Radiocommunications Agency - Feasibility Study into the Measurement of Man-Made Noise

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Abstract

This report details the work performed for the Radiocommunications Agency in support of a "Feasibility study into the measurement of man-made noise". The report first reviews the need for the study and briefly considers the overall impact of man-made noise on digital communication systems. A mathematical approach of representing man-made noise, which mainly is impulsive in nature, is outlined and the concept of using wavelets to characterise individual impulses is introduced. Models of man-made noise and data currently available, either within the ITU or from other sources, are reviewed and their limitations highlighted. The requirements of a man-made noise measurement programme, and the parameters required to characterise man-made noise are presented. Noise measurement techniques are then summarised and a digital system, which could satisfy the requirements using commercial off-the-shelf components, is outlined. Recommendations are proposed which include a risk reduction exercise.

Executive summary

When considering the design and planning of RF communication systems, radio noise defines the background signal level against which wanted signals must be demodulated. Two types of noise must be considered: natural/internal noise and man-made noise.

Natural and internal noise sources may be minimised using an appropriate frequency and good system and antenna design. Beyond this, however, the natural background noise sets the sensitivity limit of a communications system.

Man-made noise, arising due to a variety of emissions from electrical discharges and other sources, may set a higher background limit than natural and internal noise. The sources of this impulsive noise include:

a. noise from electrical machinery (particularly from commutating motors)
b. noise from spark ignition systems in petrol engines
c. switching transients
d. discharge lighting, etc

The effects of these noise sources on radio communications may be overcome locally if the specific source can be identified. Where an individual source cannot be identified these unwanted signal sources set a man-made noise background level.

The impact of man-made noise on digital communications systems depends on the characteristics of impulsive noise such as pulse power, duration and interval. The noise can impact on both the RF and IF stages and cause variations in AGC, carrier loss, synchronisation loss, and codeword errors. The detailed behaviour, however, is dependent on both the system implementation and the noise characteristics and consequently further work is required to fully characterise this.

Man-made noise models currently available within ITU are carried through from CCIR Report 258-5 [1990]. This report is largely based on measurements made in the USA in the years leading up to 1974 when digital RF systems were not widely deployed. The approaches currently adopted within ITU at lower (HF) frequencies, where a median noise level can be measured, may not be appropriate at VHF and higher frequencies particularly for digital systems. At these frequencies semi-impulsive peak levels may affect system performance even though the measured median noise level is below the internal noise level. Consequently, it is likely that the bandwidth parameter currently used to describe the non-Gaussian nature of the noise may not be adequate, particularly for wide-band systems.

The Noise Amplitude Distribution (NAD), which gives the number of pulses per second which exceed a given strength (or, strictly, a given energy) is considered to be the most appropriate noise descriptor for digital systems. A model based on this concept has not been developed but some limited measurements have been made.

The review concludes that the characteristics of man-made noise (i.e. pulse power, duration and interval) should be measured at a number of frequencies (between 40MHz and 3GHz), in differing environments and at different times of day/week to enable a more accurate model to be developed. To monitor long term variations of man-made noise these measurements should be repeated every five years.

To obtain the required man-made noise data, the requirements for a measurement programme indicate that data should be collected from 8 locations. These are: (large) city centre, factory estate, business centre, town centre, shopping centre/mall, major highway, suburban, and rural. The temporal characteristics should be obtained by performing measurements at mid morning, evening, and the rush hour (in relevant environments).

It is anticipated that statistically significant measurements may be obtained with measurement periods shorter than one hour. A system with a 10MHz measurement bandwidth sampled at 25MHz to 14 bits resolution will require 50MB of storage per second. To reduce the amount of data storage required, however, real-time on-board data pre-processing could be implemented.

The main elements of a modern digital measurement system have been considered and a system architecture is outlined. Such a digital system could be used to satisfy the measurement programme requirements detailed above. The system comprises a minimum of one general coverage receiver with an IF output of a bandwidth at least equal to the largest measurement bandwidth required. Much of the functionality of such a system can be realised by using off-the-shelf components.

The study recommends that:

1. Man-made noise data to support future digital systems and spectrum efficiency should be characterised and modelled.
2. The most appropriate method for digital systems is to produce statistics of Noise Amplitude Distributions (NAD) above a defined threshold, at a number of frequencies between 40MHz and 3GHz.
3. A risk reduction exercise should be pursued to measure the noise environment in few key locations, using low cost equipment. This will establish if narrow-band noise from computing or telecommunication equipment is likely to be a significant risk component of man-made noise. Such an exercise could also provide preliminary impulsive noise characteristics and contribute to the definition of the measurement hardware.
4. The measurement programme should consider man-made noise from differing environments such as: urban, suburban, industrial, business area, and along busy roadways, etc.
5. The programme should also consider the temporal characteristics of man-made noise and perform measurements appropriately, e.g. every four hours, weekends, seasonally.
6. The maximum communications bandwidth of at least 5MHz should be considered at frequencies ranging from 40MHz to 3 GHz.
7. In parallel to the measurement programme, the impact of impulsive noise on (technology neutral) digital communications systems be investigated to provide an indication of the amplitude thresholds critical to system disruption.

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1 Introduction

1.1 Background

1.1.1 In response to ITT 0110 (Ref: AY3952), the Defence Evaluation Research Agency (DERA) was contracted by the Radiocommunications Agency (RA) to perform a “Feasibility study into the measurement of man-made noise”. This final report details the work carried out for that contact.

1.2 Need for the study

1.2.1 When considering the design and planning of RF communication systems, radio noise defines the background signal level against which the wanted signals must be demodulated. Two types of noise must be considered when designing systems: natural/internal noise and man-made noise.

1.2.2 The main elements of natural/internal radio noise include:

a. noise generated internally in the receiving system due to thermal effects;
b. natural noise entering the receiving antenna due to lightning discharges (of main importance at frequencies below 30 MHz);
c. noise due to the black-body temperature of the ground and emissions from the sun and the galaxy.

1.2.3 The effect of such natural and internal noise sources may be minimised by good system and antenna design and by an appropriate choice of frequency. Beyond this, however, the natural background sets the limit to the sensitivity of a radio communications system.

1.2.4 Man-made noise, arising due to a variety of emissions from electrical discharges and other sources, may set a higher background limit than natural and internal noise. The sources of this man-made noise include:

a. noise from electrical machinery (particularly from commutating motors)
b. noise from spark ignition systems in petrol engines
c. switching transients
d. discharge lighting, etc

1.2.5 Man-made noise from these sources is generally broadband and the emission levels are largely controlled by manufacturing and distribution standards, such as the EMC Directive. Taking local action against a specific piece of equipment may control noise identified from nearby sources. Proliferation of such man-made noise sources, however, particularly in built-up and industrial areas, coupled with the propagation of the signal to a receiving antenna, may result in an integrated man-made noise level which may vary with location and time. This may be quantified statistically and used as a fundamental system design and planning parameter.

1.2.6 Other man-made noise sources not considered above include:

a. radiation from computing and telecommunications equipment and
b. unwanted (spurious) emissions from radio communication equipment.

1.2.7 These other man-made noise sources may exhibit discrete emissions on specific frequencies or across a frequency band. It is unclear, however, what their contribution to the background man-made noise level would be. As these emissions may be regulated, they are not considered further, except as part of a risk reduction exercise to ensure that the contamination does not hinder the measurement of impulsive man-made noise.

1.2.8 The effects of all these noise sources on radio communications may be overcome locally if the specific source can be identified. This may not be possible, however, for noise from telecommunication networks (e.g. VDSL and PLT) where the ubiquity of the wired network used for distribution may prevent avoidance action.

1.2.9 Where an individual source cannot be identified these unwanted signal sources may set a man-made noise background level. However, emissions from these unwanted and unintentional sources, which may have Gaussian noise characteristics in some cases, may make the interpretation of field noise measurements difficult. Ideally, techniques should be developed to measure the noise level by avoiding such emissions.

1.2.10 Based on the above noise considerations it is appropriate to consider a definition for man-made noise in terms of unwanted received signal power incident at a receiving antenna due to man's activities. In general, contributing noise sources may not be individually identifiable, or controlled, e.g. emissions from mobile sources. However, the resultant man-made noise background could be represented statistically in a manner appropriate for radio system design.

1.2.11 A distinction may be noted between the above approach, where the resultant received noise intensity is required, and measurements and standards of emissions from equipment. In the latter, an emission may be determined under specified test conditions, near to the specific equipment, or may be specified as a fraction of the output power of a transmitter.

1.2.12 The characteristic nature of the majority of man-made noise sources is that it is impulsive. Furthermore, the power or field strength distribution may not be Gaussian. This has been tackled in the ITU-R (when considering atmospheric noise due to lightning) by providing estimates of the median noise power and then by applying a bandwidth-dependent parameter to describe the amplitude probability distribution (APD).

1.2.13 The above approach may be suitable at lower frequencies (HF), where a median level can be measured, but may not be appropriate at VHF and higher frequencies. At these frequencies semi-impulsive peak levels may affect system performance even though the measured median level is below the internal noise level. Consequently, it is likely that the bandwidth parameter used to describe the non-Gaussian nature of the noise may not be adequate, particularly for wide-bandwidth systems.

1.2.14 Professor J D Parsons of Liverpool University has suggested an alternative approach. This approach seems to be based on the assumption that at VHF the noise sources are purely impulsive and that the noise amplitude distribution (NAD) essentially describes the number of impulses with a specified amplitude.

1.2.15 The appropriate method of describing man-made noise to meet the needs of communication system designers clearly needs to be studied, and recommendations made. Ideally, to achieve this it may be necessary to consider the modulation methods being used and proposed, as well as the required desired quality of service. It will certainly be necessary, however, to take account of the bandwidth of the communication systems.

1.2.16 The noise measurement feasibility study aims to address several of the above issues. Potential enhancements to the currently available noise models may not only optimise future (new or replacement) commercial systems, but also improve future planning and design techniques for the effective use of the RF spectrum.

1.3 Study Structure

1.3.1 The characteristics and the overall impact of man-made noise on digital communications systems is considered in Section 2. The mathematical representation of impulsive noise is outlined in Section 3.

1.3.2 The available noise models and data from the ITU and from other sources are briefly reviewed in Section 4 and Section 5 respectively, and their limitations highlighted.

1.3.3 Section 6 considers the potential requirements of a man-made noise measurement programme and Section 7 outlines typical hardware that could be used to satisfy the requirements.

1.3.4 A potential measurement programme is then described in Section 8, and a measurement strategy and budgetary costs are provided in Section 9.

1.3.5 The summary, conclusions and recommendations are reported in Section 10

2 Characteristics and impact of man-made noise

2.1 Overview

2.1.1 In this section the characteristics of man-made noise and the general impact that man-made noise may have on digital systems are discussed. A theoretical technique to distinguish man-made noise from additive Gaussian white noise is also presented.

2.2 Characteristics of man-made noise

2.2.1 By far the most important source of noise in mobile communication bands is that radiated by electrical equipment of various kinds and is often termed 'Man-made Noise' (MMN).

2.2.2 Man-made noise is usually impulsive in nature [Parsons, 2000], which means that its characteristics are fundamentally different from random noise of a thermal origin.

2.2.3 Impulsive Noise (IN) is characterised by bursts of very short duration, which may have random amplitude and random time of occurrence. Impulsive noise typically comes from electrical equipment where sparks occur. A prime example of this source is the car engine. Firstly, it is ubiquitous and secondly, the individual sources can be quite strong due to the high voltage breakdown at the spark plugs.

2.2.4 Taking the spark plug as an example, the sequence of events which leads to radiated interference is that (typically) initially contact breaker points open, interrupting the flow of current in the primary of the ignition coil and inducing a voltage of about 15 kV in the secondary (Figure 2-1 and Figure 2-2). This 15 kV is sufficient to break down the air in the spark plug gap. The spark typically lasts for less than a microsecond and sustains a time varying current, which is a function of various resonances (from parasitic inductances and capacitances), in the (mainly) high-tension wiring. Thus the pulse has an oscillatory component.

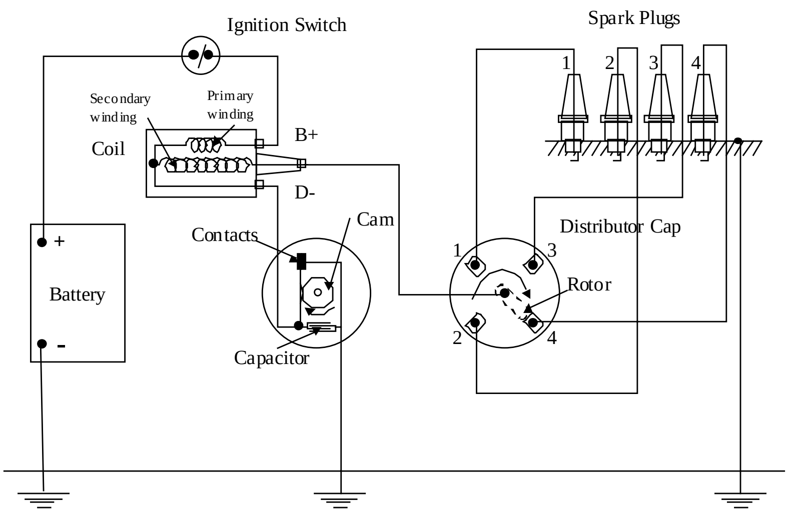


Figure 2-1 Car ignition schematic

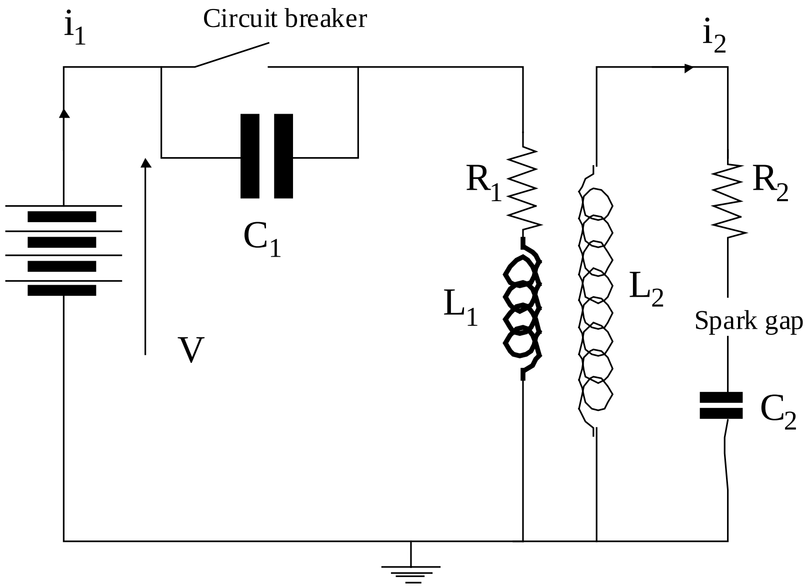


Figure 2-2 Equivalent circuit of car ignition

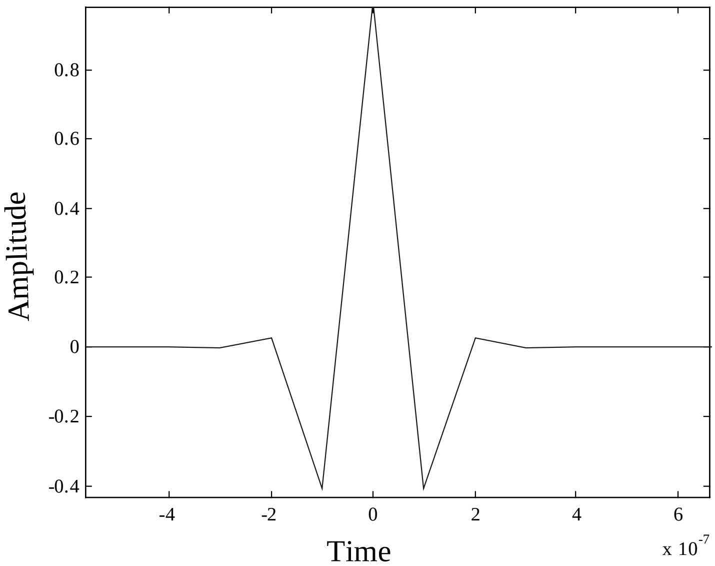


Figure 2-3 Illustrative pulse in time domain

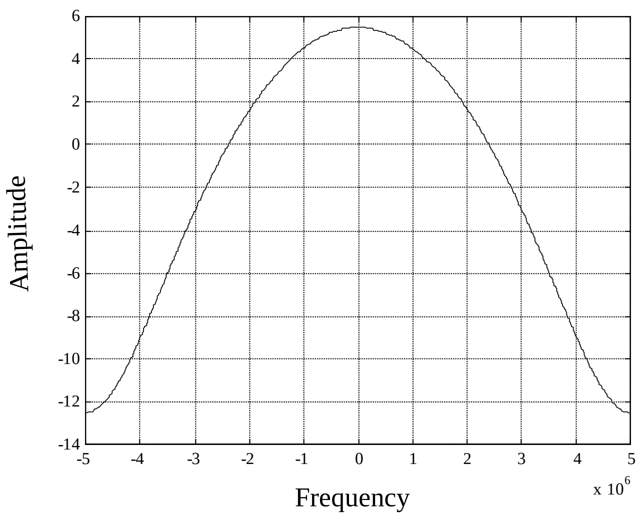


Figure 2-4 Illustrative spectral amplitude

2.2.5 Figure 2-3 and the two-sided spectrum in Figure 2-4 are for illustrative purposes. Actual pulses will differ in scale and detail from these illustrations. For example, it is anticipated that electrical interference bandwidths could exceed hundreds of MHz. MMN has been detected at frequencies up to 7 GHz [Parsons, 2000].

2.2.6 It is instructive to consider the power as a function of filter bandwidth for IN. For IN, the single pulse has a frequency spectrum, which has a phase that changes slowly with frequency (when any variation due to the definition of time origin is removed). Consequently, the *voltage* out of a filter depends on the filter bandwidth provided the filter bandwidth is much less than the impulse spectral bandwidth. Consequently, there is a 6 dB change in instantaneous power from the filter, within the impulse time, for every doubling of filter bandwidth. This 6 dB change occurs approximately up to the occupied bandwidth of the pulse. Beyond this bandwidth the power out of the filter is approximately constant.

2.2.7 In contrast, for White Gaussian Noise (WGN), the frequency spectrum components have random phase with a decorrelation frequency roughly the inverse of the time domain waveform duration. Thus, beyond the coherence bandwidth, the power out of the filter changes by 3 dB for every doubling of the filter bandwidth. Furthermore, provided the WGN is white, the power out of the filter will continue to increase with increasing filter bandwidth.

2.2.8 The instantaneous total power out of the filter will be a combination of the powers from IN and WGN and is shown schematically in Figure 2-5.

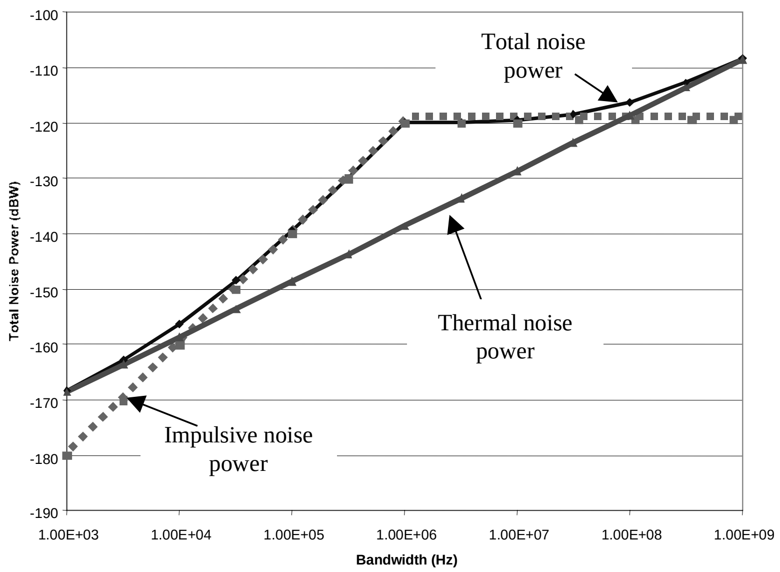


Figure 2-5 Noise power output from filters of different bandwidths

2.2.9 In Figure 2-5 the noise power output is shown for a filter for different bandwidths in a constant noise environment comprising WGN, probably from a thermal origin, and IN. The intercepts on the ordinate are arbitrary and depend, *inter alia*, on the noise figure of a receiving system and the strength of the IN environment. For reasonable combinations of IN and WGN, there will be a characteristic 'knee' corresponding to the matching of the filter bandwidth to the IN pulse bandwidth. Hence, starting at very narrow bandwidths, the response will rise at either 3 dB or 6 dB per doubling of bandwidth depending on whether WGN dominates. The relative strength of the two components is reflected in the vertical translation of one curve relative to the other. If WGN is totally dominant, the filter response will only change by 3 dB per bandwidth doubling. If IN is totally dominant, the filter response will initially change by 6 dB per bandwidth doubling followed by 0 dB per bandwidth doubling beyond the knee point.

2.2.10 Viewed in the time domain the output of a variable bandwidth filter may be observed as a function of the filter bandwidth. Starting at the narrowest bandwidth, if WGN is dominant, the impulse noise will not be visible. As the bandwidth of the filter is increased, the IN increases at 6 dB per doubling in bandwidth so that, at some stage, the IN may dominate over the WGN. At this stage, the IN will be visible as a series of short pulses above the WGN and each of duration of approximately 1/B, where B is the bandwidth of the filter. As the bandwidth of the filter is increased further, there comes a point when the WGN dominates over the IN and, at that stage the IN is no longer visible above the WGN.

2.2.11 It follows from the above discussion that the optimum filter to detect the IN has a bandwidth close to that of the IN pulses. In the circumstance where the IN pulse bandwidth is very wide, the widest possible filter bandwidth is optimum for detection. The measurement bandwidth, however, may be constrained by the system bandwidth being investigated.

2.2.12 It also follows that, when detecting IN using a filter, one with as little ringing as possible avoids the possibility of mistaken identification of additional pulses. It has already been pointed out in [Parsons, 2000] that filters with a Gaussian passband have a single pulse impulse response. Hence, filters of this design will be optimum for measurements of IN.

2.3 Impact of Impulsive Noise on Digital Communications Systems

2.3.1 The impact of random noise on digital communications systems is well known and has been extensively analysed [Mohany, 1991].

2.3.2 A digital radio communications system comprises a transmit system, propagation channel and a receive system. The interference is typically injected when the signal is propagated, but can be generated local to the receiver (e.g. when the receiver is mounted in a vehicle). What is at issue is the performance of the receive system in the presence of the combination of WGN and IN.

2.3.3 It should be noted that in the discussions below, the bandwidth and filtering stages between the antenna and receiver section are not considered. These stages may significantly band-limit the signal and minimise the impulse power at the receiver.

2.3.4 Additionally, the impact of MMN on lower level functions such as coding, interleaving and modulation is highly dependent on the implementation of that function. For example, a single impulse in a code word would be correctable with a simple code, but a sustained burst could be more of a problem. This, however, could be mitigated using burst error correcting codes, or large interleaves to spread the burst over many code words. For soft decision decoding a received sample pushed far away from its true position could cause a whole sequence of errors, but again could be mitigated by massaging the error metrics. These aspects are not considered further in this overview

2.3.5 In general, a digital receiving system (Table 2-1) comprises a number of stages corresponding to different types of processing:

Receiver Stage	Typical Functions
RF Processing	Pre-selection filtering, Low Noise Amplification, Down-conversion to IF, Automatic Level Control
IF Processing	Despreading (eg CDMA, FHSS), Further filtering to the data bandwidth, Amplification
Demodulation	Shaping, Filtering, Symbol Detection, Carrier Recovery
Baseband processing	Bit stream generation, De-interleaving, Decoding, Synchronisation, Framing

Table 2-1 Typical receiving system stages and processing performed

2.3.6 Depending on the strength of the IN, it could impact on the RF and IF stages. This may manifest itself in variations in AGC, loss of carrier and loss of synchronisation. The detailed behaviour in these circumstances requires further work, probably with realisations of receivers and IN generators. It is assumed here that the IN is within one or two orders of magnitude of the thermal noise.

2.3.7 In the case of CDMA, it can be seen that the de-spreading process may change the characteristics of the IN. However, if the IN is very wide-band, then the correlation of an impulse with a pseudo-random spreading code will have little effect on the shape of the impulse. In general, since the impulse is unlikely to coincide with a transition of the spreading code, it will emerge from the product process relatively unaltered.

2.3.8 In the case of FHSS, the desired receive band is hopped across the hopping band. Due to the wide instantaneous bandwidth of the IN, it is likely to be present in most of the hops. Hence the impact of IN is relatively unaltered by the FHSS despreading process.

2.3.9 Particularly important is the impact of the IN and WGN in the detection process. Detection, typically (PSK signals) involves the synchronised sampling of the output of matched filters [Mohany, 1991]. In QPSK, for example, following carrier lock, the baseband symbols are obtained by sampling the outputs of matched filters on the in-phase and quadrature channels at the symbol rate.

2.3.10 At any instant of time, the output of the matched filters will include:

- the signal
- the IN
- the WGN.

2.3.11 The signal and the WGN will be continuously present, whereas the IN will be output for a period after an impulse is received. At the sampling instant, there will be a combination of all three sources. The combined voltage is compared to a threshold, in order to determine the form of symbol, which is present. In the case of PSK, the in-phase and quadrature filter outputs are converted into an amplitude and phase. The symbol is detected based on the region occupied by the tip of the complex signal phasor. In the case of QPSK, the complex plane is divided into four 90-degree sectors.

2.3.12 Put succinctly what matters is the amplitude of the IN and WGN components in the matched filter bandwidth compared to the amplitude of the signal component.

2.3.13 The root-mean-squared (rms) WGN power is given by the noise power spectral density in the bandwidth of the matched filter. It is well known that the WGN amplitude is Rayleigh distributed, although the de-correlation time is of the order of the filter impulse response time (symbol duration). Provided the symbol duration is much greater than the individual impulse duration, the amplitude of the IN component is proportional to the matched filter bandwidth and the rms IN power is proportional to the square of the matched filter bandwidth. Individual power considerations aside, the characteristics of the IN and the WGN in the demodulator are essentially indistinguishable. This point is illustrated by Figure 2-6 and Figure 2-7, which compares the autocorrelation of the noise output from a square-root raised cosine matched filter for WGN and IN. It can be seen from the figures that the response is nearly identical.

2.3.14 Thus it can be seen that the *total power* of the IN and WGN in the demodulator bandwidth affects the performance of the demodulator. However, it should be noted that the IN will only affect the output whilst the IN is present on the input, to the time resolution given by the impulse response of the matched filter.

2.3.15 There are other demodulation issues for IN since the matched filter will 'ring' from a noise impulse. This means that the noise will impact on the demodulation of other symbols dependent on the strength of the IN and the ringing characteristics of the filter. This situation is in contrast to WGN where the noise is present all the time. Figure 2-8 shows the pulse output from a matched filter for a single IN pulse and illustrates the spreading out of the response over time. For strong IN this effect will be important. It should be noted that, although the matched filters are generally designed to reduce intersymbol interference, this relies on the timing of the data and the zero intersymbol interference will not apply to the IN contribution, which can arise at random times.

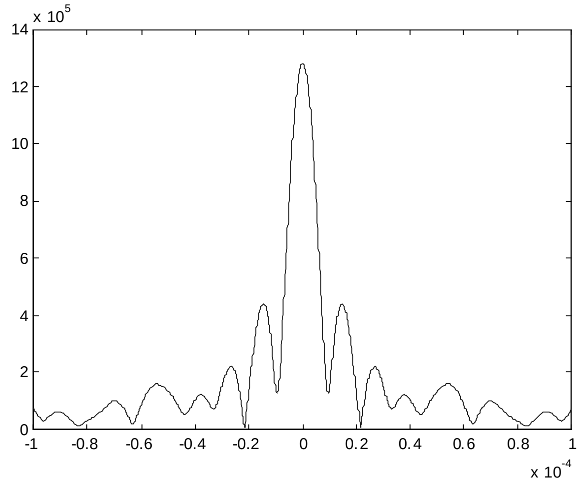


Figure 2-6 Autocorrelation for WGN out of matched filter (arbitrary vertical scale)

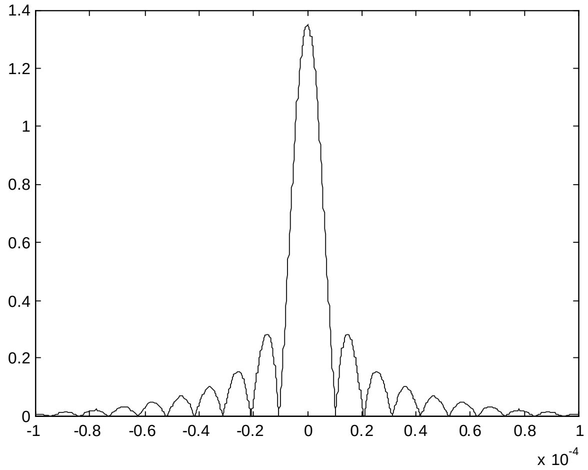


Figure 2-7 Autocorrelation for IN out of matched filter (arbitrary vertical scale)

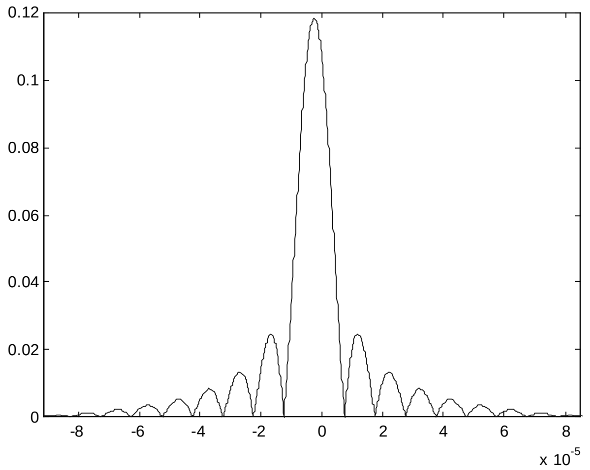


Figure 2-8 Single IN pulse output from matched filter. The symbol rate is 100 kHz

2.3.16 In a simple model, the IN arrives at the receiver at a random time, at random amplitude, but with a postulated average repetition rate. It is a working assumption that the presence of the impulse within the demodulation filter bandwidth will result in data errors. The impact of the impulse depends on a range of factors such as whether interleaving is present and the type of encoding present on the system.

2.3.17 However, given that a single impulse affects a limited number of symbols, it then follows that the symbol error rate is proportional to the number of impulses per second. Note that this is not the symbol error rate, in the conventional sense, in that conventional error rate is expressed as the fraction of errored symbols or bits compared to the total number of symbols, or bits transmitted. Hence symbol error rate (SER) due to impulse noise is given by:

$$SER \propto \frac{R_I}{R_S}$$

2.3.18 where *SER* is the symbol error rate, R_I is the rate of impulses per second and R_S is the symbol rate. Note that the above equation is in contrast to reference [Parsons, 2000] where Bit Error Rates are quoted in isolation of any particular data rate.

2.3.19 The above has provided an overview of the systems impact of impulsive noise. The detailed behaviour of impulsive noise requires further work, probably with realisations of receivers and IN generators. It has also been shown that two important characteristics of noise that should be measured and modelled are noise amplitude and noise duration.

2.4 Noise environment relation to receiver performance

2.4.1 This section addresses the relationship between descriptors of the MMN environment with receiver performance.

2.4.2 It has been proposed that the MMN environment be characterised by the Noise Amplitude Distribution (NAD). The NAD is expressed in terms of the 'spectrum amplitude' in dB(µV/MHz) against the average number of noise pulses per second. This section relates the conventional noise figure performance to the spectrum amplitude.

2.4.3 A typical receiver unit of a radio communication system is an antenna, coupled to a bandpass filter, followed by a Low Noise Amplifier (LNA). The LNA is followed by down-conversion mixing to IF followed by further amplification, before symbol and other processing.

2.4.4 The noise figure arises from the excess noise contributed by the receiver chain. The noise figure, *F*, is defined at any point in the receiver chain as:

F = Total Noise from Receiver Chain/Thermal Noise

2.4.5 where the thermal input noise is measured at the same point in the receiver chain. Thus if the gain in the receiver chain is '*G*', then:

$$F = \frac{GkTB}{GkT_0B} = \frac{T}{T_0}$$

2.4.6 where *k* is Boltzmann's constant, *T* is the effective noise temperature of the receiver chain, T_0 is the ambient temperature, and *B* is the receiver bandwidth at the point of measurement.

2.4.7 The minimum possible noise figure according to the above criteria is unity or 0 dB. Given that 0 dB noise figure is the minimum achievable, it would appear reasonable to relate the noise environment to this minimum noise figure.

2.4.8 On the assumption that environmental noise is isotropic, the antenna gain characteristics are not relevant and the noise power normalised to the antenna input is:

$$P_0 = kT_0B \qquad \text{(a)}$$

2.4.9 For a 300K ambient temperature this noise power is -143.6 dBW/MHz. Given a matched impedance of *Z*, the power is related to voltage by:

$$P_0(W/MHz) = \frac{V^2}{2Z} = \frac{(\mu V/MHz)^2}{2Z} \times 10^{-12} = 2 \times dB(\mu V/MHz) - 140 \qquad \text{(b)}$$

2.4.10 for a *Z* of 50 Ω. Combining (a) and (b) gives for the spectrum amplitude:

$$Ambient = -1.8\ dB(\mu V/MHz)$$

2.4.11 This figure provided an illustrative baseline against which man-made noise NAD may be compared to thermal noise.

2.5 Summary

2.5.1 Very large pulses have not been considered. A characteristic of IN, is that the single pulse has a frequency spectrum, which has a phase that changes slowly with frequency.

2.5.2 For impulse noise (IN) pulses, which are within some orders of magnitude of the thermal noise level, the demodulation performance of a digital receiver will depend on the total power of the IN and WGN in the demodulator bandwidth. For strong IN, the 'ringing' characteristic of the demodulator filter can cause multiple symbol errors. However the base is a single symbol error for each impulse. It is expected that the error rate will be inversely proportional to the symbol, or bit rate, for a fixed number of pulses of IN per second. This is in contrast to reference [Parsons, 2000], which states a fixed error rate for a fixed number of pulses of IN per second. The measurement bandwidth of noise is also considered.

2.5.3 The impact of impulsive noise on coding, modulation is highly implementation dependent. Much work, however, needs to be done to confirm the performance of digital systems using digital receivers and noise generators. Furthermore, the impact of very large IN needs to be investigated.

3 Mathematical representation of impulsive noise

3.1 Overview

3.1.1 In the following sections mathematical techniques used to represent impulsive noise are considered. The first technique builds on the representation of man-made noise as a set of impulses and builds on the work of Parsons [1979, 2000].

3.2 Technique to represent noise

3.2.1 A simple model that has been used for impulsive noise is the impulse function δ. Strictly speaking, this is a generalised function but can be regarded as the limit of a sequence of pulses (δ_n) such that

$$\int_{-\infty}^{\infty} \delta_n(t)dt = 1 \quad \textit{for} \quad n = 1,2,\ldots$$

and the width of δ_n tends to zero as $n \to \infty$. One thereby obtains the integral representation

$$\int_{-\infty}^{\infty} \delta(t)x(t)dt = \lim_{n\to\infty} \int_{-\infty}^{\infty} \delta_n(t)x(t)dt = x(0) \qquad (1)$$

for any continuous time signal *x*.

3.2.2 Physically, impulsive noise arises from natural sources such as electrical storms and from many different artificial sources including car ignition systems, power transmission lines, industrial plants and domestic equipment. Such noise can have an adverse effect on radio communication systems. It is therefore desirable to have a statistical framework for characterising man-made noise.

3.2.3 The essential characteristics of impulsive noise are that the individual events have a very short temporal duration and the noise voltage is random during this brief interval. Thus, an impulsive noise event $z(t)$ is confined to a short time interval $t_0 - \Delta t \le t \le t_0 + \Delta t$. Within this interval, $z(t)$ has a random and most likely oscillatory character. Outside the interval, $z(t)$ vanishes so that $z(t) = 0$ for $t < t_0 - \Delta t$ and $t > t_0 + \Delta t$. Although the impulse function is a simple and tractable representation of an impulsive noise event, it is probably too much of an idealisation for the present purposes. If the delta function equals '1' the impulse function will contain all frequencies in equal measure. Physically, one expects an impulsive noise event to have a wide but not necessarily infinite bandwidth.

3.2.4 In the next section, a model for impulsive noise will be proposed with a view to measuring various parameters at a given time and location. These measurements can then be used to fit a statistical model. In the following section, the new model will be demonstrated by means of some simple simulations. The model is built up in stages starting with a single pulse model. This is then extended to a train of pulses and then further extended to using wavelets to provide the necessary model data.

3.3 Model of a single noise impulse

3.3.1 A reasonable model for a single noise impulse is

$$z(t) = p(t - t_0)u(t) \tag{2}$$

3.3.2 where $p(t)$ is a pulse function localised at $t = 0$ and $u(t)$ is a noise-like waveform with unit amplitude. If $p(t)$ is confined to the time interval $-\Delta t \le t \le \Delta t$ then the behaviour of $u(t)$ outside the interval $t_0 - \Delta t \le t \le t_0 + \Delta t$ is unimportant. Physically, it should be possible to measure the width and magnitude of the pulse $p(t - t_0)$ as well as the time t_0 at which it occurs. The energy

$$E_z = \int_{-\infty}^{\infty} z(t)^2 \, dt \le \int_{-\infty}^{\infty} p(t)^2 \, dt \tag{3}$$

3.3.3 is also of interest and can either be measured or inferred from the duration and magnitude of $p(t)$.

3.3.4 The effect of passing the noise pulse through a linear time-invariant (LTI) filter can be simulated. If *h* is the impulse response of the filter then the output is

$$y(t) = (h * x)(t) = \int_0^{\infty} h(\tau)p(t - t_0 - \tau)u(t - \tau)d\tau \tag{4}$$

3.3.5 It has been assumed that the filter is causal which implies that $h(\tau) = 0$ for $\tau < 0$. It can be shown that if g_1 and g_2 are functions which vanish outside the intervals $[\alpha_1, \beta_1]$ and $[\alpha_2, \beta_2]$ respectively then $g_1 * g_2$ vanishes outside the interval $[\alpha_1 + \alpha_2, \beta_1 + \beta_2]$. Thus, if the pulse $p(t)$ is confined to $-\Delta t \le t \le \Delta t$ and the impulse response $h(\tau)$ is confined to $0 \le \tau \le T$ then $y(t)$ vanishes outside the interval

$$t_0 - \Delta t \le t \le t_0 + T + \Delta t .$$

3.3.6 This incidentally shows that a short impulse response or equivalently a large bandwidth transfer function will reduce the amount by which the pulse is spread out after passing through the filter.

3.3.7 Using standard analytical results, it can be shown that

$$|y(t)| \le \|h\| \max|p| \quad \text{for all } t$$

where $\|h\| = \int_0^{\infty} |h(t)| dt$ and $\max|p|$ is the maximum value of $|p(t)|$. Furthermore,

$$E_y = \int_{-\infty}^{\infty} y(t)^2 \, dt \le \|h\| E_z .$$

3.3.8 The constant $\|h\|$ is determined by the normalisation of *h*. For a short impulse response, $h(t)$ will be localised near $t = 0$. On account of the expected behaviour of a good filter and (1), it is reasonable to assume that $\|h\| \approx 1$.

3.4 Model of a train of noise impulses

3.4.1 Man-made noise may not comprise a single impulse but a train of pulses. These impulses can be represented as a sum

$$z(t) = \sum_n p_n(t) u_n(t) \tag{5}$$

3.4.2 of individual noise impulses. In order to obtain a model that can be parameterised to some extent, it is convenient to choose a canonical pulse $p(t)$. Then the individual pulses $p_n(t)$ can be represented in the form

$$p_n(t) = a_n p\left(\frac{t - t_n}{\Delta_n}\right)$$

3.4.3 where a_n is the amplitude of the pulse, t_n is the time of occurrence and Δ_n is the duration of the pulse. The model (5) for impulsive noise then becomes:

$$z(t) = \sum_n a_n p\left(\frac{t - t_n}{\Delta_n}\right) u_n(t).$$

3.4.4 The amplitude a_n, time of occurrence t_n and duration Δ_n are three parameters which characterise an individual pulse and which can be measured with suitable instrumentation. Since the factor a_n is associated with each impulse, it can be assumed that the noise waveform $u_n(t)$ either has unit amplitude or at least does not exceed unit amplitude for most of the time interval

$$t_n - \frac{\Delta_n}{2} \le t \le t_n + \frac{\Delta_n}{2}$$

3.4.5 occupied by the pulse.

3.5 Properties of noise Impulses in the frequency domain

3.5.1 The frequency characteristics of impulsive noise or filtered impulsive noise are considered below. Taking the Fourier transform of (2) gives

$$Z(f) = \int_{-\infty}^{\infty} e^{-2\pi i t_0 \nu} P(\nu) U(f-\nu) d\nu \qquad (6)$$

where:

$Z(f)$, $P(f)$ and $U(f)$ are the Fourier transforms of $z(t)$, $p(t)$ and $u(t)$ respectively. Similarly, the Fourier transform of $y(t) = (h * z)(t)$ is

$$\begin{aligned} Y(f) &= H(f) Z(f) \\ &= H(f) \int_{-\infty}^{\infty} e^{-2\pi i t_0 \nu} P(\nu) U(f-\nu) d\nu \end{aligned} \qquad (7)$$

3.5.2 Little can be said about (6) or (7) without some knowledge of the random waveform $u(t)$. Since $P(f)$ has a large bandwidth and $U(f)$ is likely to have a large bandwidth, $Z(f)$ is well spread out and $Y(f)$ will probably occupy most or all of the bandwidth of $H(f)$.

3.5.3 This above illustrates why impulsive noise is a problem that must often be dealt with in the time domain.

3.6 Modelling from statistical data

3.6.1 The measurable quantities, time of occurrence t_n, pulse duration Δ_n and pulse amplitude a_n can be used to obtain statistics about the impulsive man-made noise in a given location at a given time. A series of measurements would produce a time series

$$\{(t_1, \Delta_1, a_1), (t_2, \Delta_2, a_2), \ldots, (t_N, \Delta_N, a_N)\}$$

representing the impulsive noise over a given period and at a given location.

3.6.2 One useful statistic for the design of radio communications systems would be the average time interval between impulses with an amplitude exceeding some level A say. In fact, this is just the Noise Amplitude Distribution proposed by Parsons [1979]. This could be estimated from the data using the formula

$$T_A = \frac{1}{M-1} \sum_{k=2}^{M} \left(t_{n(k)} - t_{n(k-1)} \right)$$

3.6.3 where $t_{n(1)}, t_{n(2)}, \ldots, t_{n(M)}$ are the time indices of pulses with amplitude $a_{n(k)} \geq A$.

3.6.4 An estimate of the average noise power is given by

$$\overline{P} = \frac{P_0}{t_N - t_1} \sum_{n=1}^{N} a_n^2 \Delta_n$$

where

$$P_0 = \int_{-\infty}^{\infty} p(t)^2 dt$$

3.6.5 is a constant determined by the choice of the canonical pulse $p(t)$.

3.7 MATLAB demonstration of proposed noise model

3.7.1 Model of single Impulse

3.7.1.1 Figure 3-1 demonstrates the proposed model for a single noise impulse. The envelope $p(n)$ is a Gaussian function and the noise waveform $u(n)$ is a sequence of random numbers uniformly distributed in the interval $[-1,1]$.

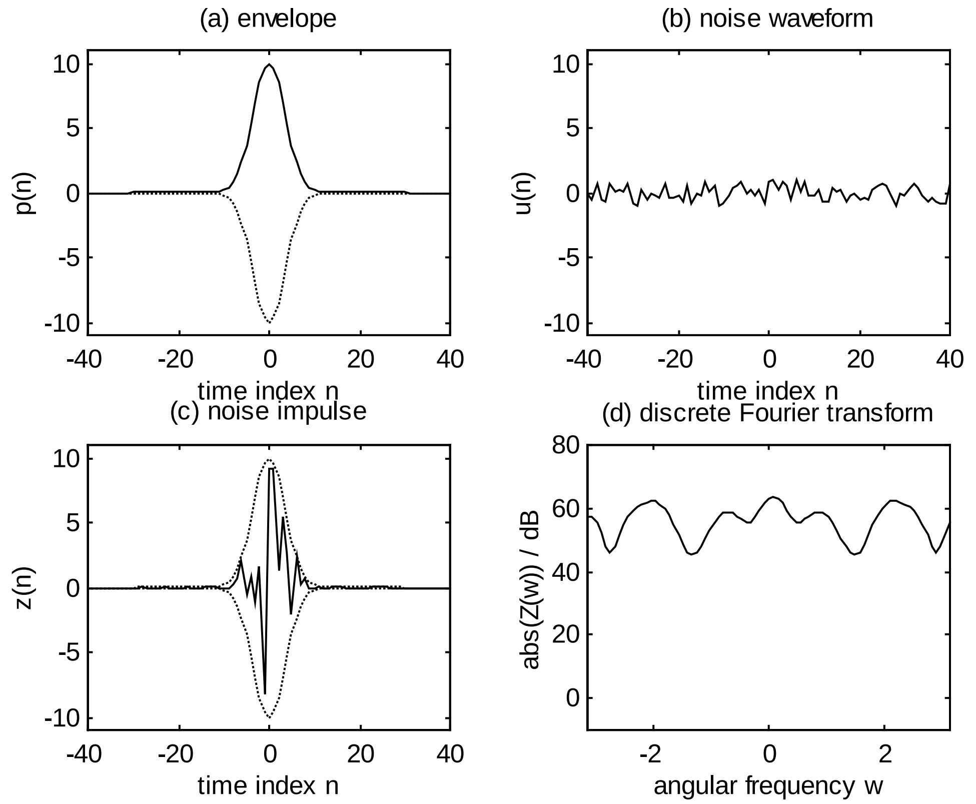


Figure 3-1 Noise impulse

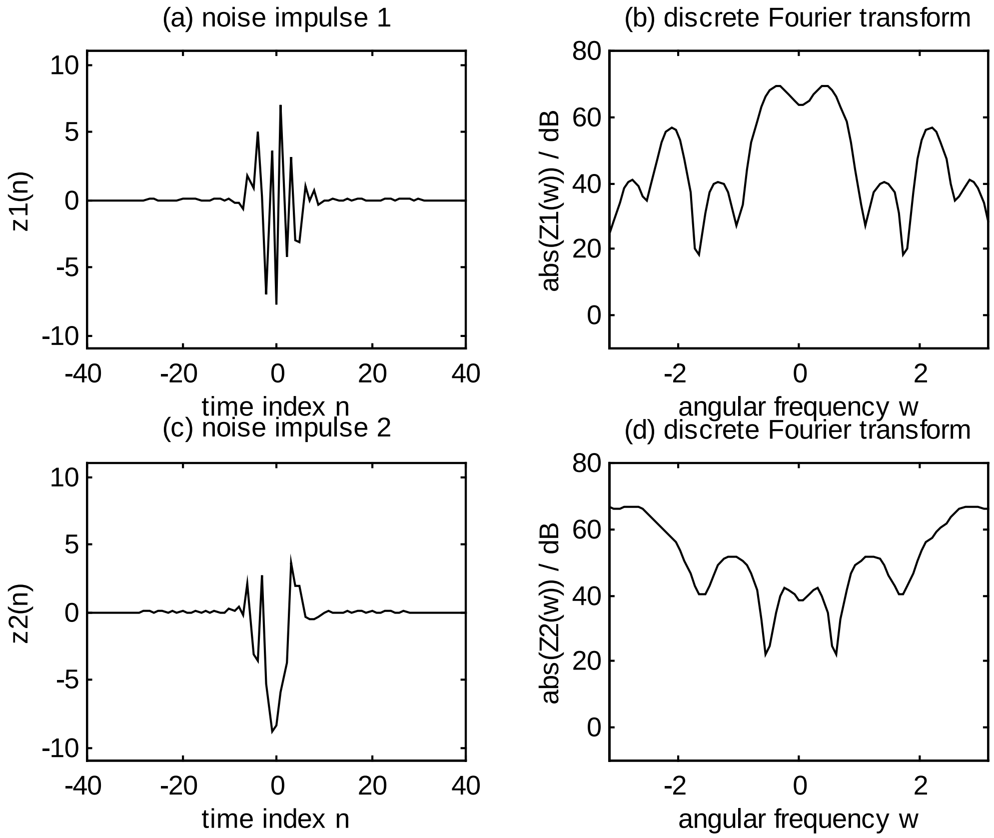


Figure 3-2 Spectra of two noise impulses

3.7.1.2 Figure 3-2 shows the discrete Fourier transforms of a pair of noise impulses with the envelope $p(n)$ and noise waveform $u(n)$ as in Figure 3-1. Though broadly similar in terms of being in the 20dB-60dB range and spread across the entire normalized frequency band, the two spectra differ in shape because of the random character of $u(n)$.

3.7.2 Model of pulse train

3.7.2.1 Finally, Figure 3-3 demonstrates how a train of noise impulses can be regarded as a linear superposition of individual noise impulses.

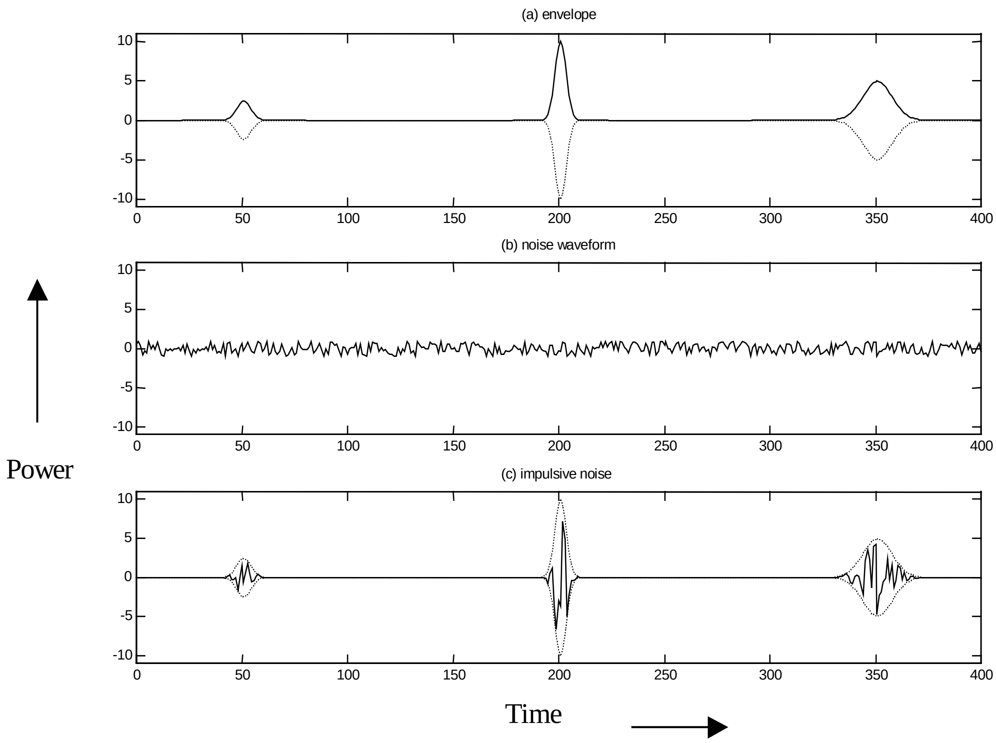


Figure 3-3 Train of noise impulses

3.8 Data analysis using wavelets

3.8.1 A potentially fruitful approach, which might be developed to characterise individual noise impulses is the use of wavelets. A brief outline of wavelets is provided below and by Frazier [1999] and Burrus *et al*. [1998].

3.8.2 If $\psi(t)$ is a square integrable function (e.g a finite energy signal) and *j* and *k* are integers, then $\psi_{j,k}(t)$ is the scaled and translated version of ψ :

$$\psi_{j,k}(t) = \frac{1}{\sqrt{2^j}}\psi\left(\frac{t-2^j k}{2^j}\right)$$

3.8.3 This is standard notation in wavelet theory. As illustrated in Figure 3-4 $\psi_{j,k}$ is obtained by scaling the basic function ψ and shifting this scaled version along the t-axis. If ψ is a special kind of function called a wavelet then every square integrable function can be expanded in terms of the translated and scaled wavelets $\psi_{j,k}$. In other words, if $g(t)$ is square integrable (a finite energy signal for example) then there is a sequence of coefficients $c_{j,k}$ such that

$$g(t) = \sum_j \sum_k c_{j,k}\psi_{j,k}(t) \qquad (8)$$

3.8.4 It is even possible to choose ψ so that the set $\{\psi_{j,k}\}$ forms an orthonormal basis of the Hilbert space $L^2(\mathbf{R})$ of square integrable functions (finite energy signals). Such a wavelet is called an orthonormal wavelet. If ψ is an orthonormal wavelet then the coefficients $c_{j,k}$ in (8) represent a partitioning of the total energy

$$E_g = \int_{-\infty}^{\infty} |g(t)|^2 dt$$

3.8.5 because the Hilbert space generalization of Pythagoras' theorem gives

$$E_g = \sum_j \sum_k |c_{j,k}|^2$$

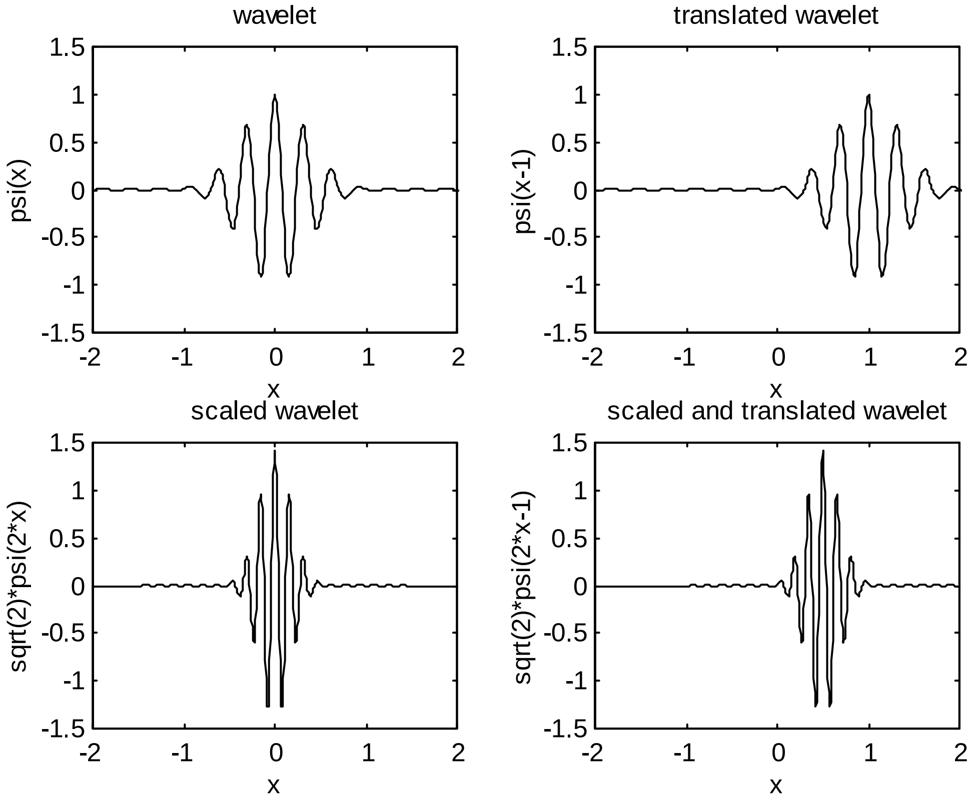


Figure 3-4 Scaling and translation

3.8.6 Although this is not an *a priori* requirement, a wavelet ψ is usually localized around $t = 0$. Thus, if $\psi(t)$ vanishes outside the interval $-1 \le t \le 1$ then $\psi_{j,0}(t)$ vanishes outside $-2^j \le t \le 2^j$ and $\psi_{j,k}(t)$ vanishes outside $2^j(k-1) \le t \le 2^j(k+1)$. Note that the basis functions $\psi_{j,k}$ always overlap except for simple wavelets, which lack desirable properties. The amount of overlap depends on the choice of wavelet and can be considerable. Thus, $|c_{j,k}|^2$ can be taken to represent the energy content of ψ at scale 2^j and in the time interval

$$2^j\left(k - \frac{1}{2}\right) \le t \le 2^j\left(k + \frac{1}{2}\right)$$

3.8.7 Since j can be positive or negative, the scale 2^j can be arbitrarily large or small. In a signal processing context, scale is closely related to the idea of frequency and $|c_{j,k}|^2$ can be conceptualised as the signal energy contained in a tile of the time-frequency plane. For this reason, the basis functions $\psi_{j,k}$ are referred to as *time-frequency atoms* in a signal processing context.

3.9 Analysis of noise using wavelets

3.9.1 It is reasonable to assume that a real noise impulse has finite duration and limited amplitude. In fact, since it is physically impossible to have a truly discontinuous change from one voltage level V_1 to a distinct voltage level V_2, a noise waveform must be continuous. It can, therefore be concluded that noise impulses are amenable to wavelet analysis provided they can be measured and digitised with equipment having an adequate bandwidth.

3.9.2 If $z(t)$ is a noise signal with wavelet transform

$$z(t) = \sum_j \sum_k c_{j,k} \psi_{j,k}(t)$$

3.9.3 then the full set of coefficients $(c_{j,k})$ contain enough information to fully reconstruct the signal $z(t)$. In general, the sequence $(c_{j,k})$ may have infinitely many non-zero terms but $z(t)$ can be approximated to arbitrary precision with a finite number of terms. Furthermore, efficient algorithms exist for computing the coefficients from a sampled signal. The technology and methodology for generating the wavelet transform is therefore readily available and largely an issue of software development or using existing software tools. Wavelets are closely related to sub-band transforms and therefore suited to the implementation of filter banks. As discussed earlier, Figure 2-5, a filter bank may provide a means of extracting information about impulsive noise embedded in thermal noise.

3.9.4 Many wavelets exist and, as can be seen from Figure 3-5 to Figure 3-7, some of these have very different characteristics. In particular, some wavelets are smooth and can be differentiable to any required order while other wavelets have a noise-like character. Intuitively, it seems that these noise-like wavelets might be an approach for characterising the structure of noise. Furthermore, filter banks may be implemented by the use of wavelets, and the use of a suitably designed filter bank may be an effective means of (a) distinguishing impulsive noise from thermal noise and (b) obtaining measurements of the impulsive noise.

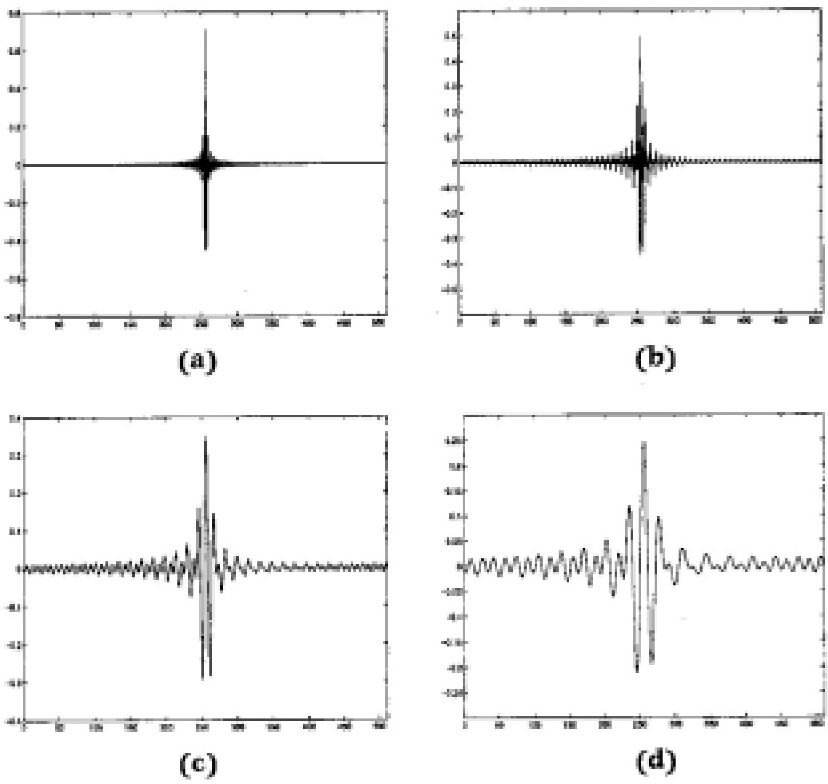


Figure 3-5 Shannon wavelets

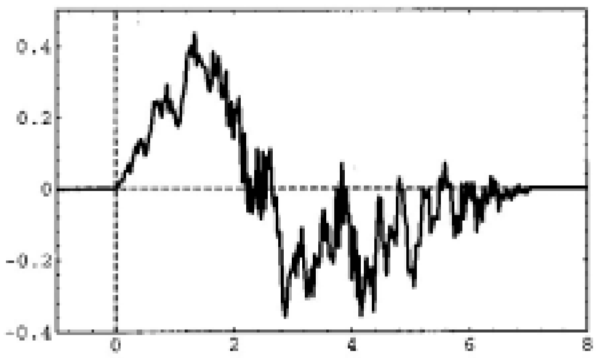


Figure 3-6 Flat wavelet

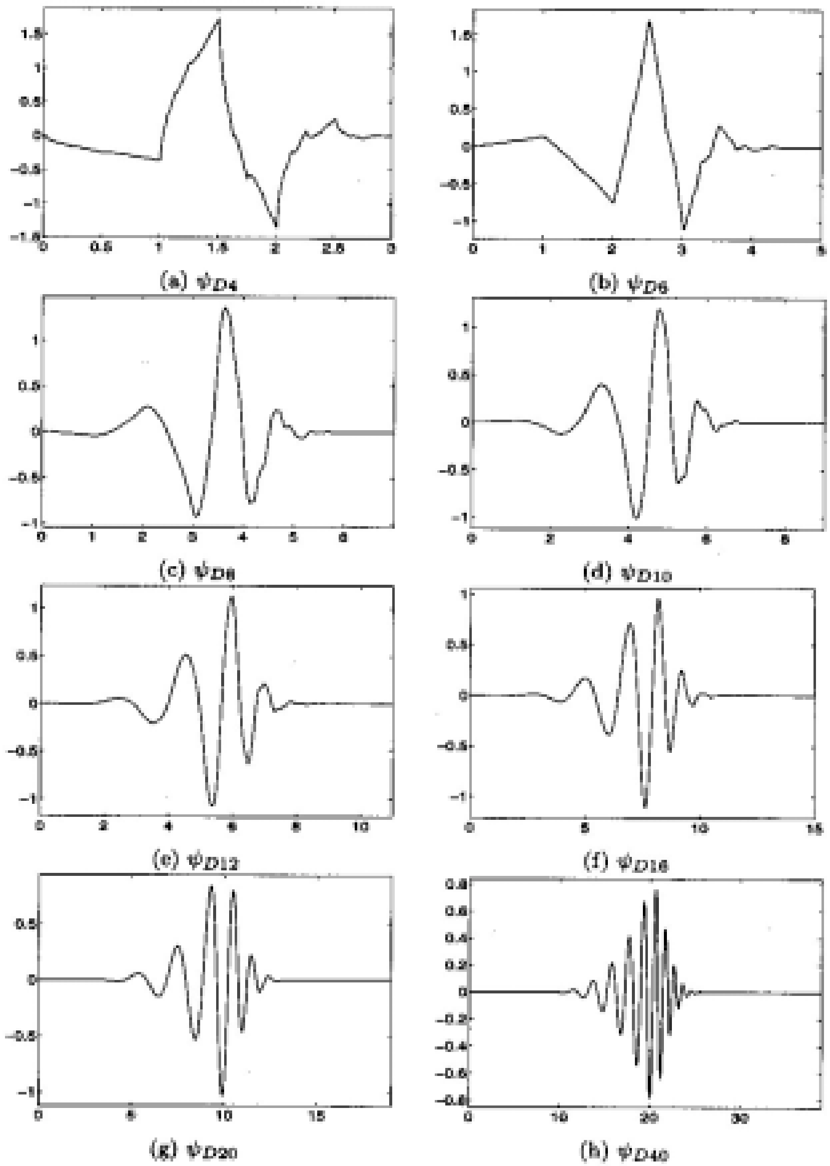


Figure 3-7 Daubechies wavelets

3.10 Summary

3.10.1 The mathematical representation of noise as a set of impulses has been considered and a noise model for a single and a train of pulses is proposed. The difficulty of representing noise in the frequency domain, and why it is often dealt with in the time domain is also demonstrated. A technique using wavelets, that could be useful to characterise the structure of impulse noise, is introduced.

4 Summary of noise models and data within the ITU

4.1 Overview

4.1.1 In this section the available noise models, particularly those that are readily available from the ITU, are summarised. The aim is to consider the adequacy of the current techniques. A summary of data available outside the ITU is reported in Section 5.

4.2 Radio Noise: ITU-R Recommendation P.372-7

4.2.1 The current ITU Radio Noise Recommendation P.372-7 [2000] is an amalgamation of a number of earlier documents concerning radio noise. In particular it includes the CCIR Reports 322-3 [1986] entitled “Characteristics and Applications of Atmospheric Radio Noise”, and Report 258-5 [1990] “Man-made Radio Noise”.

4.2.2 The earlier version of the Recommendation, P.372-6, was approved in 1993 and this version remained unchanged until 2000, when an addition was made to the section on man-made noise, based on a contribution from the USA.

4.2.3 Most of the studies of the characterisation of external radio noise have been undertaken for atmospheric noise due to lightning in the frequency range between 10 kHz and 30 MHz. This type of noise is impulsive in nature and the studies were aimed at mapping the temporal and spatial variations in noise intensity and in finding ways to characterise its non-Gaussian nature. Later work within the ITU forum sought to characterise man-made noise at frequencies up to UHF using the same approach, although little information has been provided in the ITU text on its non-Gaussian character. Thus the method used for the presentation of atmospheric noise due to lightning will be discussed first.

4.3 Presentation of atmospheric noise due to lightning

4.3.1 Atmospheric noise data (Recommendation ITU-R P. 372-7 [2000]), which reproduces material from the earlier CCIR Report 322-3) is presented for four-hour time blocks in the four seasons. For each block, maps are presented (and are also available in numerical form) for the median external noise figure, F_{am}, at 1 MHz.

4.3.2 The external noise figure, F_a, for any time percentage, is defined as:

$$F_a = 10 \log f_a$$

where:

$$f_a = \frac{P_n}{k\, t_0\, b}, \qquad \text{and}$$

P_n = available noise power from an equivalent loss less antenna

k = Boltzmann’s constant = 1.38×10^{-23} J/K

t_0 = reference temperature (K) taken as 290 K

b = noise power bandwidth of the receiving system (Hz).

4.3.3 For a short ($h << \lambda$) vertical monopole above a perfect ground plane, the vertical component of the rms field strength is given by:

$$E_n = F_a + 20\log f_{MHz} + B - 95.5 \qquad dB(\mu V/m)$$

where:

E_n = field strength in bandwidth b *(where* $B = 10\log b$*)*, and

f_{MHz} = centre frequency (MHz);

and similarly for a half-wave dipole in free space:

$$E_n = F_a + 20\log f_{MHz} + B - 99.0 \qquad \text{dB}(\mu\text{V/m})$$

4.3.4 The Recommendation also gives, for each time block, the variation of F_{am} with frequency, the decile ratios of F_a, and the standard deviations of the median and decile values.

4.3.5 However, the noise power, while needed in determining the signal-to-noise ratio, for example, is seldom sufficient to determine system performance (white Gaussian background noise being the only exception). Appropriate probabilistic descriptions of the impulsive nature of the received random noise waveform are required. Methods of treating the impulsive nature of atmospheric radio noise, particularly for the lower frequencies and narrow receiver bandwidths, were extensively studied in the 1950's and 1960's. The methods explored are described by Horner [1964].

4.3.6 The method eventually used was to specify the Amplitude Probability Distribution (APD) of the received envelope. The method was based on the feature that the ratio of rms to mean amplitudes, in decibels, V_d did not depend markedly on receiver bandwidth [Spaulding et al , 1962]. Curves, with V_d as parameter, for a bandwidth of 200Hz were constructed, which had a Rayleigh distribution for levels exceeded for large time percentages, and a distribution which has a straight line on Rayleigh paper at small time percentages. A circular arc on Rayleigh paper joined these two segments. The resultant curves continue to be included in the ITU-R Recommendation and are shown in Figure 4-1. The Recommendation provides a set of curves for the conversion of V_d values for other bandwidths and then, using the appropriate value for V_d , gives curves for the APD (Figure 4-1).

4.3.7 It is not clear how much attention was given at that time to HF noise levels at wider bandwidths. Some of the curves given by Clarke [1962], however, and quoted by Horner [1964], cover the frequency range from VLF to HF. Horner does state that "the curves are slightly unrealistic, however, in that experimental distributions are often limited rather more abruptly at the high voltage end, and the probabilities of very high voltages are therefore somewhat less than that indicated by the idealised curves".

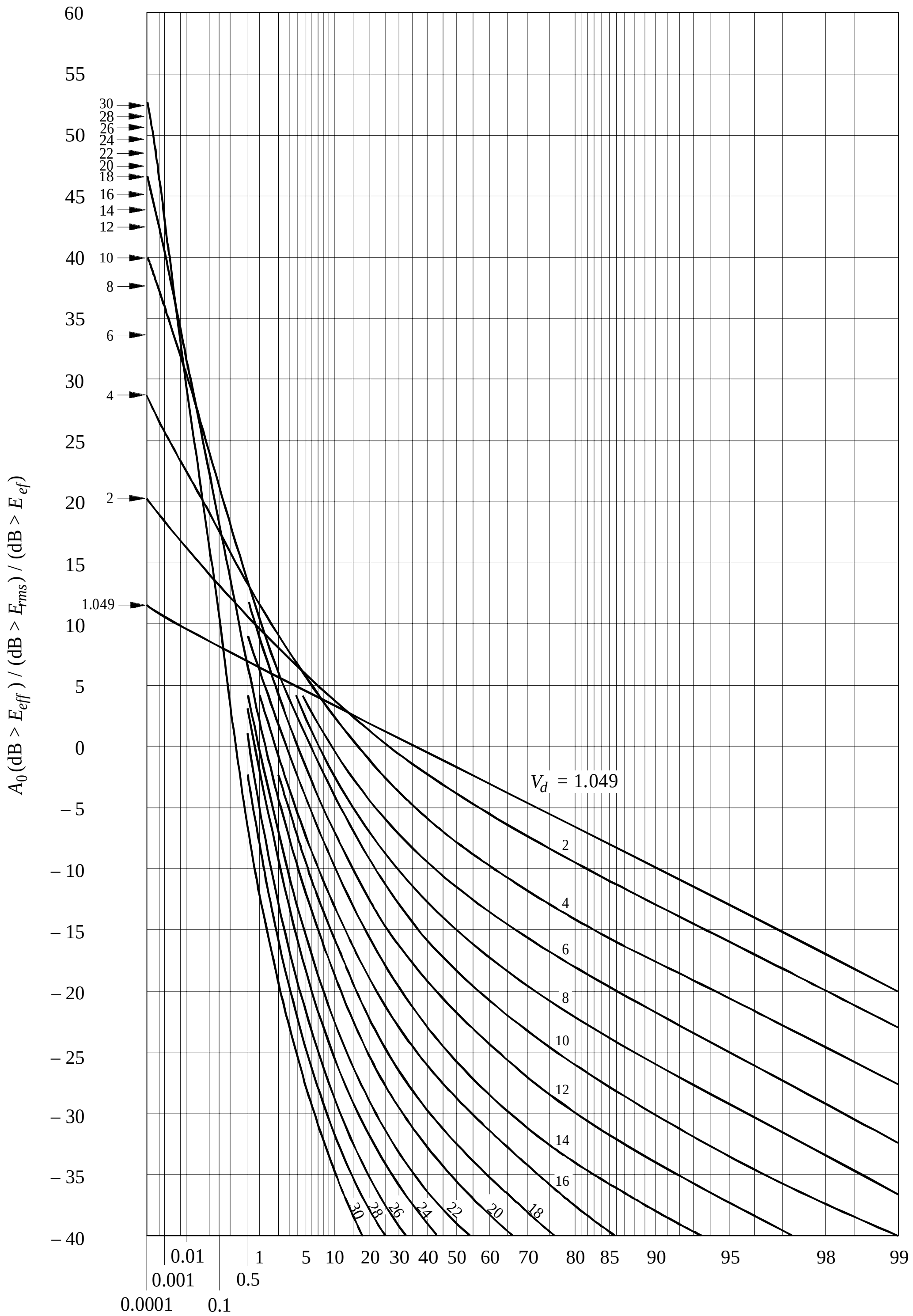


Figure 4-1 Amplitude probability distribution for atmospheric radio noise for various values of V_d

4.3.8 The Recommendation has not included all the information previously given in CCIR Report 322 [1986]. The bandwidth ratios covered for the conversion of V_d are now up to 14 times the reference bandwidth of 200 Hz; previously it extended to 28 times greater or less than 200 Hz. Additional information was also given for the standard deviation of the APD. This technique is based on work by Spaulding *et al.* [1962].

4.4 Man-made noise

4.4.1 As regards man-made noise, much of the information is carried through into the ITU-R Recommendation from CCIR Report 258-5 [1990]. This report is largely based on measurements in the USA made in the years leading up to 1974 when digital RF systems were not widely deployed. Figure 4-2 gives the values for F_{am} for man-made noise given in the Recommendation.

4.4.2 The Figure 4-2 includes a curve for galactic noise based on measurements made with a vertical monopole.

4.4.3 The man-made noise curves have a linear variation of the median value, F_{am}, with frequency f of the form:

$$F_{am} = c - d \log f$$

where f is expressed in MHz; c and d have the values given in Table 4-1.

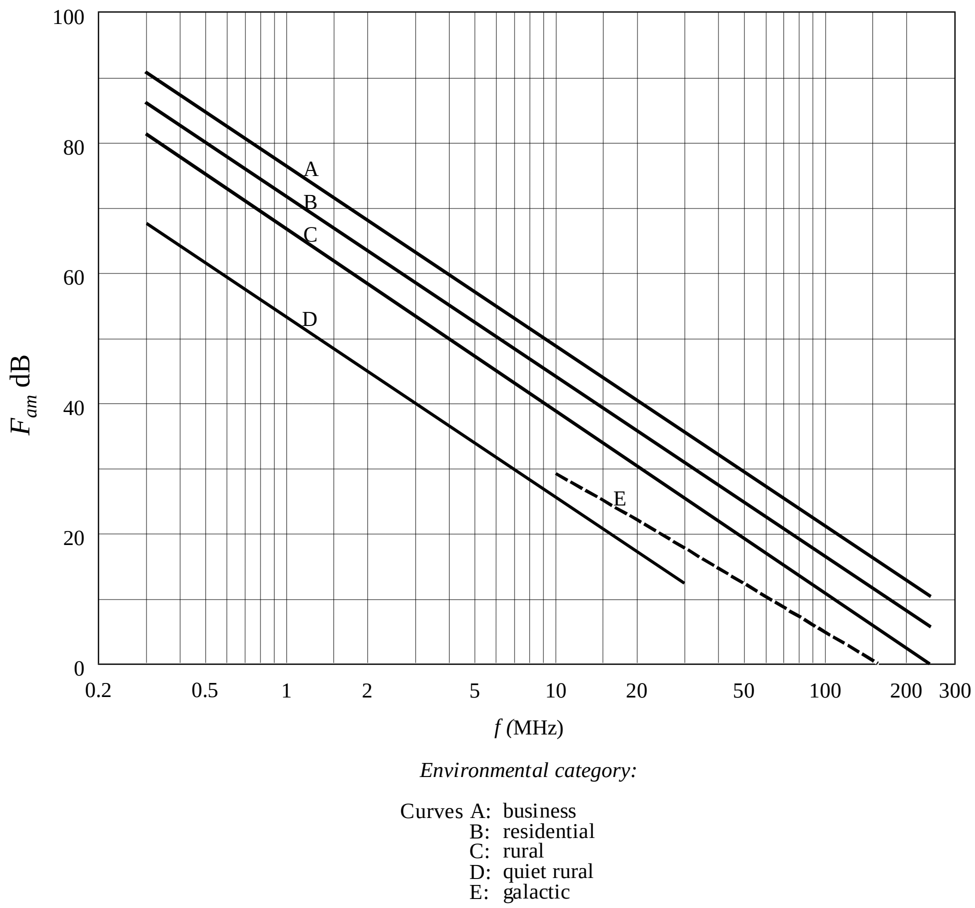


Figure 4-2 Median values of man-made noise power for a short vertical lossless grounded monopole antenna

Environmental category	*c*	*d*
Business (curve A)	76.8	27.7
Residential (curve B)	72.5	27.7
Rural (curve C)	67.2	27.7
Quiet rural (curve D)	53.6	28.6
Galactic noise (curve E)	52.0	23.0

Table 4-1 Values of the constants c and d

4.4.4 This relationship is reported to be valid in the range 0.3 to 250 MHz for all the environmental categories except those of curves D and E where the limits are indicated in Figure 4-2.

4.4.5 For the business, residential and rural categories, the Recommendation gives average values over the frequency range from 0.3 to 250 MHz of the decile deviations of noise power with time and with location. These are given in Table 4-2. It is assumed that these variations are uncorrelated and it is indicated that it is sufficient to assume log-normal half distributions each side of the median.

Category	Decile	Variation with time (dB)	Variation with location (dB)
Business	Upper	11.0	8.4
	Lower	6.7	8.4
Residential	Upper	10.6	*5.8*
	Lower	*5.3*	*5.8*
Rural	Upper	9.2	6.8
	Lower	4.6	6.8

Table 4-2 Values of decile deviations of man-made noise

4.4.6 It is noted that the values were measured in the 1970s and may change with time, dependent on the activities, which generate man-made noise.

4.4.7 The Recommendation extends the median information, for business areas only, up to 900 MHz:

$$F_{am} = 44.3 - 12.3 \log f \qquad \text{for } 200 \text{ MHz} < f < 900 \text{ MHz}$$

4.4.8 However there is insufficient data to determine the decile variations.

4.4.9 The earlier CCIR Report 258-5 [1990] gave additional data, although much of this was not taken forward into the Recommendation since it reported specific measurement results which could not easily be used for general modelling.

4.4.10 Two environmental categories were identified in the report in addition to those given in Table 4-1. These are *Interstate highways* (c=73.0; d=27.7) and *parks and university campuses* (c=69.3; d=27.7).

4.4.11 Table 4-3, taken from the report gives the noise parameters from which Table 4-1 and Table 4-2 were derived.

4.5 Approaches to modelling the amplitude distribution

4.5.1 Hagn and Sailors [1979] examined four approaches to the representation of the noise amplitude distribution, and these are shown in Table 4-4.

*4.5.2 Simple Gaussian model (*Table 4-4 *columns 3 and 4)*

4.5.2.1 For this model the standard deviation of the temporal variability is obtained as:

$$\sigma_T = \frac{1}{1.28}\sqrt{\frac{D_u^2 + D_l^2}{2}}$$

4.5.2.2 where D_u and D_l are the upper and lower deciles as given in Table 4-4. The total standard deviation is obtained in the usual way as:

$$\sigma_N = \sqrt{\sigma_{NL}^2 + \sigma_{NT}^2}$$

*4.5.3 Composite Gaussian model (*Table 4-4 *columns 3, 5 - 8)*

4.5.3.1 This is the modelling method which is currently recommended. A half log-normal distribution is used, with the appropriate standard deviation on each side of the median as given in the table, which also lists the corresponding decile values (1.28 σ).

*4.5.4 Chi-squared model (*Table 4-4 *columns 9 - 11)*

4.5.4.1 The χ-squared distribution is a powerful way of representing the skewness in a distribution, if justified by the data. The table gives values for the number of degrees of freedom, ν, and for two parameters *a* and *b* where the mean value:

$$\overline{F}_a = a + b\nu, \text{ and}$$
$$\sigma_{N_{\chi^2}} = b\sqrt{2\nu}$$

*4.5.5 Gaussian model derived from the χ-squared analysis (*Table 4-4 *columns 12 & 13)*

4.5.5.1 Finally, Gaussian parameters derived from the χ-squared analysis are given, presumably with the intention of providing some smoothing to the model.

4.6 Noise Amplitude Distribution (NAD) within ITU-R Recommendation 372-7

4.6.1 Although it may be expected that VHF man-made noise would be at least partially impulsive in character, no information on the APD or any characterisation in terms of V_d is given in the Recommendation. Reference is made to several sources and models for APDs, but no data are given.

4.6.2 Instead, the Recommendation includes a section on the noise amplitude distribution (NAD). It notes that at VHF a significant component of man-made noise is due to ignition impulses from motor vehicles. For this contribution, noise may be presented as an impulsive noise amplitude distribution (NAD) (the impulsive noise spectrum amplitude as a function of impulse rate). Figure 4-3 is an example of the noise amplitude distribution at 150 MHz for three categories of motor vehicle density.

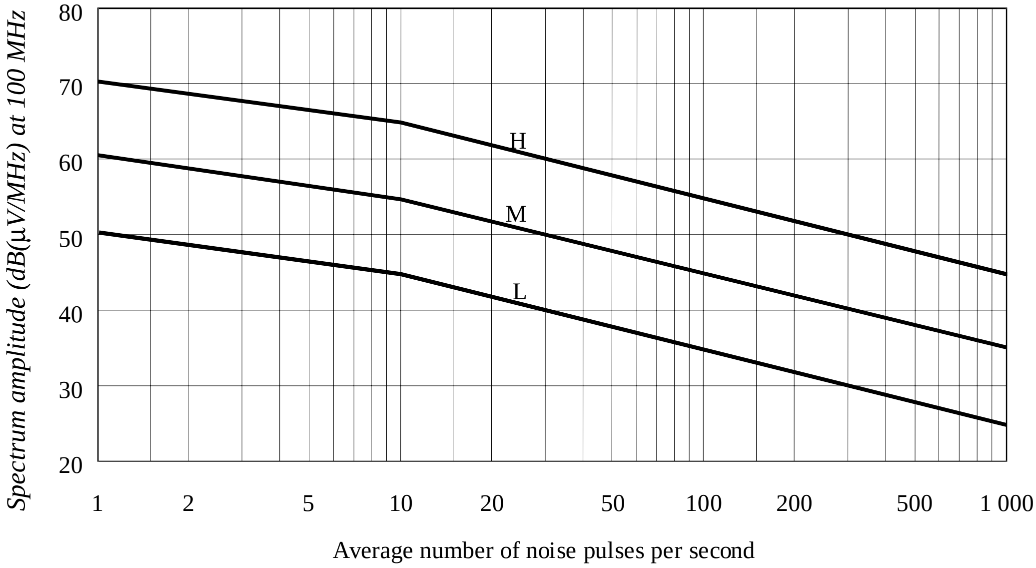
4.6.3 The NAD for other frequencies may be determined from the relationship:

$$A = 106 + 10\log V - 28\log f \qquad \text{dB } (\mu\text{V/MHz})$$

where:

V= traffic density (vehicles/km^2), and *f* = frequency (MHz)

4.6.4 The precise source of this figure is not known, but it is believed to date from the work of Parsons and colleagues in about 1980. Changes in e.m.c. requirements since that time may have affected the impulsive noise from vehicle ignition systems.



For frequencies other than 150 MHz, raise or lower curves H, M, and L in accordance with the formula below:

$$A = C + 10 \log V - 28 \log f$$

where A = dB(μV/MHz) at 10 pps.

Curves H: high noise location (V = 100)
M: moderate noise location (V = 10)
L: low noise location (V = 1)

Figure 4-3 Noise amplitude distribution at base station(150MHz)

4.7 Summary

4.7.1 The current ITU models and the techniques used to represent impulsive noise have been described. These models have value, but are likely not to be sufficient for digital modulation methods at VHF and UHF. The reasons for this are further discussed in Section 5.

Frequency (MHz)	Environmental category											
	Business				Residential				Rural			
	F_{am} (dB (kT_0))	D_u (dB)	D_1 (dB)	σ_{NL} (dB)	F_{am} (dB (kT_0))	D_u (dB)	D_1 (dB)	σ_{NL} (dB)	F_{am} (dB (kT_0))	D_u (dB)	D_l (dB)	σ_{NL} (dB)
0.25	93.5	8.1	6.1	6.1	89.2	9.3	5.0	3.5	83.9	10.6	2.8	3.9
0.50	85.1	12.6	8.0	8.2	80.8	12.3	4.9	4.3	75.5	12.5	4.0	4.4
1.00	76.8	9.8	4.0	2.3	72.5	10.0	4.4	2.5	67.2	9.2	6.6	7.1
2.50	65.8	11.9	9.5	9.1	61.5	10.1	6.2	8.1	56.2	10.1	5.1	8.0
5.00	57.4	11.0	6.2	6.1	53.1	10.0	5.7	5.5	47.8	5.9	7.5	7.7
10.00	49.1	10.9	4.2	4.2	44.8	8.4	5.0	2.9	39.5	9.0	4.0	4.0
20.00	40.8	10.5	7.6	4.9	36.5	10.6	6.5	4.7	31.2	7.8	5.5	4.5
48.00	30.2	13.1	8.1	7.1	25.9	12.3	7.1	4.0	20.6	5.3	1.8	3.2
102.00	21.2	11.9	5.7	8.8	16.9	12.5	4.8	2.7	11.6	10.5	3.1	3.8
250.00	10.4	6.7	3.2	3.8	6.1	6.9	1.8	2.9	0.8	3.5	0.8	2.3

F_{am} median value
D_u , D_1: upper, lower decile deviations from the median value within an hour at a given location
σ_{NL}: standard deviation of location variability

Table 4-3 Representative values of selected measured noise parameters for business, residential and rural environmental categories

Environmental category	Freq (MHz)	Simple Gaussian		Composite Gaussian				χ-square			Gaussian from χ-square	
		F_{am} (dB (kT_0))	σ_N (dB)	σ_{NU} (dB)	σ_{NL} (dB)	D_{Nu} (dB)	D_{Nl} (dB)	ν	a	b	$F_{a\chi^2}$ (dB (kT_0))	$\sigma_{N\chi^2}$ (dB)
Business	0.25	93.5	8.3	8.8	7.8	11.3	9.9	92.16	37.51	0.61	93.9	8.3
	0.50	85.1	11.6	12.8	10.3	16.4	13.2	32.12	39.26	1.46	86.1	11.7
	1.00	76.8	6.3	8.0	3.9	10.2	5.0	3.51	69.77	2.46	78.4	6.5
	2.50	65.8	12.4	13.0	11.8	16.7	15.1	142.29	-38.56	0.74	66.3	12.4
	5.00	57.4	9.2	10.5	7.8	13.5	10.0	16.58	31.70	1.62	58.5	9.3
	10.00	49.1	7.7	9.5	5.3	12.1	6.8	4.95	38.38	2.49	50.7	7.8
	20.00	40.8	8.7	9.6	7.7	12.3	9.9	32.66	6.18	1.08	41.5	8.7
	48.0	30.2	11.1	12.5	9.5	16.0	12.2	20.91	-4.69	1.73	31.4	11.2
	102.00	21.2	11.4	12.8	9.8	16.4	12.6	21.95	-15.62	1.73	22.3	11.5
	250.00	10.4	5.6	6.4	4.5	8.3	5.8	12.28	-2.80	1.13	11.1	5.6
Residential	0.25	89.2	6.8	8.1	5.3	10.3	6.8	8.67	75.88	1.66	90.3	6.9
	0.50	80.8	8.5	10.5	5.7	13.5	7.4	4.67	69.42	2.84	82.7	8.7
	1.00	72.5	6.5	8.2	4.3	10.5	5.5	4.02	64.49	2.37	74.0	6.7
	2.50	61.5	10.4	11.3	9.4	14.4	12.0	45.36	12.58	1.09	62.2	10.4
	5.00	53.1	8.4	9.6	7.1	12.3	9.1	17.11	29.28	1.45	54.1	8.5
	10.00	44.8	6.1	7.2	4.9	9.2	6.2	10.38	31.57	1.36	45.7	6.2
	20.00	36.5	8.3	9.5	6.9	12.2	8.8	14.80	14.75	1.54	37.5	8.4
	48.00	25.9	8.8	10.4	6.8	13.3	8.7	8.90	8.53	2.11	27.3	8.9
	102.00	16.9	7.9	10.1	4.6	13.0	5.9	3.09	8.98	3.35	19.0	8.2
	250.00	6.1	4.9	6.1	3.2	7.8	4.1	4.13	0.00	1.74	7.2	5.0
Rural	0.25	83.9	7.2	9.1	4.5	11.7	5.7	3.52	75.82	2.80	85.7	7.4
	0.50	75.5	8.5	10.7	5.4	13.7	6.9	3.78	65.57	3.17	77.6	8.7
	1.00	67.2	9.5	10.1	8.8	13.0	11.3	75.34	9.41	0.77	67.7	9.5
	2.50	56.2	10.2	11.2	9.0	14.4	11.5	28.78	18.36	1.35	57.1	10.2
	5.00	47.8	9.4	9.0	9.7	11.5	12.4	260.87	154.61	0.41	47.6	9.4
	10.00	39.5	6.8	8.1	5.1	10.4	6.5	7.49	27.37	1.78	40.7	6.9
	20.00	31.2	6.9	7.6	6.2	9.7	8.0	39.08	0.87	0.79	31.7	7.0
	48.00	20.6	4.5	5.2	3.5	6.7	4.5	9.84	11.27	1.02	21.3	4.5
	102.00	11.6	7.1	9.0	4.5	11.6	5.8	3.72	3.25	2.71	13.3	7.4
	250.00	0.8	3.0	3.5	2.3	4.5	3.0	9.20	-5.29	0.71	1.2	3.0

Table 4-4 Summary of noise model parameters

5 Non-ITU sources of noise data

5.1 Overview

5.1.1 The main centres for radio noise studies were at Boulder, Colorado (CRPL, ITS, NTIA) (Dr Don Spaulding) and in the earlier days at Slough (RRS, RSRS Appleton laboratory) (Dr F Horner). Much of the results of the studies by or for those two organisations formed the basis of the ITU documentation. In the period around 1980 the group at Liverpool University also studied VHF man-made noise (Prof J D Parsons), and some of the results also appear in the ITU Recommendation. The relevant information from some of these other sources is summarised below.

5.2 Hagn and Shepherd

5.2.1 Hagn and Shepherd [1984], SRI International, reported the work of Disney [1972] who measured the noise figure, F_a, and V_d for 10s samples at 250 MHz near a road for both vertical and horizontal polarisation. The comparison of the results for the two polarisations are shown in Figure 5-1 and Figure 5-2.

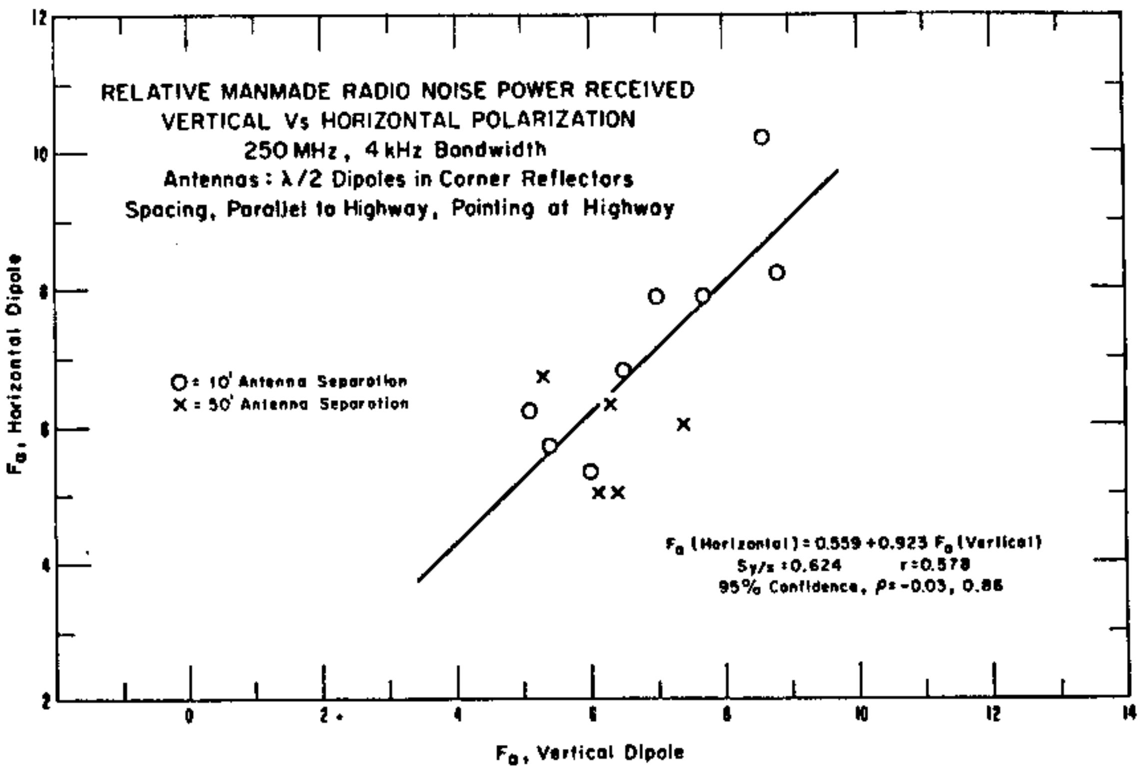


Figure 5-1 Relative man-made noise power received on 250 MHz horizontal and vertical dipole spaced 10 and 50 feet apart

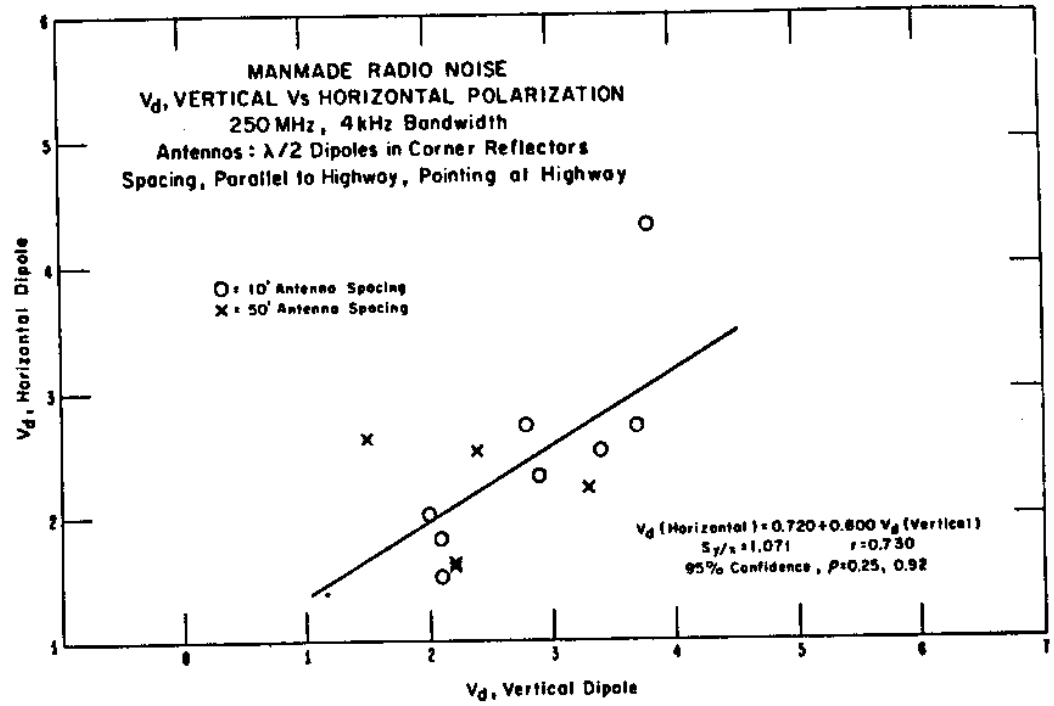


Figure 5-2 Comparison of V_d on 250MHz horizontal and vertical dipoles spaced 10 and 50 feet apart.

5.2.2 This set of results indicates that the median noise power is similar for the two polarisations, but that horizontally polarised noise is less impulsive. Presumably the main source of noise in this case is from petrol engines.

5.2.3 The man-made noise data in the ITU Report 258-5, as shown in Figure 4-2, is based on measurements in the USA. Some measurements in the UK by Marconi Research Laboratories (data not available) in the 1970s had indicated that equivalent environments had lower intensities. Hagn and Shepherd [1984] made some measurements in Frankfurt at HF and these are shown in Figure 5-3. No indication is given of the level of atmospheric noise at the time. Although the measurements were made during winter mornings, it is possible that atmospheric noise may have affected the results for rural and residential locations.

5.2.4 Hagn and Shepherd also report some Canadian measurements (Lauber and Bertrand 1984) at UHF and these are shown in Figure 5-4. These show a flatter variation of *Fa* with frequency than the ITU recommendation for VHF, and Hagn gives relationships for frequencies above 200 MHz as follows:

Business: $F_{am} = 49.4 - 15.8\log_{10} f_{MHz}$

Residential: $F_{am} = 45.2 - 15.8\log_{10} f_{MHz}$

Rural: $F_{am} = 39.2 - 15.8\log_{10} f_{MHz}$

5.2.5 There is no indication in the report of the receiver noise factor, and this may have affected the rural results in particular.

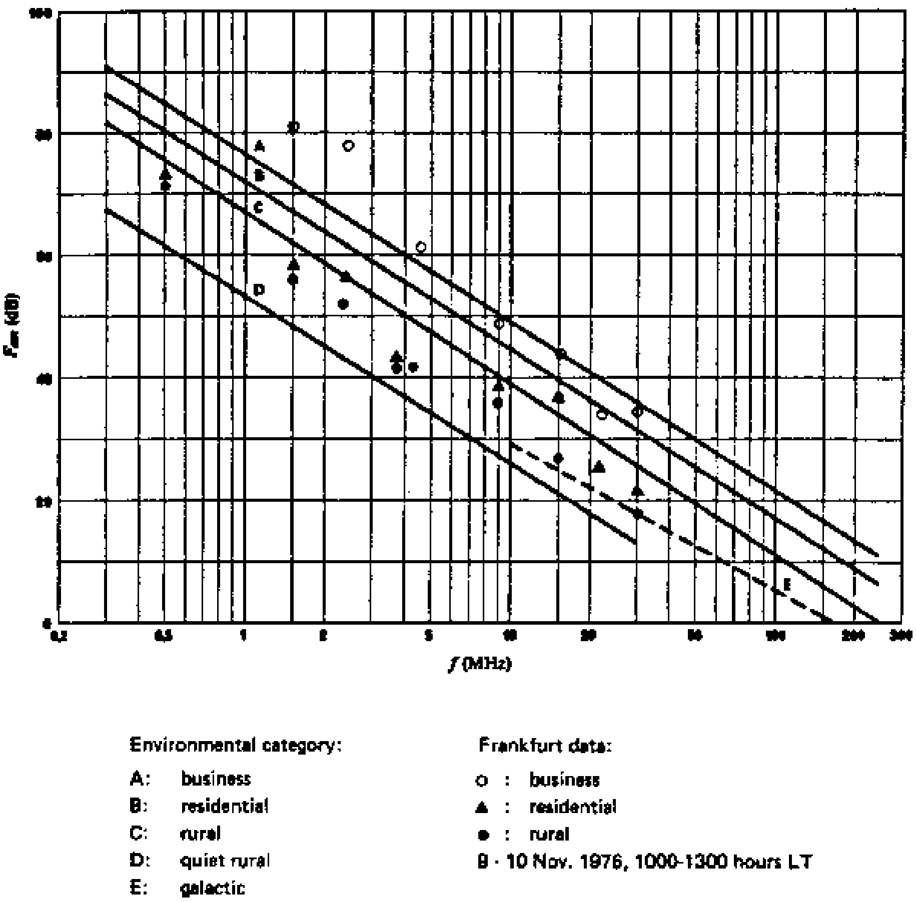


Figure 5-3 Comparison of daytime median man-made noise data measured in Frankfurt, FRG, in November 1976 using 6-ft rod antenna with CCIR report 258 predicted mean values.

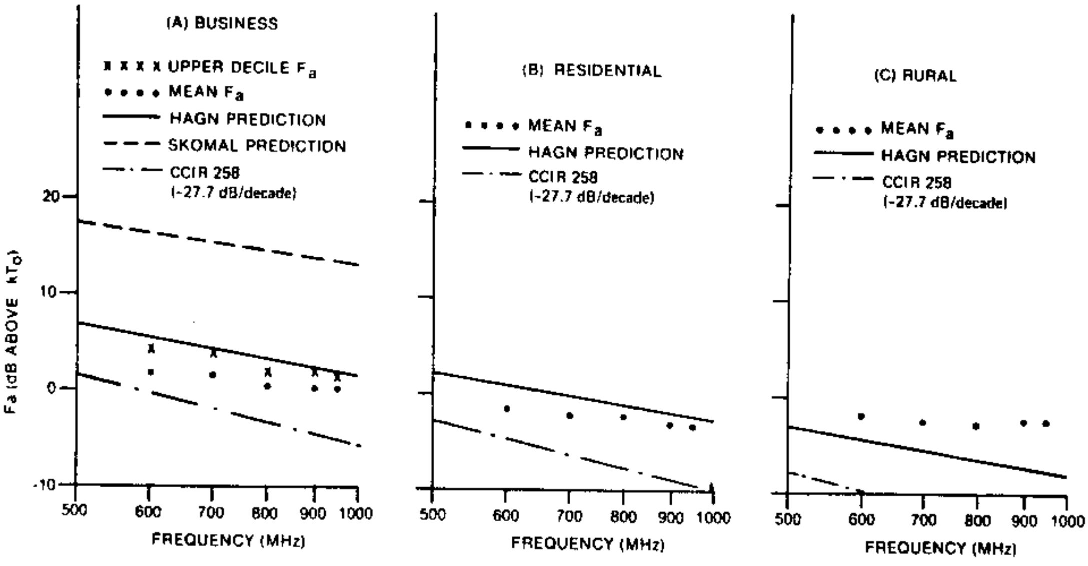


Figure A-4 COMPARISON OF CANADIAN UHF MAN-MADE NOISE MEASUREMENTS WITH PREDICTIONS

Figure 5-4 Comparison of Canadian UHF man-made noise measurements with predictions

5.3 Barnard

5.3.1 Barnard [1967] made measurements of man-made noise at 118 MHz while flying at 26000 ft over London and Birmingham. One of the Figures from this report is reproduced in Figure 5-5. The scale is given as the AGC voltage, and based on calibration data it indicates that the received noise over central London is about 10 dB higher than that over the surrounding rural area.

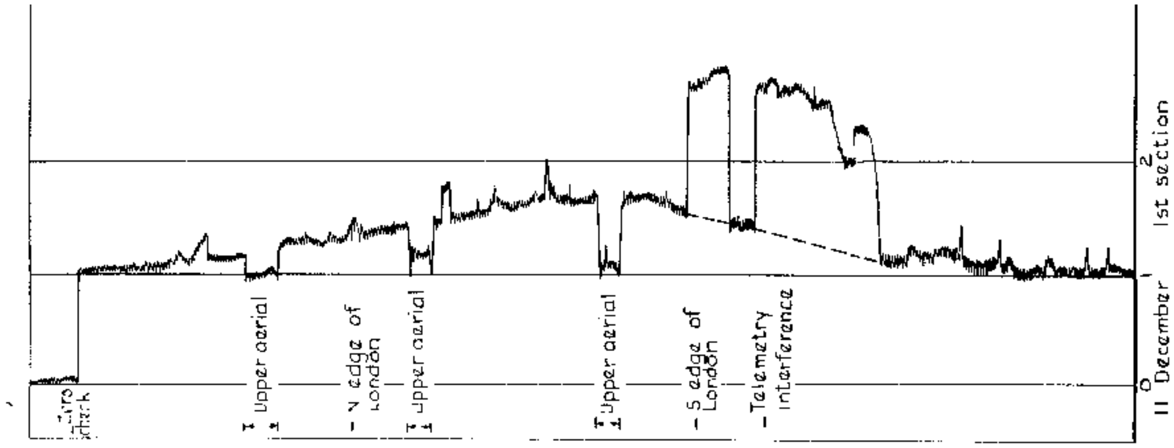
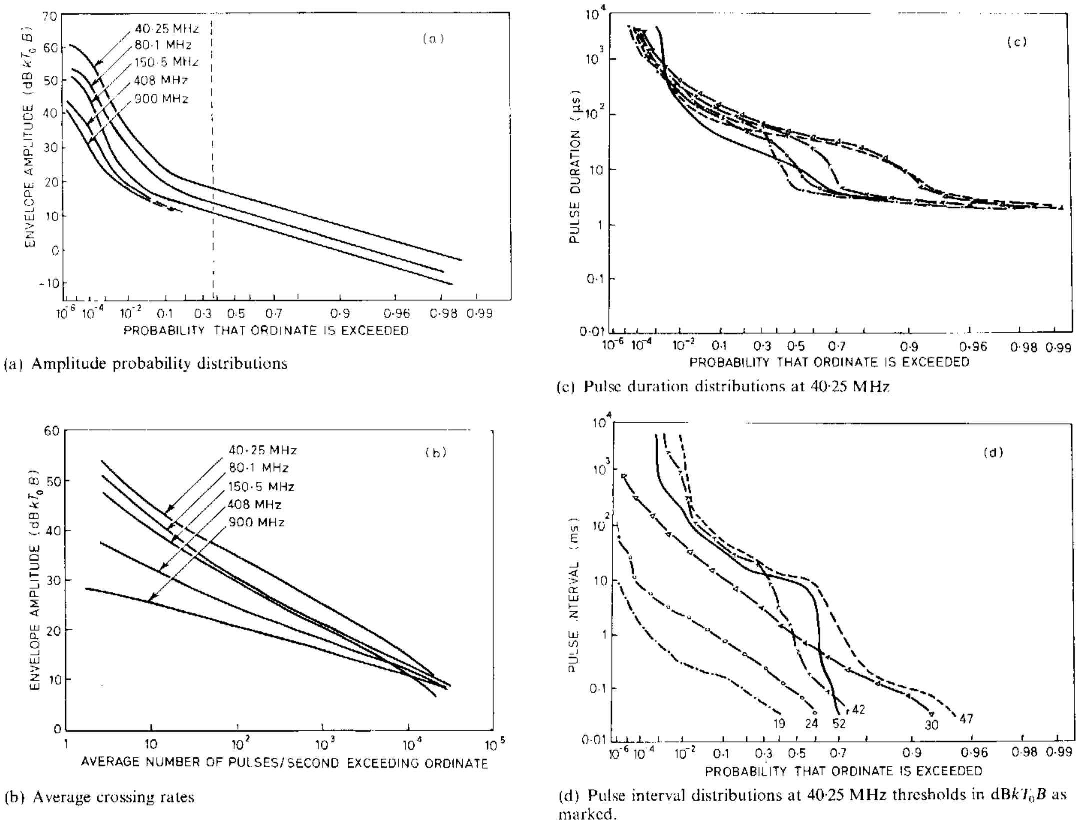


Figure 5-5 Measurements at 118 MHz while flying over London

5.4 Parsons

5.4.1 The concept of the Noise Amplitude Distribution was developed by Parsons and his group, and is summarised in Parsons [2000]. It is based on treating noise as very narrow impulses. This is reasonable considering that ignition discharges are the dominant source of noise at VHF and UHF for mobile systems. It may be noted that he concentrated on the effects of noise from ignition discharges on wide-band private mobile radio systems, where the assumption of narrow pulses is expected to be entirely appropriate. Parsons notes that the “impulsiveness ratio” can by obtained from the APD, but implies that NAD, specified by a single parameter, is more useful as a measure of ignition interference.

5.4.2 The NAD gives the number of pulses per second, which exceed a given strength (or, strictly, a given energy). A prediction method based on this concept has not been developed but some measurements have been made. Sheikh and Parsons [1983] give some results for suburban, urban and city areas and these are reproduced in Figure 5-6, Figure 5-7 and Figure 5-8. These figures also give the distributions of pulse duration and pulse interval for some frequencies. The bandwidths used for these measurements were about 500 kHz at 40 and 80 MHz (using a spectrum analyser) and about 20 kHz at the higher frequencies. The Figures also include APDs, but the point is made in the text that much of these distributions is below the receiver noise level. The inability to determine the average level at VHF and UHF casts doubt on the technique of specifying an APD in terms of V_d.



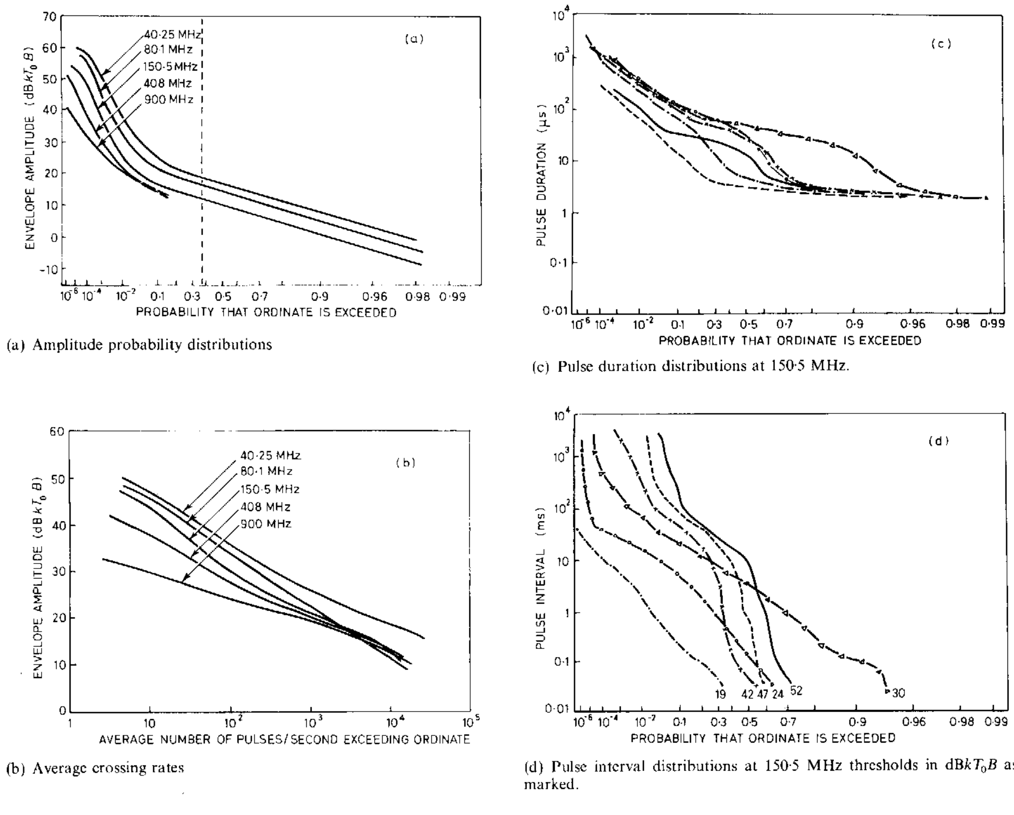
(a) Amplitude probability distributions

(c) Pulse duration distributions at 40·25 MHz

(b) Average crossing rates

(d) Pulse interval distributions at 40·25 MHz thresholds in dBkT_0B as marked.

Figure 5-6 Noise statistics: suburban areas



(a) Amplitude probability distributions

(c) Pulse duration distributions at 150·5 MHz.

(b) Average crossing rates

(d) Pulse interval distributions at 150·5 MHz thresholds in dBkT_0B as marked.

Figure 5-7 Noise statistics: urban areas

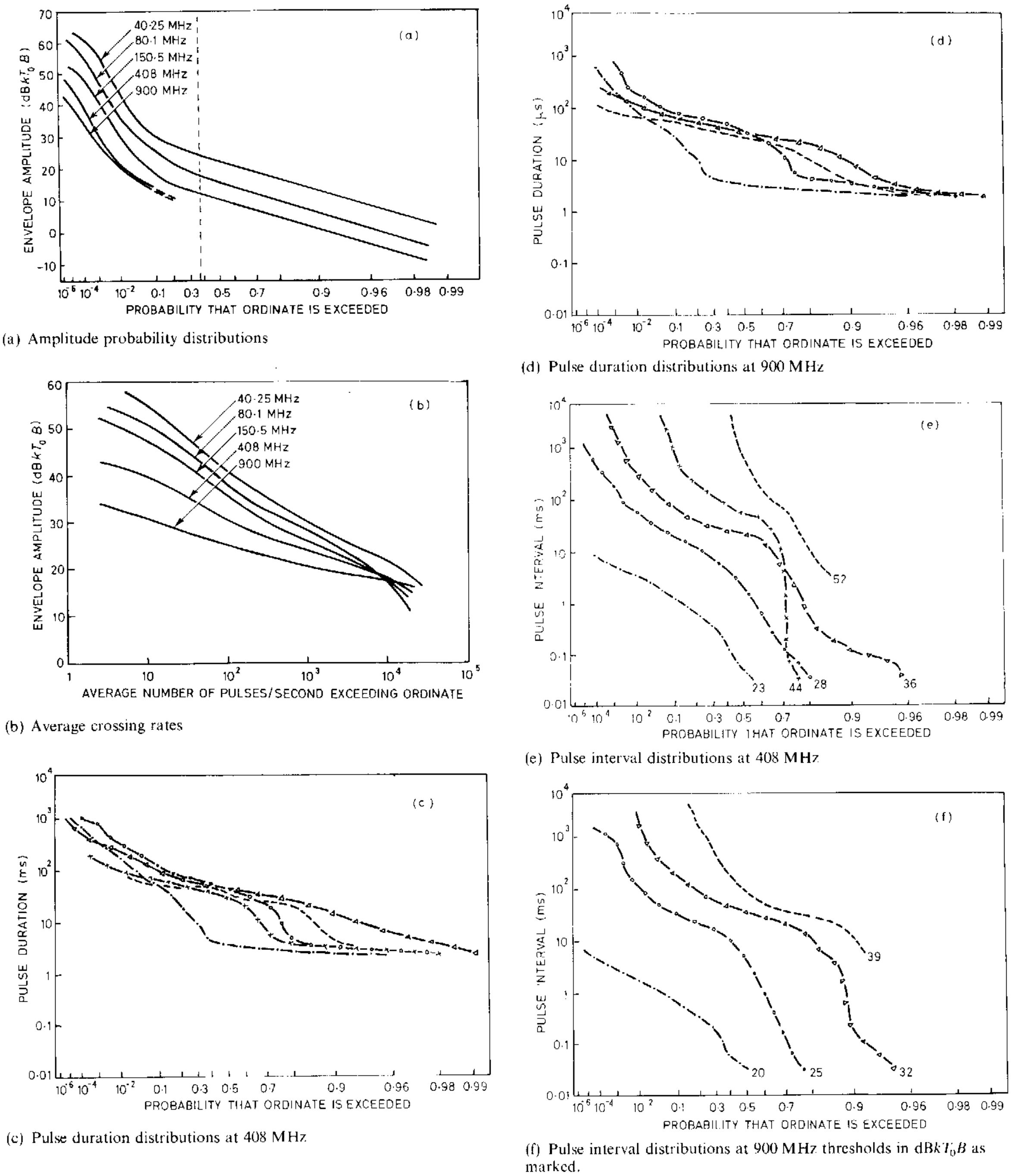


Figure 5-8 Noise statistics: city area

5.5 Masoum and Gardiner

5.5.1 In 1991 the RA placed a contract with Bradford University for a study of man-made noise measurements in the frequency range of 1.5–2.5 GHz. Some measurements were reported at 1.5 GHz, which were made using an antenna with about 15 dBi gain pointed at various elevation angles.

5.5.2 These measurements were intended for use in the design of mobile satellite systems and will not be further considered. In some cases the directional antenna was pointed horizontally, but there seems to be some doubt as to the number of noise sources which would have been included with such an antenna. The aspect of the directionality of the antenna may require further discussion, but it is assumed that the most relevant environmental characterisation will be provided with an omnidirectional antenna.

5.5.3 The report gives results of other measurements in the frequency range 1.5 – 2.5 GHz using an omnidirectional discone-type antenna. Figure 5-9 is an example of the results obtained.

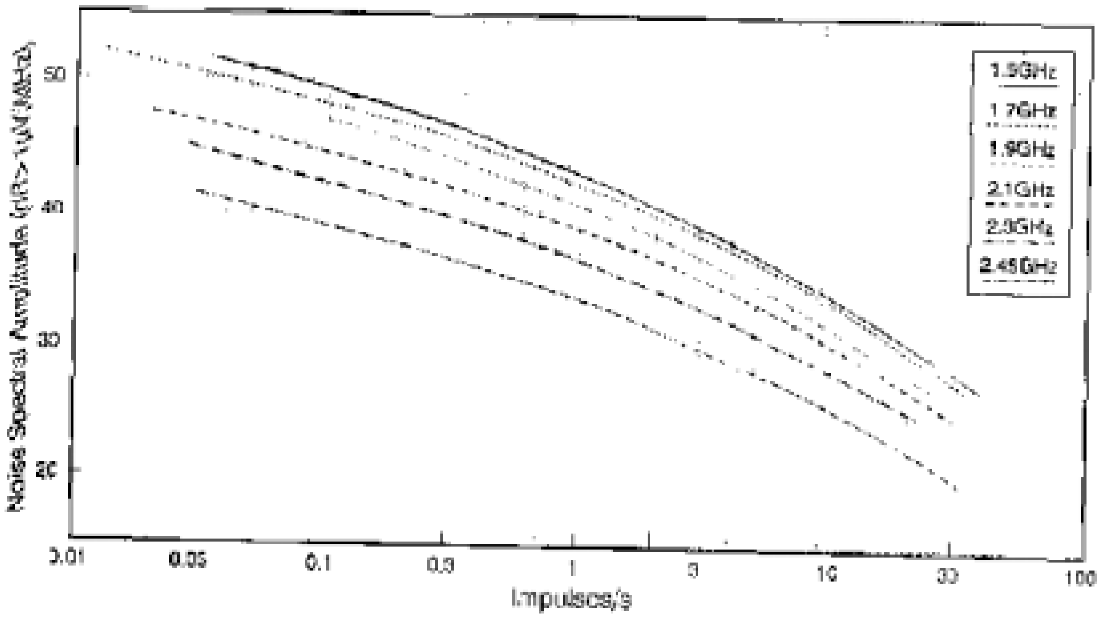


Figure 5-9 NAD results measured with a vehicle moving in Bradford city centre rush hour

5.5.4 The study was not extended to the preparation of typical results, which could be used for planning purposes, but the results will be of value in comparison with new results obtained over a wider variety of geographical environments some 10 years later.

5.6 Summary

5.6.1 There is a limited amount of information regarding man-made noise data. Unfortunately, it was either recorded before digital systems were deployed, or at limited bandwidths and at frequencies below 900MHz.

5.6.2 The currently available models (ITU or other) have value but are likely not to be sufficient for digital modulation methods at VHF and UHF since:

- digital system performance is likely to be dependent on both the amplitude probability distribution and on additional parameters of noise.
- at higher frequencies only a part of the APD may be above the internal noise background.
- the form of the APD for man-made noise has not been established.
- NAD measurements have been made but these have not been developed to give recommendations of noise models for different environments.
- noise measurements have been made with small or modest bandwidths.

- noise levels may change with time, with changes in the use of electrical and electronic equipment, and with legislative changes relating to unwanted emissions from equipment.

5.6.3 In conclusion, there is a need to produce models, representative of current environmental conditions, and with appropriate bandwidths (and therefore time-resolutions) commensurate with current technology. These may be used to define a basis for system planning and design. The establishment of a firm baseline for such models now will enable future changes in the environment to be detected and the spectrum to be utilised more effectively.

6 Man-made Noise Measurement Requirement

6.1 Overview

6.1.1 The main campaigns for the measurement of atmospheric radio noise were undertaken in the 1950s and 60s. It had been recognised that noise was impulsive in character and that the noise power was the dominant required parameter.

6.1.2 Man-made noise measurements were subsequently made using similar techniques and later using the NAD approach. While the general approaches used in the past may continue to be suitable, the need to cater for extended requirements and the capabilities of modern measuring equipment will require a re-examination of the measurement techniques and the establishment of a suitable programme.

6.1.3 In this section we consider what requirements would be imposed for the measurement of man-made noise. These requirements are then used in Section 7 to define the hardware that could satisfy the requirements.

6.2 Measurement system requirements

6.2.1 The main type of man-made noise of relevance to this study is impulsive. However, there may be a significant wide-band (e.g. digital clock harmonics) component and any proposed measurement system should be capable of characterising both.

6.2.2 In order to adequately characterise the effect of man-made noise (and particularly that of impulsive nature) on communications systems, the measurement system should ideally have a tunable bandwidth. This should be greater than, or at least commensurate with, the bandwidth of any relevant communications systems. In practice, this implies that a design decision will have to be taken regarding the maximum bandwidth required. At this stage it is assumed that a 5MHz maximum bandwidth will be sufficient. Measurements in lower bandwidths could be obtained by filtering the wide-band data (for example, using digital down-converters, DDCs).

6.2.3 The system must be capable of tuning its measurement bandwidth anywhere within the required measurement frequency range (e.g. 40MHz to 3GHz). In order to reduce measurement time several parallel channels, each independently measuring a different band could be implemented. The degree to which this parallelisation can be carried out will be limited by system cost rather than hardware capability. Alternatively, a sequential measuring process may be adopted.

6.2.4 The noise measurement system must have a capability to record data. This could be direct storage of unprocessed digital data to disk (using a RAID array) or storage of pre-processed data. Issues of data storage are discussed below.

6.2.5 The choice of antenna must be carefully considered. The antenna pattern and siting could have a significant effect on the results of any noise measurement exercise and is discussed further in Section 6.5

6.3 Data storage

6.3.1 For an extended measurement period using a wide measurement bandwidth, a large amount of storage capacity would be required to store raw data. For example, a system with a 10MHz measurement bandwidth sampled at 25MHz to 14 bits resolution requires

50MB of storage per second. It is anticipated that statistically significant measurements may be obtained with measurement periods shorter than one hour.

6.3.2 To reduce the amount of storage required, real-time on-board data pre-processing could be used. In the case of impulsive noise, the system could calculate a detection threshold based on the thermal/continuous noise statistics and then record the occurrences of pulses above this threshold (i.e. pulse width, amplitude, time). For wide-band signals, such as digital clock harmonics, the pre-processor could calculate the Fast Fourier Transform of the measurement bandwidth and record occurrences of spectral components above a self-determined threshold.

6.3.3 Ideally, the measurement process should include as many frequencies as possible and cater for bandwidths of current and future systems. Practically, however, it may be difficult to locate "quiet" areas of the spectrum to perform measurements. The quiet bands (if located) may also be geographically dependent. A number of bands, however, could be considered such as:

- Radio astronomy bands and bands that are used for passive satellite monitoring
- UMTS (~2GHz) ,GSM (900MHz), and Tetra (400MHz) bands whose signals have a known time division so that services are easy to identify and ignore.

6.4 Noise Data Statistics Required

6.4.1 It is assumed that most of the data analysis will be performed off-line either using raw data (if collected) or pre-processed data. The aim of the data analysis should be to determine the key noise characteristics and identify non-noise like measurements (e.g. CDMA).

6.4.2 Ideally the data analysis should provide statistics on:

a. Noise amplitude distribution

b. Noise pulse duration

c. Noise pulse interval

6.5 Antennas

6.5.1 The antennas characteristics and the measurement sites will require careful consideration. For example, the noise environment seen by an antenna close to ground level in a city street may be significantly different from that seen at rooftop level where a communications micro- or pico-cell antenna could be situated. In this latter scenario a pico-cell antenna may be angled down to street level to give street level coverage. The polar diagram in both elevation and azimuth of the antenna will directly contribute to the noise measured. Consequently, measurements may (ideally) be required using scanning antennas.

6.5.2 The antenna system must also exhibit good broadband characteristics (commensurate with the maximum required measurement bandwidth) in order not to distort the time domain characteristics of impulsive interference. This may result in using a number of antennas appropriate to the frequency band being measured.

6.6 Receiver

6.6.1 Receivers with wide-band IF outputs (i.e. greater than 10MHz) are available from several manufacturers. As with the antenna system, they must be capable of correctly preserving the shape of transient impulse.

6.7 Summary

6.7.1 The hardware and measurement requirements of a man-made noise programme are considered. Ideally the measurements (and analysis) should provide statistics on noise amplitude distribution (NAD), noise duration and noise pulse interval.

6.7.2 The main type of man-made noise of relevance to this study is impulsive. However, there may be a significant wide-band (e.g. digital clock harmonics) component and any proposed measurement system should ideally be capable of characterising both.

6.7.3 It is anticipated that statistically significant measurements may be obtained with measurement periods shorter than one hour. To reduce the amount of data storage required, real-time on-board data pre-processing could be used. The system must be capable of tuning its measurement bandwidth anywhere within the required measurement frequency range (e.g. 40MHz to 3GHz) and select a variable bandwidth appropriate to the frequency being considered. Careful consideration should be given to the antennas used.

7 Measurement hardware

7.1 Overview

7.1.1 The main campaigns for the measurement of atmospheric radio noise were undertaken in the 1950s and 60s. It had been recognised that noise was impulsive in character and that the noise power was the dominant parameter. This led to the design of an rmss measurement system, the American ARN-2 receiver. Currently components are readily available for measuring rms parameters, leading to the measurement of noise power.

7.1.2 Instruments are available calibrated for quasi-peak measurements. The disadvantages of these are outlined below.

7.1.3 For measurement of the parameters associated with NAD, Parsons and Sheikh [1979] have discussed the considerations necessary for a noise measuring receiver. Turkmani and Parsons [1986] describe the design of suitable receiver, covering 20 MHz to 1 GHz with a 50 dB dynamic range which could be used for measurements. These should be taken into consideration when developing a new hardware receiver.

7.2 CISPR Quasi-peak measurement techniques

7.2.1 In addition to the above methods of measuring noise APD and NAD, quasi-peak noise measurements are also defined by CISPR (Comite Internationale Special des Perturbations Radioelectrotechnique).

7.2.2 The CISPR technique is an internationally agreed noise/interference detection method implemented on many receivers and aimed at analogue sound broadcasters concerned with intelligibility and sound (music) quality. The technique collects data in a prescribed manner enabling the data to be compared against other measurements made using differing hardware.

7.2.3 The quasi-peak value of the input signal is weighted and averaged in accordance with the CISPR 16 Publication and depends on the pulse repetition frequency and pulse amplitude. For example, a single pulse event is weighted such that the detector output is low (i.e. ~40dB below the peak), while multiple pulses cause higher detector outputs. The method was agreed over 20 years ago and optimised for analogue measurement systems. In modern receivers, the digital simulation of an analogue meter has to be incorporated to cater for the analogue time constants; these constants are also frequency dependent. The CISPR technique, therefore, relies on significant processing and provides the user with a specific interpretation of the noise/interference observed within a nominal bandwidth of 10 kHz.

7.2.4 Although the technique is useful in detecting noise/interference on operational audio links, it appears to have limited applicability to the generation of improved man-made noise models for digital systems due to the pre-processed and limited (e.g. peak power, pulse frequency) noise/interference parameters stored.

7.2.5 It is concluded that the NAD approach offers the best way of collecting and analysing man-made noise for use in connection with digital systems. APD may provide some additional information and more limited measurements of this should also be made.

7.3 Generalised digital wide-band data capture/analysis system

7.3.1 Figure 7-1 illustrates the main elements of a modern measurement system. It comprises a minimum of one general coverage receiver with an IF output of a bandwidth at least equal to the largest measurement bandwidth required. This IF output is converted into a digital format with a digital-to-analogue converter and then fed to one or more digital down-converters (DDCs) which select a programmable sub-band of the input spectrum and down convert to baseband. These will allow different measurement bandwidths to be selected and processed by the digital signal processor. Pre-processed data from the digital signal processor could be stored directly on to a hard disk in the controller PC.

7.3.2 The output from the digital-to-analogue converter can be fed directly to a RAID disk array (or other suitable storage medium) if it is necessary to store raw data for off-line processing. A system with a 10MHz measurement bandwidth sampled at 25MHz to 14 bits resolution will require a 50MB of storage per second. A typical SCSI/IDE RAID array with a capacity of 614GB would allow 3.4 hours of storage at moderate cost assuming a sampling rate of 25MHz to 14 bits resolution.

7.3.3 RAID arrays with capacities of more than 2TB are available (allowing more than 11 hours of storage) but at much greater cost. Assuming that samples are taken for less than one hour at a time, using two 614GB, or smaller, RAID arrays, it will be possible to process the results from one array while measurements continue to be stored to the second array

7.3.4 A second receive channel is illustrated which would allow simultaneous measurement of another part of the spectrum. One of the strengths of this architecture is the potential for a high degree of parallelisation allowing multiple segments of the spectrum to be measured simultaneously. Such wide-band techniques could assist identyfying man-made noise as opposed to noise like communications traffic which will be narrow-band.

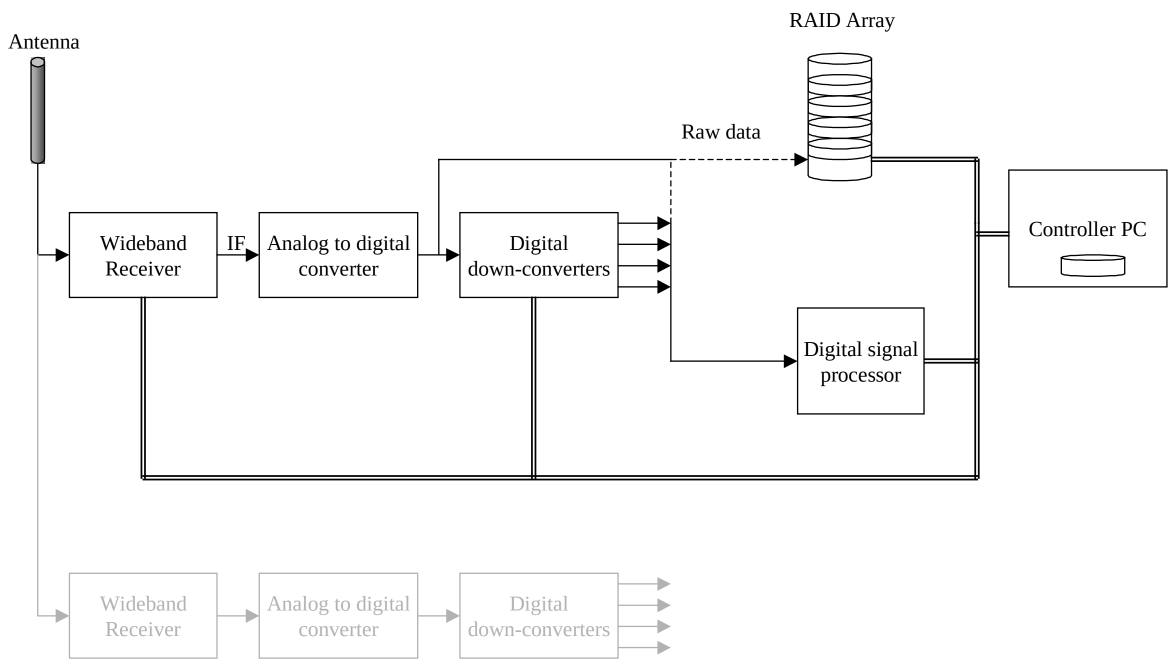


Figure 7-1 Illustration of possible measurement system architecture for man-made noise

7.3.5 Much of the functionality of such a system can be realised by using off-the-shelf components. High speed digital-to-analogue converters and wide-band DDCs are available at modest cost largely as a result of the massive investment in the mobile communications industry.

7.4 Wide-band Military Spectral Surveillance Systems

7.4.1 The military requirement for wide-band spectral surveillance and emitter location has led to the development of state-of-the-art systems, which are now in service. The SHARK system provides the capability of direction-finding (DF) and position-fixing fast frequency hopping radios through the use of a highly parallel wide-band architecture anywhere between 20MHz and 1GHz. These high technology systems are capable of up to 76 million DF operations per second using special processing hardware. Once the data is captured sophisticated processing algorithms can be used to process and identify complex modulation formats.

7.4.2 As commercial hardware has now become available which can offer acceptable levels of performance, spectral surveillance systems can be developed more rapidly and at lower cost. This enables more effort to be directed towards developing novel and efficient processing techniques without incurring the risk of developing special hardware.

7.4.3 Such technology may be adapted for commercial exploitation, particularly to measure man-made noise, which poses a similar problem as impulse jammers, and interfering systems.

7.5 Summary

7.5.1 A number of measurement hardware techniques are considered. It is concluded that the NAD approach offers the best way of collecting and analysing man-made noise data for digital systems. APD may provide some additional information and more limited measurements of this should also be made.

7.5.2 The main elements of a modern digital measurement system are considered and a system architecture is outlined. The system comprises a minimum of one general coverage receiver with an IF output of a bandwidth at least equal to the largest measurement bandwidth required. Much of the functionality of such a system can be realised by using off-the-shelf components.

7.5.3 Wide-band spectral surveillance and emitter location systems may be modified more rapidly and at lower cost and risk.

8 Measurement programme

8.1 Risk Reduction programme

8.1.1 It is desirable to obtain confirmation of the characteristics of VHF and UHF man-made radio noise. As a risk reduction exercise, to investigate the risk of contamination from narrow-band noise, a short measurement programme should be pursued.

8.1.2 This initial programme should be undertaken in a few selected locations, e.g. business centres, alongside a main highway using commercial equipment (e.g. spectrum analyser, digital oscilloscope, digital receiver). The purpose of these initial tests would be to firstly determine the character of narrow-band (i.e. from computing or telecommunication equipment) noise, and secondly, to establish whether it is a significant component.

8.1.3 The data could also be used to confirm the characteristics of wide-band noise. (For example, confirm the variation of noise power with bandwidth at a low VHF frequency along with the median noise power at several bandwidths). APDs should be determined at low VHF frequency with a (minimum) 25 KHz bandwidth, and repeated with a wider bandwidth.

8.1.4 Dependent on the results obtained, APDs may also be determined with a wider bandwidth and sample measurements of NAD obtained. These results should be used to determine a suitable integration period for the measurements.

8.1.5 Based on the results of these initial tests a measurements programme should be planned and undertaken. The following programme is recommended, although this may need to be modified based on the results of the initial tests.

8.2 Measurement parameters

8.2.1 It is recommended that the main programme of noise measurements should be based on the parameters associated with the NAD method. Consequently the following parameters should be ideally measured:

a. Noise amplitude distribution
b. Noise pulse duration
c. Noise pulse interval

8.2.2 For each of these characteristics statistical profiles should be obtained, representative of different environments and different times of day, week and year.

8.3 Measurement locations

8.3.1 To characterise the noise environment, measurements in the following environments should be considered, namely:

a. large city centre,
b. factory estate
c. business centre,
d. town centre
e. shopping centre/mall
f. major highway

g. suburban
h. rural

8.4 Measurement frequencies

8.4.1 Measurements should be made at about 40 MHz, and then at each octave up to about 640 MHz and then about every 500 MHz from 1 to 3 GHz. In each case monitoring should be undertaken and the results assessed to ensure the use of a clear channel for the measurements. Additional frequencies may need to be identified if computer or telecommunication noise is evident in some bands.

8.5 Measurement period

8.5.1 It is important to be able to characterise the noise environment as a function of day, week and season. It is recommended therefore that measurements be taken:

a. mid morning
b. evening
c. rush hour (in relevant environments)

8.5.2 Ideally, the diurnal variability of man-made noise should be investigated, but as noted earlier, the data storage requirements may preclude this exercise. Measurements should also be made at weekends.

8.5.3 A seasonal effect may be observed (e.g. greater car density in winter, heating systems, etc). A seasonal experiment should, therefore, be considered. This could be minimised to summer and winter data to investigate the upper and lower noise limits. These measurements, however, should only be performed based on the conclusions and results obtained from the sites investigated earlier.

8.6 Measurement repeat frequency

8.6.1 Because of the rapid changes in the uses of electrical and technological equipment, it will be desirable to repeat some measurements of noise characteristics every five years. A decision, as to which environments should be measured on a regular basis, should be made when the results of the first measurement programme are available.

8.7 Summary

8.7.1 A risk reduction programme is proposed. This initial programme should be undertaken in a few selected locations, e.g. alongside a city street and a main highway using commercial equipment. The purpose of these initial tests would be to determine the character of narrow-band noise and establish whether it is a significant component. The data could also be used to confirm the characteristics of wide-band noise at a low VHF.

8.7.2 Measurement parameters are recommended along with locations that noise should be measured in. It is important to be able to characterise the noise environment as a function of day, week and season. It is recommended, therefore, that measurements be taken appropriately. Due to the rapid changes in the uses of electrical and technological equipment, it will be desirable to repeat some measurements of noise characteristics every five years.

9 Measurement Strategy and Budgetary Costs

9.1 Overview

9.1.1 This section considers budgetary costs for both a risk reduction and the full measurement programme. These figures are not a formal offer, but are intended to provide RA with a budgetary estimate.

9.2 Typical costs of risk reduction

9.2.1 The noise environment in representative locations should be explored with either a spectrum analyser or digital oscilloscope to establish if noise (e.g. from computing or telecommunication equipment) is a significant component of MMN. If such sources are important then the measurement programme may have to be closely specified.

9.2.2 A similar approach could also be used to perform a risk reduction exercise to investigate the noise environments in the differing locations (e.g. urban, major highways). This will provide data against which a system can be developed. The risk reduction exercise should be limited to two or three sites, a few frequency bands and a single time of day. The measurements could be based on simulated test environments.

9.3 System development, deployment and analysis costs.

9.3.1 Illustrative costs to build a single channel digital receiver (similar to that described in Section 7.4) to measure noise data within a tuneable frequency range have been estimated for budgetary purposes only. The costs include elements such as a high quality wide-band receiver with an IF bandwidth of 40MHz, ADC units, DDC, RAID (~ 700GB) array for data storage, PC control unit and control software. The design, development and testing costs are also included along with some basic algorithm development within the receiver units to detect noise characteristics. Such a unit could be deployed, depending on complexity and noise data collection time, in less than 6 months.

9.3.2 The measurement costs are highly dependent on the number of locations and measurement frequency. The measurements could be performed for single locations in a 24 hour period. These measurements could be repeated at a minimum of twice a year for a period of 5 years to map any trends.

9.3.3 The data analysis and model development will be highly dependant on the data available and the locations measured. It is anticipated that high quality data from a single scenario could be analysed and a preliminary model and visualisations developed. Once the first model has been developed models for other scenarios may be developed at a significantly reduced cost, depending on data quality.

9.4 Impact of Man-made Noise on Systems

9.4.1 There is currently limited data regarding the impact of man-made noise on commercial digital systems. To supplement the man-made noise measurements and model, simulations should be performed to investigate its impact on a number of illustrative communications systems. The aim of the simulations should be to assess what peak-power, duration, etc., causes a significant impairment to the digital system.

10 Summary, Conclusions and Recommendations

10.1 Summary

10.1.1 When considering the design and planning of RF communication systems, radio noise defines the background signal level against which wanted signals must be demodulated. Two types of noise must be considered: natural/internal noise and man-made noise.

10.1.2 Natural and internal noise sources may be minimised using an appropriate frequency and good system and antenna design. Beyond this, however, the natural background noise sets the sensitivity limit of a communications system.

10.1.3 Man-made noise, arising due to a variety of emissions from electrical discharges and other sources, may set a higher background limit than natural and internal noise. The sources of this impulsive noise include:

a. noise from electrical machinery (particularly from commutating motors)

b. noise from spark ignition systems in petrol engines

c. switching transients

d. discharge lighting, etc

10.1.4 The effects of these noise sources on radio communications may be overcome locally if the specific source can be identified. Where an individual source cannot be identified these unwanted signal sources set a man-made noise background level.

10.1.5 The impact of man-made noise on digital communications systems depends on the characteristics of impulsive noise such as pulse power, duration and interval. The noise can impact on both the RF and IF stages and cause variations in AGC, carrier loss, synchronisation loss, and codeword errors. The detailed behaviour, however, is dependent on both the system implementation and the noise characteristics and consequently further work is required to fully characterise this.

10.1.6 Man-made noise models currently available within ITU are carried through from CCIR Report 258-5 [1990]. This report is largely based on measurements made in the USA in the years leading up to 1974 when digital RF systems were not widely deployed. The approaches currently adopted within ITU at lower (HF) frequencies, where a median noise level can be measured, may not be appropriate at VHF and higher frequencies particularly for digital systems. At these frequencies semi-impulsive peak levels may affect system performance even though the measured median noise-level is below the internal noise level. Consequently, it is likely that the bandwidth parameter currently used to describe the non-Gaussian nature of the noise may not be adequate, particularly for wide-band systems.

10.1.7 The Noise Amplitude Distribution (NAD), which gives the number of pulses per second which exceed a given strength (or, strictly, a given energy), is considered to be the most appropriate noise descriptor for digital systems. A model based on this concept has not been developed but some limited measurements have been made.

10.1.8 The review concludes that the characteristics of man-made noise (i.e. pulse power, duration and interval) should be measured at a number of frequencies (between 40MHz and 3GHz), in differing environments and at different times of day/week/year to enable a more accurate model to be developed. To monitor long term variations of man-made noise these measurements should be repeated every five years.

10.1.9 To obtain the required man-made noise data, the requirements for a measurement programme indicate that data should be collected from 8 locations. These are: (large) city centre, factory estate, business centre, town centre, shopping centre/mall, major highway, suburban, and rural. The temporal characteristics should be obtained by performing measurements at mid-morning, evening, and the rush hour (in relevant environments).

10.1.10 It is anticipated that statistically significant measurements may be obtained with measurement periods shorter than one hour. A system with a 10MHz measurement bandwidth sampled at 25MHz to 14 bits resolution will require a 50MB of storage per second. To reduce the amount of data storage required, however, real-time on-board data pre-processing could be implemented.

10.1.11 The main elements of a modern digital measurement system have been considered and a system architecture is outlined. Such a digital system could be used to satisfy the measurement programme requirements detailed above. The system comprises a minimum of one general coverage receiver with an IF output of a bandwidth at least equal to the largest measurement bandwidth required. Much of the functionality of such a system can be realised by using off-the-shelf components.

10.2 Conclusions

10.2.1 The current approaches within ITU at lower (HF) frequencies, where a median noise level can be measured, may not be appropriate at frequencies above VHF, particularly for digital systems. At these frequencies semi-impulsive peak levels may affect system performance even though the measured median noise level is below the internal noise level. Consequently, it is likely that the bandwidth parameter used to describe the non-Gaussian nature of noise may not be adequate, particularly for wide-band systems. Regarding currently available man-made noise models, much of the current information within the ITU forum is carried through from CCIR Report 258-5. This report is largely based on measurements in the USA made in the years leading up to 1974 when digital RF systems were not widely deployed.

10.2.2 The Noise Amplitude Distribution, which gives the number of pulses per second, which exceed a given strength (or, strictly, a given energy), is considered to be most appropriate for digital systems. A prediction method based on this concept has not been developed but a series of (limited) measurements have been made.

10.2.3 Much work needs to be done to confirm the performance of commercial digital receivers in a man-made noise environment. The impact of very large impulses needs to be investigated, as strong impulses may cause 'ringing' within the demodulator filter, resulting in multiple symbol errors.

10.2.4 It is concluded that a measurement for man-made noise may be implemented using digital technology using off-the-shelf components.

10.3 Recommendations

10.3.1 It is recommended that:

1. Man-made noise data to support future digital systems and spectrum efficiency should be characterised and modelled.
2. The most appropriate method for digital systems is to produce statistics of Noise Amplitude Distributions (NAD) above a defined threshold, at a number of frequencies between 40MHz and 3GHz.
3. A risk reduction exercise should be pursued to measure the noise environment in a few key locations, using low cost equipment. This will establish if narrow-band noise, from computing or telecommunication equipment is likely to be a significant risk component of man-made noise. Such an exercise could also provide preliminary impulsive noise characteristics and contribute to the definition of the measurement hardware.
4. The measurement programme should consider man-made noise from differing environments such as: urban, sub-urban, industrial, business area, and along busy roadways, etc.
5. The programme should also consider the temporal characteristics of man-made noise and perform measurements appropriately, e.g. every four hours, weekends, seasonally.
6. The maximum communications bandwidth of at least 5MHz should be considered at frequencies ranging from 40MHz to 3 GHz.
7. In parallel to the measurement programme the impact of impulsive noise on (technology neutral) digital communications systems should be investigated to provide an indication of the amplitude thresholds critical to system disruption.

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