MAN-MADE RADIO NOISE

PART I: ESTIMATES FOR BUSINESS, RESIDENTIAL, AND RURAL AREAS

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The Office of Telecommunications, Institute for Telecommunication Sciences (OT/ITS), over the past several years, has accumulated a data base of man-made radio noise measurements in the frequency range from 250 kHz through 250 MHz taken in a number of geographical areas. This data base has been analyzed to provide estimates of the expected characteristics of man-made radio noise in business, residential, and rural areas. The parameters used are the average available power spectral density, the ratio of the rms to the average voltage of the noise envelope, and the ratio of the rms to the average logarithm of the envelope voltage. The variation of these parameters as a function of frequency, location, and time are shown and discussed. Examples of amplitude and time statistics of the received man-made radio noise process also are shown and discussed. The use of the estimates is shown (principally by references in Part II, Bibliography) in the solution of problems encountered in frequency management and telecommunication system design.

Key words: Man-made radio noise, noise levels, noise characteristics, non-Gaussian noise, impulsive noise, system performance.

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1. INTRODUCTION

The interference environment present at a receiving terminal of a telecommunications system is one of the factors determining whether or not that link of the system will perform satisfactorily. In either the solution of a spectrum management problem or the design of a particular system, the determination of system performance is a prime consideration. In spectrum management, not only is information on the effect of the interference environment on the proposed system necessary, but also the change in the environment caused by the proposed system must be considered. In the design of any proposed system, these two effects need to be considered, though the effect of the environment on the system is generally the primary concern.

The interference environment will consist of all discrete signals present other than the desired signal (usually referred to as unwanted or undesired signals), broadband impulsive noise, the receiver's own internally generated noise, and various other unintended radiations. Often this composite interference environment, whether predominantly noise or unwanted signals, is referred to simply as "noise." In this report, the impulsive noise background will be termed "noise." This radio noise, as distinguished from unwanted signal interference, is a broad-band phenomenon often covering several octaves in frequency, and its spectrum can be considered flat across any bandwidth that is a small percentage of the center frequency of the receiving system.

In order to estimate the behavior of a telecommunications system at some future time, two types of interference information are required. One is the determination of the effect of all of the various kinds of interference environments on the system under consideration, and the other is the estimate of the interference environment that will be present at the time and place of actual system operation. The latter

involves a prediction process for estimating the characteristics of the environment within some degree of accuracy. The primary purpose here is to provide the best estimate possible of those characteristics of the noise process basic to systems design and analysis. In addition, some guidance in the use of these estimates in determining system performance is given in the text and in the references. To provide a better understanding of the estimates, short descriptions of the data base used for preparing the estimates and the equipment employed in the measurement program are included.

Part II of the report is a bibliography listing publications which give man-made noise measurements, techniques of measurement, and system design and analysis in impulsive noise environments.

2. NOISE PARAMETERS

The characteristics of the interference environment that determine the performance of a system will be dependent on the modulation-demodulation scheme employed; however, some characteristics of the radio noise process will greatly influence the operation of any system regardless of the detection scheme used. The most basic single parameter of the broadband interference is its power spectral density; that is, the noise power per unit bandwidth (OTP, 1970). This parameter must be known as a function of time, location, and frequency and should be given in a form which allows it to be compared with and combined with other types of interference, such as unwanted signals, internal receiver noise, etc. For the proper design or analysis of any modem, the probability density function of the detected noise envelope is generally required. This is generally given as the percentage of time the envelope voltage exceeds various voltage levels and as such is the amplitude probability distribution (APD). While the APD gives the amplitude behavior of the noise process, the time behavior is

also of importance for many types of interference. The time statistics most generally required for system analysis are the autocovariance function, the average crossing rates of the noise envelope (ACR), pulse spacing distributions (PSD), and pulse duration distributions (PDD). The last three, the ACR, PSD, and PDD, are a function of envelope voltage level. The above statistics are for the detected noise envelope; that is, for the noise process as seen by the receiving system under consideration (Montgomery, 1954; Watt et al., 1958; Middleton, 1960; CCIR, 1964, 1966; Wozencraft and Jacobs, 1965; Conda, 1965; Halton and Spaulding, 1966; Hall, 1966; JTAC, 1968; Bello and Esposito, 1969, 1970; Crippen et al., 1970; Akima et al., 1969; Omura, 1969; Shaver et al., 1972; Gillilland, 1972; and others in Part II, Bibliography). The envelope statistics are required since we are, in general, dealing with a narrowband noise process (i.e., describable by an envelope and phase) and the phase is uniformly distributed.

The basic unit used to describe the noise in these predictions is the power spectral density expressed in terms of an effective antenna noise factor, F_a (CCIR, 1957, 1964; OTP, 1970). The definition of F_a is

$$F_a = 10 \log_{10} f_a \quad , \tag{1}$$

where

$$f_a = \frac{p_n}{kT_o b} \tag{2}$$

and p_n is the external noise power available from an equivalent lossless antenna in bandwidth b, in watts, k is Boltzmann's constant $= 1.38 \times 10^{-23}$ Joules/°K, T_o is the reference temperature = 288° K, and b is the noise power bandwidth in hertz. Note that f_a is a dimen-

sionless quantity, being the ratio of two powers. The quantity f_a, however, gives, numerically, the available power spectral density in terms of kT_o and the available power in terms of $kT_o b$. For this reason, one commonly sees F_a with units attached (i.e., dB > kT_o or dB > $kT_o b$).

Relation (2) can be given as

$$P_n = F_a + B - 204 \text{ dBW} , \tag{3}$$

where $P_n = 10 \log p_n$, $B = 10 \log b$, and $-204 = 10 \log kT_o$.

Other methods commonly used to express the noise power are related simply to F_a (CCIR, 1957). For example, for the case of a short ($h << \lambda$) grounded vertical monopole, the corresponding vertical component of the rms field strength is given by

$$E_n = F_a + 20 \log f_{MHz} + B - 95.5 \left(\text{dB} > \frac{1 \mu V}{m} \right) , \tag{4}$$

where E_n is the rms field strength for the bandwidth b in dB > 1 μV/m, f_{MHz} is the frequency in megahertz, and λ is the wavelength in meters. Similar expressions for E_n can be derived for other antennas.

The relationship between f_a and the noise power in terms of an effective antenna noise temperature is given by

$$f_a = T_a / T_o , \tag{5}$$

where T_a is the effective antenna noise temperature in °K.

Since the noise level may result from a combination of noise generated internal to the receiving system and external noise, it is convenient to express the resulting noise by means of Norton's (1953) generalization of Friis' (1944) definition of the noise figure of a radio receiver. The system noise factor can be defined in terms of the

losses and actual temperatures of the various parts of the system. Loss in the circuit is taken here to be the ratio of available input power to available output power and will differ from the loss in delivered power unless a matched load is used. The noise factor of the antenna circuit, f_c, is

$$f_c = 1 + \frac{T_c}{T_o}(\ell_c - 1) , \tag{6}$$

where ℓ_c is the loss factor in the antenna and associated circuit, T_c is the actual temperature of the antenna circuit and nearby ground, and T_o is the reference temperature (288°K).

Similarly, the transmission line loss factor, ℓ_t, and temperature, T_t, will determine a noise factor, f_t, for the transmission line given by

$$f_t = 1 + \frac{T_t}{T_o}(\ell_t - 1) . \tag{7}$$

Using a receiver noise factor of f_r, and assuming the receiver is free of spurious responses, we can use Friis' method of combining noise figures in cascade to obtain a system noise factor, f, including external noise, f_a, which is

$$f = f_a + (\ell_c - 1)\frac{T_c}{T_o} + \ell_c(\ell_t - 1)\frac{T_t}{T_o} + \ell_c\ell_t(f_r - 1) . \tag{8}$$

If all temperatures are equal to T_o, equation (8) becomes

$$f = f_a - 1 + f_c f_t f_r . \tag{9}$$

The rms of the noise envelope voltage was used for all power measurements taken for this report. Calibration techniques allow this rms measurement to be referred to the terminals of an equivalent loss-

less antenna and given in terms of F_a in decibels. With the exception of the few measurements made using a half wave dipole in a corner reflector, all values of F_a were obtained using a short vertical antenna.

For an envelope having a deterministic waveform, a definite relationship between the rms voltage, the mean voltage, and other average values (such as the antilog of the mean logarithm, ALML, of the envelope voltage) can be found. A simple case would be a sine wave modulation, and a trivial case would be a constant CW signal. In the case of a random waveform such as that resulting from broadband impulsive noise, no definitive relationship exists. The ratios of the rms to the mean and ALML of the noise envelope voltage vary as the impulsive character of the noise varies with time, location, and frequency. A knowledge of these ratios provide useful information on the impulsive character of the received noise. For example, the ratio of the rms to the mean for white Gaussian noise is approximately 1 dB, while the ratio of the rms to the ALML is approximately 2.5 dB. As the noise becomes more impulsive in nature, these ratios will increase. Thus, if these ratios are known, or can be predicted, some information can be inferred on the distribution of the instantaneous envelope voltages (APD). Since the APD is required information for determining the expected performance of telecommunications systems, estimates of the expected values of these two ratios are useful. The ratio of the rms to the mean voltage is the voltage deviation (V_d in decibels). The ratio of the rms to the antilog-mean logarithm of the envelope voltage is the log deviation (L_d in decibels). For detailed definitions, see Crichlow, et al. (1960).

A direct relationship between the predicted moments (F_a, V_d, and L_d) and the most likely or expected APD is not presently available for man-made noise in a form such as that given for atmospheric radio noise by Crichlow et al. (1960) and later adopted in a simplified form

by CCIR (1964). A given APD will define a unique set of moments. The converse is not true, however, as a given set of the three moments could have resulted from any one of a family of APD's. The man-made noise generally is composed of contributions from a number of sources and will change rapidly in character with time and location as the noise contributions from the various sources change in relative amplitude. On the average, an APD similar to that observed for atmospheric radio noise is found for man-made radio noise. Typical APD's and their variations have been given for urban residential man-made radio noise by Spaulding et al. (1971).

3. ESTIMATION METHODS AND THE DATA BASE

Estimates of future man-made radio noise levels and other characteristics of the noise process can be of two forms. One is based directly on past measurements, and the other depends on the correlation of the noise with some predictable parameter of the environment for use as a "predictor" of the future noise. The first form, based on past measurements of the behavior of the noise at "typical" locations, assumes that the behavior patterns noted will continue into the future. The direct analysis of the available data base will then provide the estimates of the future man-made radio noise conditions that will exist at other locations. This process has been used to obtain the predictions for three types of locations: business areas, residential areas, and rural areas. The business area is defined here as any area where the predominant usage throughout the area is for any type of business. This includes stores and offices, industrial parks, large shopping centers, main streets or highways lined with various business enterprises, etc. The residential area is defined here as any area used predominantly for single or multiple family dwellings with a density of at least two

single family units per acre and no large or busy highways. An occasional isolated business such as a drugstore or filling station can be included, but a city block or more of concentrated business enterprises should be considered a business area. This definition applies to both urban and suburban residential areas. Rural areas are defined here as locations where land usage is primarily for agricultural or similar pursuits, and dwellings are no more than one every five acres.

In attempting to group the measurements in the data base into these classifications, some areas were found unsuitable for inclusion in any of the three groups. Some notable examples of these areas are interstate highways outside of the main towns or cities and fairly large parks and university campuses within cities. The available data for these three types of areas were not included in the general analysis but were analyzed separately to give an indication of what might be expected at such locations. In using the predictions, personal judgment will have to be used in selecting the "typical" area classification to be employed for any specific estimate.

The data base used in this report consists of some 300 hrs of F_a, V_d, and L_d data collected for each parameter simultaneously on eight frequencies over the period from 1966 through 1971. The measurements were made in six states--Colorado, Maryland, Texas, Virginia, Washington, Wyoming--and in Washington, D.C. The measurements were made in 103 areas; the area size ranging from a few square blocks in a business area to several square miles in some of the rural locations; the criteria usually being that the type of area remain the same for any one set of measurements or a measurement run. The period of measurement for each mobile run varied from approximately 15 min to over an hour. A few stationary measurements were made for a period of 24 hrs or longer. For many of the mobile runs in the business

and residential areas, average vehicle density information was obtained from past vehicle counts made by the local traffic engineering groups for the highways included in the area of the run. During one period, actual traffic counts were obtained during the measurement period.

The measurements used in the analysis for business areas were recorded at 23 areas in Boulder, Colorado Springs, and Denver, Colorado; San Antonio, Texas; Cheyenne, Wyoming; and Washington, D.C. The residential area data consist of measurements made at 38 areas in the cities and suburbs of Boulder, Colorado Springs, and Denver, Colorado; San Antonio, Texas; and Cheyenne, Wyoming. The data used for rural areas were recorded in 31 rural areas in Colorado, Maryland, Virginia, Washington, and Wyoming. Continuous runs were made for 24 hrs on the grounds of the Department of Commerce Boulder Laboratories. Two locations were used for these runs, one near the main radio building and the other near Broadway (the main highway passing in front of the Laboratory grounds). Additional data are in the ITS man-made radio noise data base, but they were not used for the present purpose because of the incomplete frequency coverage of those measurements or because of the specialized nature of the individual measurements.

To insure the complete compatibility of all data used to provide the estimates in this report, only data recorded using the OT/ITS equipment in the mobile radio noise laboratory were considered. A description of this equipment and the mobile noise laboratory is given in Appendix A. With the exception of the 24-hr runs on the Boulder Laboratory grounds, all measurements were made during the daytime hours, generally in the pre-noon period when atmospheric radio noise was at a low enough level so that man-made radio noise was the predominant factor at all frequencies. At times, the atmospheric radio noise dominated the readings at the lower frequencies in rural areas, but

these periods were edited out of the data as well as possible before the analysis was performed.

In some instances, again principally in rural locations, some limitation at 250 MHz was experienced due to the recording system noise factor (Appendix A, fig. A4).

Most of the data were recorded using short vertical monopole antennas essentially at ground level. No attempt has been made here to provide information on the effect of antenna height or direction of arrival of the man-made radio noise. Measurements during a short run using two dipole antennas in corner reflectors at 250 MHz simultaneously with one antenna in a vertical and the other in a horizontal configuration provide some information on the effect of polarization of the received man-made radio noise.

The second type of estimation involves the correlation of the received noise with various aspects of the environment which can be used as "predictors." There are three requirements for a predictor if it is to be of value in determining expected future interference levels. First, of course, the noise must correlate well with the statistics of the predictor. The second requirement is that statistical information concerning the predictor must be readily available, and third, an estimate of the future pattern of behavior of the predictor must be available. If these three requirements are met, then an estimate of the pattern of behavior of the predictor in the future will provide an estimate or prediction of man-made radio noise interference for the same future period. A number of possible predictors have been investigated, including obvious ones such as population density, electrical power consumption, and traffic density. The most successful predictor found to date in the frequency range above about 20 MHz is traffic density (Spaulding, 1971; Spaulding et al., 1971), and a method of estimating noise levels from automotive ignition systems near main highways is given in Appendix

B. This, combined with traffic engineering estimates of future highway usage, may provide the best estimate of future radio noise levels at many locations.

Relatively good correlation was found between power consumption in an area and the radio noise power below 20 MHz. Unfortunately, in most areas, statistics on power consumption are very difficult, if not impossible, to obtain. Statistics on population density are readily available for small areas (called a standard location area or SLA for the 1960 census) from the Census Bureau. Population density in a SLA, however, shows very poor correlation with the noise level measured in the SLA (Spaulding et al., 1971).

4. MAN-MADE RADIO NOISE ESTIMATES

4.1 Available Noise Power, F_a

In determining the expected man-made radio noise power and its variation for any given location from measurements made at other locations, several factors must be taken into consideration. The main factor, of course, is the similarity between the areas where the measurements were made and the area in question. For any particular location the noise level may be due to particular sources, such as factories in which a large number of arc welders are employed, power lines, etc. The estimates given here are in terms of business, residential, and rural areas, and a physical examination of the area in question should determine which of these types of areas will most closely correspond to the selected area. In addition to these three basic types of areas, estimates are also given for interstate highways and parks and university campuses. Estimates for power lines are also given.