms value as the impulsive man-made noise sample shown. If the SNR for satisfactory operation in a Gaussian noise environment is used when the actual environment is predominantly man-made noise, an error of several decibels in required signal power could be obtained. For example, consider a binary noncoherent frequency shift keying (NCFSK) system for which a bit error of 10^{-4} or less is required.

For this system, the probability of bit error is given by one half the probability that the instantaneous noise envelope level exceeds the signal level (Montgomery, 1954). Therefore, from figure 33, the required SNR to achieve this performance is 9.5 dB for Gaussian noise, while for man-made impulsive noise (shown on fig. 33) a 29 dB SNR is required to achieve this same performance.

Two examples of methods used to find system performance in atmospheric radio noise are given in CCIR (1964). By using the values of F_a, V_d, and L_d given here, the same type of analysis can be performed for man-made radio noise.

The application of the amplitude statistics of man-made radio noise in determining system performance (i.e., the required SNR) is well documented in Part II, Bibliography, of this report, especially for various types of digital communications systems. Examples of work in this area have been given by Shaver et al. (1972), Gillilland (1972), Bello and Esposito (1969, 1970), Akima et al. (1969), Omura (1969), Halton and Spaulding (1966), Bello (1965), Conda (1965), and Lindenlaub and Chen (1965). These references specify the determination of system performance in impulsive noise.

6. MATHEMATICAL MODELING OF THE NOISE PROCESS

A number of schemes have been developed in the past to improve the operation of various telecommunications systems operating in the presence of noise environments. In the design of optimum detection schemes, the noise usually has been assumed to be Gaussian for lack of a better model that could be handled mathematically. This was the case even though it has long been recognized that the Gaussian model is rarely found unless the limiting noise is due to noise internal to the receiving system or from galactic radio noise. Several methods have been devised for providing better operation in the presence of impulsive noise. However, all of the more commonly used of these systems, e.g., wideband noise limiting or clipping, hole punching, smear-de-smear, etc., approached the problem by attempting to make the noise less impulsive or more Gaussian in character so that the available detection scheme would be operating in the type of noise for which it was optimized. While these methods do improve system operation under certain conditions, much greater improvement can be obtained by designing the system to match the noise.

For good system design and the determination of the optimum receiving system, more information about the noise is required than generally can be obtained from measurements. Therefore, a mathematical model for the random noise process (as seen by a receiver) must be developed. The problem is to develop a model for the noise that: (1) fits all the available measurements, (2) is physically meaningful when the noise sources, their spatial distribution, etc. are considered, and (3) is simple enough so that the required statistics can be obtained for solving the signal detection problem. In short, the problem is to do for the non-Gaussian man-made noise channel what statistical communications theory has achieved for the Gaussian channel.

Many attempts have been made in the past to model narrowband impulsive noise processes (Furutsu and Ishida, 1960; Bowen, 1963; Beckman, 1964; Galejs, 1966; for example). These models are essentially similar to each other in that they take the received noise to be composed of a sum of filtered impulses whose amplitude and occurrence in time follow various probability distributions. While the above forms are motivated well physically and can be made to fit measured first-order statistics (APD of the noise envelope and ACR, for example), they have several disadvantages as far as the signal detection problem is concerned. For example, these forms generally assume independence in the noise which is not always the case. They are not directly relatable to the physical characteristics of the noise sources, and the resulting statistics are so mathematically complicated that no attempt has been made to apply them to signal detection problems.

Various empirical models have been developed and related to measurements of impulsive noise (especially for atmospheric noise). These models do not represent the noise process, but only the measured statistics of the process and, therefore, are not, in general, applicable to determining optimum systems for the particular noise under consideration. These models have been used to determine the performance of various suboptimum receivers. Reference to all the above work can be found in the Bibliography, Part II, of this report.

Hall (1968) has developed a different model for impulsive phenomena and applied it to signal detection problems considering LF atmospheric noise. This model, in modified form, also has been shown to be appropriate for HF atmospheric noise and some kinds of man-made noise (Disney and Spaulding, 1970). While optimum receiving structures have been derived and the performance obtained, the Hall model is not easy to relate to the physical environment. Therefore, the proper values of the parameters that specify the model are difficult to obtain. Also, the model has infinite variance for a physically appropriate range of values. Recently, Giordano and Haber (1972) developed an excellent model for atmospheric noise based on the distributions and characteristics of the noise sources, and their approach might be applicable to man-made radio noise problems.

Recent work at OT/ITS has led to the development of a statistical-physical model for man-made noise (Middleton, 1972, 1973, 1974). This model is based on the actual physical parameters of the interference environment (source distributions in space and time, source waveforms, propagation, etc.). Received waveform statistics have been derived for this model, and they presently are being compared with measurements. Work on the analysis of system performance, deriving of optimal detection schemes, obtaining the performance of these optimal structures, waveform designs, etc. is in progress at OT/ITS using this basic statistical model.

7. CONCLUSIONS AND DISCUSSION

Estimates of the levels of man-made radio noise that will occur at locations and times in the future have been given. These estimates were obtained from the analysis of the OT data base of measurements made over the past several years. A method for obtaining the available noise power at a receiving location from the automotive traffic densities in the vicinity of this location has been developed. Also, measurements showing the noise power to be expected from high voltage transmission lines have been included. Some indication regarding the relationship between the horizontal and vertical components of the noise field has also been given.

Estimates of the average and average logarithm of the noise envelope voltage are given for two bandwidths, 10 kHz and 4 kHz. It has been shown that the parameters V_d and L_d are highly correlated, but that the noise level, F_a, is uncorrelated with the noise impulsiveness (as characterized by V_d). In addition, examples of detailed amplitude and time statistics of the received noise process have been shown.

While the OT/ITS data base is undoubtedly the largest single source of noise data available, it is still a relatively small sample considering the few areas actually investigated. One can ask if the results given are typical of all cities since most of the business and residential area measurements were made in medium or small size metropolitan areas. There appears to be no really good way of relating the man-made noise data to what would be found in a large metropolitan area such as New York City or Los Angeles until compatible measurements in this type of area are available for comparison. However, the following reasons seem to indicate that, with care, the estimates given here will be applicable: In general, the noise in the business and residential areas seems to be principally due to the noise sources within a fairly short distance of the receiving location. This is evidenced by the substantial changes in noise level that take place within a block when mobile measurements are being taken (Spaulding et al., 1971). A small area within a business area, as large as it is homogeneous, should not have too different characteristics, whether it is in Boulder, Colorado, or New York City. As long as traffic densities, power distribution systems, and other man-made radio noise sources are comparable and the general character of the areas is the same, the number of additional noise sources in the larger population area cannot be increased greatly per block. The only exception might possible be the presence of numerious high-rise office buildings, such as exist in some New York City business areas. In an area where freeways must carry large numbers of vehicles moving at a relatively high speed, the amount of traffic could be considerable higher, as might be the case when comparing Denver with, say, Los Angeles. However, when considering the business areas of these two locations, the street widths and speed limits are comparable; thus, traffic density cannot vary by a large amount, since traffic congestion is found at both places. From these considerations, it seems reasonable to expect the noise estimates to be as valid for New York City as for, say, Albuquerque, New Mexico, even though there is a twenty-to-one population difference.

Most of the rural data were taken in the sparsely populated areas of the western United States. Comparison with data from the few rural areas measured in the eastern United States does not seem to show significant differences, since these values were within the range of variations found from place to place in the western areas. The presence of nearby power lines, however, should be considered in all areas but especially in rural areas and at frequencies below about 20 MHz.

The analysis in this report indicates that the noise power decreases with increasing frequency at a rate of 27.7 dB/decade. Whether this same trend continues at frequencies above 250 MHz is unknown; in fact the 250 MHz values would suggest that the noise power might not decrease as rapidly, or even decrease at all, with increasing frequency for frequencies above about 100 MHz. There are some contentions that the man-made radio noise from ignition systems will show a peak between 300 and 500 MHz. However, the AMA peak measurements on individual cars do not bear this out, although peak values cannot be related to the received noise power. Also, the 250 MHz OT/ITS values may be high because of the editing process necessitated by the recording system noise factor at this frequency.

The results given in this report can only give estimates of the man-made noise at average or typical locations and at ground level. Any strictly local unusual effects must also be considered. For example, OT/ITS personnel found strong elevator control noise at 1.7 GHz to be the predominant source of interference at the top of an 18-story building, noise from computers and peripheral equipment to be even higher than traffic noise on the highway near the buildings at the old NBS site in Washington, D.C., and that the highest noise source at Pow Main, Alaska, was a beacon light on top of a 200-ft tower.

In 1967 the authors of this report prepared an estimate of the man-made radio noise expected in urban, suburban, and rural locations for JTAC (1968). Since the present estimates show as much as a 10 dB difference from the previous JTAC estimates and since the JTAC estimates have been widely used, a comparison of the two sets of estimates is in order here and is shown in figure 52. Note the scale change for the three types of areas on this figure to provide separation of the sets of curves. The first noticeable difference is in the shape of the JTAC curves with a break between 10 and 20 MHz. This occurred when data were combined from measurements made by various investigators at different times, locations, and frequencies, with no one set of data covering the whole frequency range. The break seemed not unlikely at the time since between 10 and 20 MHz the predominant noise sources change from those associated with power lines to automotive ignition systems. It appears now, though, that the real cause was due to the time and location variation, the incomplete frequency coverage of the measurements, and the attempt to relate dissimilar parameters.

The next obvious difference is in the nomenclature used to describe the types of areas. The designations of business, residential, and rural were chosen in place of urban, suburban, and rural, since the latter are based more on political divisions than on the uses of the area. For example, urban is within the limits of a city, while suburban is considered to be a fairly populous area surrounding a city but outside the city limits. However, the man-made radio noise is similar for residential areas or for business areas (shopping centers, manufacturing and service locations), whether they are within the political boundaries of a city or in a suburban area. Therefore, the new designations are more definitive and can be better identified and described without the ambiguities arising from using the previous designations.

The analysis of additional data has decreased the difference between the average values for the three types of areas. A good part of this difference results from the fact that the JTAC rural curve below 20 MHz was greatly influenced by the inclusion of the CCIR man-made rural noise data (CCIR, 1964). In the present analysis, these data were not included in the general rural area estimates since the data were from locations carefully selected in each case to be as free of man-made radio noise as possible. In addition, the data base from these locations far exceeded the amount of data collected at all other rural locations and would give undue influence to an estimate utilizing all rural data in one group. Altogether, a much better estimate of the man-made radio noise ant its location and temporal variations should be obtained from the present estimates than from the JTAC values.

8. ACKNOWLEDGMENTS

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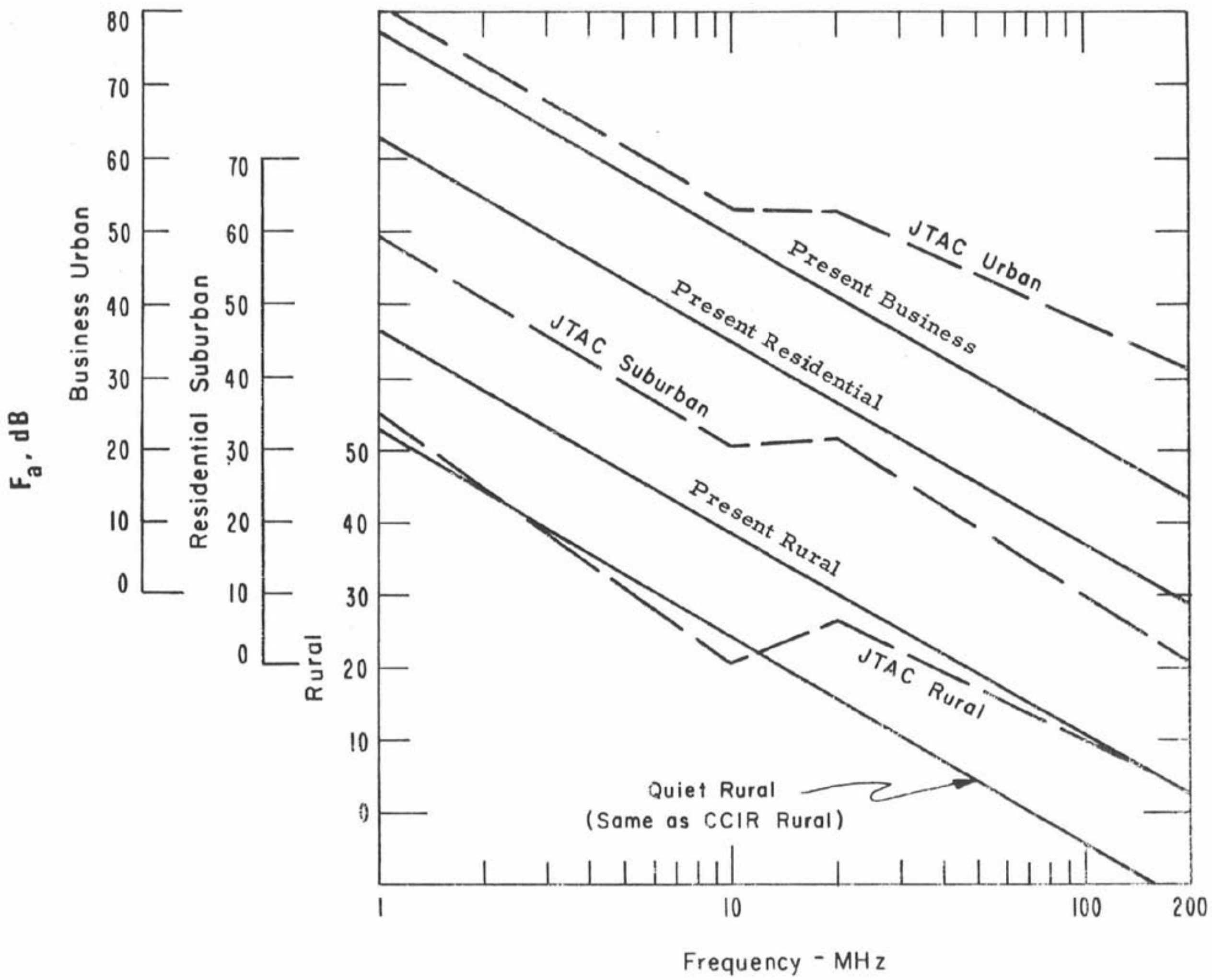

Figure 52. Comparison of present estimates with JTAC (1968) estimates.